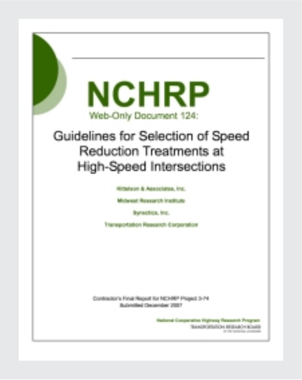

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Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections

Kittelson & Associates, Inc.
Midwest Research Institute
Synectics, Inc.
Transportation Research Corporation

Contractor's Final Report for NCHRP Project 3-74
Submitted December 2007

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Abstract

This project identified and evaluated treatments and developed guidelines for reducing vehicle speeds on approaches to high-speed intersections (approach speeds of 45 mph or greater). Phase I involved conducting a literature search and state agency survey to obtain information about speed reduction treatments currently being used throughout the nation, developing a testing plan for conducting treatment testing, and creating a framework for the research guidelines. Phase II involved conducting field testing of three types of treatments (transverse pavement markings, rumble strips, and dynamic warning signs) at ten sites in Oregon, Washington, and Texas, and developing a set of Guidelines for applying speed reduction treatments.

The research focused on geometric design treatments and considered traffic signs and pavement markings on signalized, unsignalized, and roundabout intersections. The treatments investigated were: reduced lane width, visible shoulder treatments, speed tables, rumble strips, roadway environment, approach reverse curvature, roundabouts, splitter islands, wider longitudinal pavement markings, transverse pavement markings, and dynamic warning signs.

Speed reduction treatments were investigated to determine their applicability, key features, speed effects, safety benefits, multimodal impacts, and maintenance issues. A survey of state highway agencies provided information about the types of speed reduction treatments that are currently being used and the agencies' estimated effectiveness of each treatment.

The research team coordinated with state agencies to identify candidate treatment testing sites and conduct a treatment selection and implementation process. Before-and-after testing was conducted using tape switches to estimate the effectiveness of each type of treatment installed. Transverse pavement markings were installed at five sites in Oregon. Dynamic warning signs were installed at two sites in Washington and Texas. Rumble strips were installed at three sites in Texas.

As a final research product, the research team wrote the *NCHRP Report 3-74: Guidelines for Selecting Speed Reduction Treatments at High Speed Intersections ("Guidelines")* to assist roadway planners, designers, and operators as they consider and select appropriate speed reduction treatments at intersections located in high-speed environments. The application of these treatments most often applies to existing intersections that experience undesirably high speeds; however, the information is also relevant to new intersection designs.

The *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 U.S. and abroad, including their effectiveness and implementation considerations. The *Guidelines* also provide insights on the relationship between speed and facility operations. 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 Introduction

1.1 PROJECT OVERVIEW

The purpose of this research project was to identify and evaluate treatments and develop a set of guidelines that can be used by transportation professionals for reducing vehicle operating speeds on approaches to high-speed intersections. The research focused on geometric design treatments and also considered traffic signs and pavement markings. The treatments focused on signalized and unsignalized intersections with approach speeds of 45 mph or greater.

The products that resulted from this research are a prioritized list of potential speed reduction treatments for intersection approaches that might be used and a menu of different applications (e.g., new design versus retrofit, high crash locations, and crash locations exhibiting specific crash types) and a set of guidelines on the application of these treatments as design features for newly constructed intersections, and mitigation treatments for existing intersections, including the results of a testing program that determines treatment effectiveness.

To provide an appropriate technical basis for the guidelines, the research team developed and conducted a treatment testing program at ten intersections in Oregon, Washington, and Texas. The team assessed the most appropriate methods to evaluate those treatments to determine their effectiveness in reducing speeds on intersection approaches and chose to use actual field testing in cooperation with state highway agencies. Once potential treatment sites were identified, the team worked with the state and county agencies to identify appropriate treatment installations, develop a treatment location layout, design the treatment and layout the data collection plan.

1.2 THE PURPOSE OF THIS FINAL REPORT

This Final Report is to document the entire research effort including the research methodology, findings, and suggested future research. This report summarizes the literature review findings, state agency survey, testing plan, treatment installation, data collection plan, testing results, and the development of the Guidelines. A key finding is that, although speed has been studied frequently, intersection-specific information about speed, the factors that affect speed, potential speed reduction treatments, and specific applications of these treatments is limited. Based on these findings, the research team has developed Guidelines for selecting treatments and potential testing plan that could be applied to potential speed reduction treatments. The Guidelines is being published as a separate document than this Final Report. Therefore, this report provides an overview of the Guidelines development and information included in each section.

1.3 SUMMARY OF PHASE I RESEARCH ACTIVITIES

The research team conducted a literature search on an extensive list of potential speed reduction treatments. The search included national and university online catalogues and databases [e.g. Transportation Research Board (TRIS), University of California, Berkeley (Melvyl), and Northwestern University (NuCAT)]; federal agencies (FHWA, NHTSA, and the Access Board); transportation organizations (ITE); and general search engines (Google and Yahoo). In addition to these formal searches, our team members contacted numerous colleagues and professionals to obtain information or leads on new sources. Key words used during the literature search were identified from the Research Plan and were tried in a variety of alternative forms to retrieve as many potential information sources as possible. Examples of key words include "speed reduction treatments," "high-speed intersections," and "intersection safety."

Abstracts were collected for each document that appeared to be relevant to the project objectives. A list of these documents is provided in *Appendix A*. To help prioritize the documents and identify which documents to obtain, a list of criteria was developed to screen the collected abstracts. The criteria summarized the critical concepts and general information outlined in each task of the Amplified Research Plan. A source that did not provide insight on the criteria was screened out as not having specific relevance to the research goals. The criteria used for screening the abstracts are shown in *Appendix B*.

The following represents a summary of the information trends that have resulted from this review:

- There is a significant amount of information associated with speed characteristics and factors that affect speed, but little quantifiable data on those factors.
- There is very little information specific to speed at intersections; most information relates to roadway segment locations.
- There is extensive information about safety but little direct correlation between speed and safety, especially for intersections.
- There are a variety of potential speed reduction treatments, but very little quantifiable data about their effectiveness.

There are numerous documents on understanding speed issues (design, operating, and posted). There is extensive information and interest about speed reduction (traffic calming and construction work zones). However, much of the information relates to segment or roadway volumes. Relatively little published research or testing results have been found for speed reduction treatments specifically for intersection approaches.

The quantity and quality of the information available and collected for each treatment varied. For example, the team collected substantial information on rumble strips, speed tables, roundabouts, transverse pavement markings, reduced lane width, and dynamic warning signs. However, limited information was found regarding visible shoulder treatments, roadway environment, splitter islands, approach reverse curvature, and wider longitudinal pavement markings.

The research team prepared and distributed a survey to a variety of highway agencies. The survey solicited specific suggestions on potential treatments, and requested expressions of interest in participating in the treatment evaluation process later in the project. Multiple ways to respond were provided to maximize the number of responses. Hard copies of the survey were distributed on October 15, 2004. Emails were distributed on October 16, 2004.

The research team compiled and evaluated the results from the state agency survey. A total of 36 responses were received, out of the 50 questionnaires that were mailed, for a response rate of

72 percent. The highway agency responses to each question in the survey were summarized to determine the types of speed reduction treatments that are currently being used and the agencies estimated effectiveness of each treatment. No new information regarding speed reduction treatments was uncovered from the state highway agency survey; however, several agencies expressed an interest in this study and reaffirmed the necessity of such research.

The survey was designed to allow agencies to share their input about what speed reduction treatments they felt were most important to be evaluated when determining a level of effectiveness. The survey responses indicated that dynamic-warning speed activated signs and rumble strips in the traveled way are the most important treatments to be tested for effectiveness.

The team also identified agencies interested in testing potential treatments during Phase II of this project. The State Agency Survey section of the Interim Report presents the treatments that are being sought for study along with which states have indicated a willingness to cooperate in such a study. These results were used to prioritize treatments for the testing plan. The team plans to follow-up with these state agencies to obtain additional details about their implementation plans and begin coordination for testing.

Another information trend that has been investigated by the research team is the feasibility of measuring safety effects of speed reduction treatments. Overall, it is difficult to measure the safety effects; safety evaluations can potentially last many years to adequately assess the short, mid, and long-term effects of a treatment. Therefore, the research team's focus was to develop a testing plan that will determine which treatments reduce vehicle speeds and quantify the expected amount of speed reduction, although it is widely agreed in concept that reducing operating speeds of vehicles at intersections should reduce the severity of crashes. Therefore, a treatment that does not prove be effective at reducing speeds would not be carried forward to a safety evaluation. Further, if a treatment was found to be ineffective at reducing speeds (although there may be other benefits), the profession would benefit by having this documented.

1.4 SUMMARY OF PHASE II RESEARCH ACTIVITIES

One of the primary outcomes of the Phase I activities was a testing plan and a list of four treatments that the research team recommended for testing. These treatments included: rumble strips, transverse pavement markings, dynamic warning signs, and approach curvature. A "before-and-after" approach was used to evaluate the effect each treatment has on speed. Speeds were measured at selected locations on the intersection approach before and after the subject treatments were implemented. The "after" measurements were taken a minimum of three months following a treatment's installation. This acclimation period allowed the novelty of the treatments to subside and motorists to adjust to their presence.

This research project funded the treatment tests; however, the cost to install the treatment was the responsibility of the state or county agency involved. Therefore, the research team contacted various individuals and groups to identify states or counties that were interested in participating in the research and/or had plans to install a speed reduction treatment. As multiple candidate sites were identified in states throughout the nation, the team underwent a site screening process to refine the list of potential sites and screen sites that did not seem to meet the research objectives.

The final list of candidate sites included ten intersections in Oregon, Washington, and Texas. The Oregon sites installed transverse pavement markings at all five sites, the Washington site installed a dynamic warning sign and the Texas sites installed rumble strips at three sites and a dynamic warning sign at one site. Approach curvature was prohibitive as a treatment because it requires construction and is more costly than other treatments, based on the need for roadway widening and partial roadway reconstruction in some cases.

After the treatment selection process was completed and a treatment was identified for each site, the team used aerial images and the existing roadway and intersection features to identify appropriate locations for the treatment installations. For the majority of the sites, treatment schematics were developed to illustrate the appropriate treatment implementation locations. In addition to the treatment layout schematics, the research team also designed some of the treatments for specific sites.

In conjunction with the treatment selection and layouts, the research team also investigated various data collection equipment and procedures to determine the most comprehensive and effective means of collecting speed data during field testing. The methodologies that were investigated are: Hi-Star devices, tape switches, and video photography. Based on conversations with many other researchers and the team’s own investigation, tape switches were ultimately determined to be the most appropriate device for the speed data collection.

As part of the Phase I activities, the research team developed a data collection scheme with four data collection points on each subject intersection approach. Based on this data collection scheme, the research team prepared data collection plans for each of the sites, identifying the appropriate locations to collect speed data during “before” and “after” data collection.

Before-and-after testing was conducted from April 2006 to March 2007. Once the before testing was completed, the research team coordinated with each agency to install treatments at each of the testing sites. Due to the three-month acclimation period, installing the treatments in a timely manner was a high priority to meet the overall project timeline.

Data analysis and summarization of the testing results occurred after each of the testing sites was completed. In addition, all of the testing results and data analysis was refined after the completion of testing at all sites. 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
- Analysis by Treatment Type – to quantify the effect of each treatment across all intersection approaches at which it was installed

Overall conclusions from the testing results include:

- All three treatment types may reduce speeds on high-speed intersection approaches; however, 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 intersection would first become visible to the driver or where the driver might first react to the intersection.

- Of the three treatment types tested, dynamic warning signs activated by speed may be the most effective at reducing speeds. However, this conclusion is based on only three intersection approaches.

- Peripheral transverse pavement marking also appear 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.

As described previously, the purpose of this research project was to identify and evaluate treatments and develop a set of guidelines that can be used by transportation professionals for reducing vehicle operating speeds on approaches to high-speed intersections. Therefore, in addition to the treatment testing, Phase II also included the development of NCHRP Report 3-74: *Guidelines for Selecting Speed Reduction Treatments at High Speed Intersections* ("*Guidelines*"). This document is intended to assist roadway planners, designers, and operators as they consider and select appropriate speed reduction treatments at intersections located in high-speed environments. While the application of these treatments most often applies to existing intersections that experience undesirably high speeds, the information is also relevant to new intersection designs. The Guidelines are not a new standard for implementing treatments. Rather, they are informational, describing good practices for selecting treatments.

The *Guidelines* apply to intersections with approach speeds of 45 miles per hour (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. This document focuses on public roadway intersections; however, many principles also apply to private driveways that include public-roadway–like features.

The *Guidelines* include the following four sections and appendices:

- *Section 1* introduces the *Guidelines* and presents their purpose, scope and applicability.

- *Section 2* focuses on the role of speed in an intersection environment and discusses the ways in which speed affects intersection performance and the adjacent environment.

- *Section 3* guides users through the process of selecting speed reduction treatments for intersection approaches. The process includes: intersection pre-screening; treatment screening; and treatment implementation.

- *Section 4* describes speed reduction treatments in detail. 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. Photos and diagrams are also provided. The

- The appendices to the *Guidelines* provide a diagnostic flow chart, scenario-based case studies, testing data and results from the testing plan, and references to other relevant studies.

In addition to the research findings and *Guidelines* that resulted from this NCHRP project the research team found as many questions as it did answers throughout the course of this research effort. Therefore, given the limits and focus of this research project, during Phase II the team also identified other research topics for future consideration.

1.5 FINAL REPORT ORGANIZATION

This Final Report is organized into seven chapters with supplemental information provided in the appendices:

- *Chapter 1* – Introduction
- *Chapter 2* – Preliminary Findings
- *Chapter 3* – Testing Plan
- *Chapter 4* – Treatment Installation
- *Chapter 5* – Testing Results
- *Chapter 6* – Guidelines
- *Chapter 7* – Future Research Suggestions
- *Appendix A* – Literature Review Abstracts
- *Appendix B* – Criteria for Prioritizing Sources
- *Appendix C* – State Agency Survey
- *Appendix D* – State Agency Survey Mailing List
- *Appendix E* – Process for Selecting Recommended Treatments
- *Appendix F* - Histograms of Speed Profile Data at 10 Sites
- *Appendix G* - Speed Analysis by Individual Approach Location
- *Appendix H* - Secondary Analysis of 85th-Percentile Speeds

2 Preliminary Findings

2.1 SPEED CONSIDERATIONS

2.1.1 Introduction

Improving safety has long been a goal of the FHWA, NHTSA, AASHTO, ITE, and safety advocacy groups such as the Insurance Institute for Highway Safety. With over three million intersections (300,000 signalized) and nearly 9,000 intersection fatalities per year in the United States, improving safety at roadway junctions has received increased focus and energy. High-speed environments increase the potential for more fatalities and injury severity for motorists and non-motorists alike.

While 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, 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 to 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.

The following 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 and highlights some physical conditions and user characteristics that may make an intersection particularly sensitive to speed.

2.1.2 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. As described in the *Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections,* which was developed as part of this research effort, intersections can be defined by geometric and operational influence areas:

- **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 (such as 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.

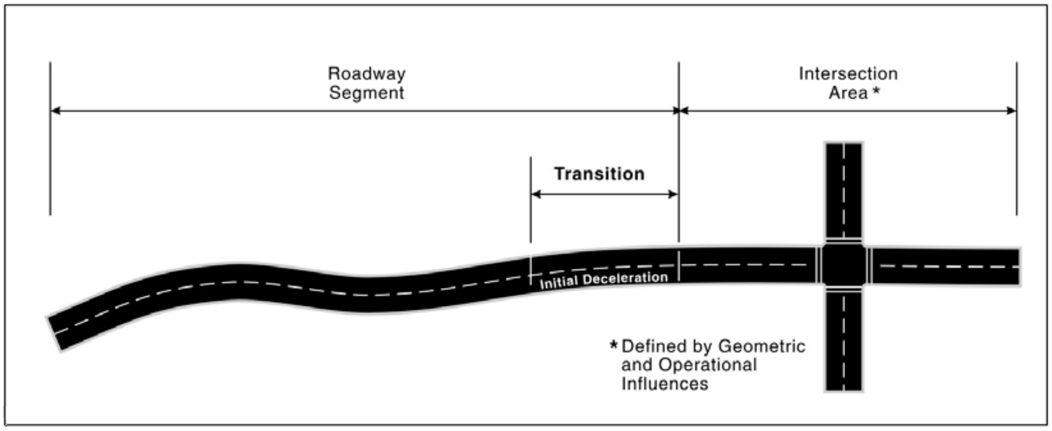


Exhibit 2-1 Roadway Segment and Intersection Speed Relationships

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 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).

2.1.3 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, with higher speeds generally associated with longer trips and lower speeds generally associated with shorter trips or with facilities that have more frequent access. Posted speeds frequently correlate with these intended uses. High-speed facilities serve key network needs and 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 that may not be apparent 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; it is typically 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. At intersections, drivers must perceive and comprehend a greater variety of situations than they need to 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.

2.1.4 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. The 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.

2.1.4.1 Facility Size

Drivers' perception-reaction time 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 stopping-sight-distance dimensions 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 intersection sight distance values from the *AASHTO Green Book* for the case of a right turn from a stop or a crossing maneuver, the intersection-sight-distance value for 45 mph is 430 feet. This value increases to 575 feet 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.

2.1.4.2 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 elderly, young, and disabled people, may be particularly sensitive to high speeds.

2.1.4.3 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 increased traffic volume), and consequence (which 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; while 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 creates high differentials in speeds between vehicles traveling in the same direction. For example, 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. 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, 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 higher crash frequency may result.

High-speed travel may affect crash avoidance because faster moving vehicles travel farther 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, while 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.

2.1.4.4 Traffic Operations

Traffic operations refers to the performance of a roadway facility 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 intersections has little effect on overall travel time.

2.1.4.5 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 3-46 (Capacity and Level of Service at Unsignalized Intersections) found that speed did not have a significant effect on 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 queues vehicles are starting from a stopped position, a vehicle's speed through an intersection is not relevant in the calculation.

2.1.4.6 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 1000 feet, the travel time difference between a vehicle traveling at 50 miles per hour versus a vehicle traveling at 30 miles per hour through the intersection is less than 10 seconds, assuming an uncontrolled approach or a "green light" without interfering queues.

2.1.5 Factors that Affect Speed

A driver's selection of a safe speed and path is determined by his or her judgments, estimates, and predictions based on highway characteristics, traffic, and traffic control devices. (NCHRP 3-50(2)). Roadway design elements, environment, traffic type, and other factors help drivers determine an appropriate speed. Some elements affect traffic flow directly, while 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 in drivers' speed choice.

2.1.5.1 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*.

Exhibit 2-2 Roadway Facility Characteristics That May Affect Intersection 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 undeveloped 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.

2.1.5.2 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.

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.

2.1.5.3 Intersection Design and Characteristics

The physical characteristics of the intersection proper affect speed as do the changing conditions at the intersection such as the 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.*

Exhibit 2-3 Intersection Characteristics That May Affect Intersection Speed

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.

2.1.5.4 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.

2.1.5.5 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.

2.1.6 Identifying Conditions Potentially Sensitive to Speed

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

2.1.6.1 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 Table 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 sensitivite to speed. Examples include:

- **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** – require 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.

2.1.6.2 Observed Field Conditions

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

2.1.6.3 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 cues 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).

2.1.6.4 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.

2.1.6.5 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 2.3.4), 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.

2.1.6.6 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 *AASHTO Green Book*'s 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.

2.1.6.7 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:

- **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
- **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.

2.1.7 Highway Safety Information System (HSIS)

One of the most comprehensive sources available to analyze crash characteristics and trends associated with specific geometric roadway and traffic volume conditions is the Highway Safety Information System (HSIS) database. The HSIS database was developed by the Federal Highway Administration and is currently maintained by the University of North Carolina Highway Safety Research Center. The database includes detailed crash data from nine participating states. The HSIS data files vary from state to state because they are reflective of the particular data elements and characteristics that each state deems relevant for use in managing the safety issues involved in its highway system.

As part of the development of the FHWA guide, *Signalized Intersections: An Informational Guide*, a detailed analysis was conducted of the California HSIS database. The California database includes the greatest breadth of data elements and characteristics for signalized intersections of the participating states.

The objective of the safety analyses was to measure the relative risk and safety effectiveness for various treatments and characteristics of signalized intersections.

The interim report developed for the FHWA *Signalized Intersection Guide* project titled "Task A – Critical Review of Literature and Comparison of Risk Levels Associated with Different Treatments at Signalized Intersections" (Kittelson & Associates, Inc., Synectics Inc., and CH2M Hill, March 2002) provides an analysis of relative safety risk for various roadway geometric and traffic design characteristics such as:

- Intersection type
- Traffic control type
- Mainline number of lanes
- Mainline left-turn channelization

Crash summaries were also provided for various thresholds of average daily traffic volumes.

Since the scope of the risk analysis conducted for the FHWA Signalized Intersection Guidelines project was to evaluate whether any risk differentials exist among signalized intersections due to different roadway-related characteristics and attributes (e.g., operations and geometrics), driver-related causes of collisions such as 'speeding' were not part of the study. Also, the project included intersections of both lower speed and higher speed intersections, not just high-speed intersections. Thus, the findings from the analysis are not relevant to NCHRP 3-74.

The HSIS database for California and Minnesota could be further investigated to identify the characteristics of crashes at intersections where excessive speeding was listed as a contributing factor. In addition, an analysis could be performed to identify safety characteristics of intersections based on the posted speed and design speed of the approaching roadways. In principal, one could conduct an analysis to identify whether any particular intersection type experiences over-representation of collisions where the speeding is the major factor. However, study results would have several limitations due to missing data in the database. It is not recommended that the HSIS databases be explored further, given the limitations that will be associated with the results and the time and effort that will be expended in obtaining the data from HSIS, organizing the data, and setting up the analysis specs, and given the little return expected in advancing our knowledge and understanding of intersection types and their characteristics that are most affected by speeding and unsafe speed-related factors.

A detailed HSIS database investigation and statistical analysis is outside of the scope of NCHRP 3-74 and was not be conducted as part of this work effort. However, future research projects might focus on or include a robust evaluation of HSIS data to better understand the safety relationship between posted and operating speeds at intersections.

2.1.8 Summary

Reduced speeds do not guarantee safety, 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.

2.2 TREATMENT DESCRIPTIONS

2.2.1 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, while others are specific intersection applications. Once the intersection characteristics described in Section 3 have been assessed, the user can use the information in the chapter 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 reverse curvature

- Splitter islands
- Speed tables
- Reduced lane width
- Visible shoulder treatments
- 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.

2.2.2 Dynamic Warning Signs

Overview

Documented applications for high-speed intersections	Three test sites: one in Washington and two in Texas
Function	Alert drivers of the need to reduce their speed, encourage earlier deceleration
Applicability	Rural unsignalized, in advance of abnormal roadway features
Design Variations	Speed activation, message, image, size, location
Secondary Effects, Considerations	Driver workload, power supply

2.2.2.1 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 they are brought to their attention (Maze, 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 the Washington and Texas for the NCHRP 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 expect 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 the pedestrian and bicycle zones, they are not expected to impact multimodal users.

Exhibit 2-4 Dynamic Warning Sign (Photo: WSDOT)

Exhibit 2-5 Dynamic curve-warning sign (Photo: TXDOT)

Exhibit 2-6 Dynamic warning sign used as a Collision Avoidance System (Photo: PennDOT)

2.2.2.2 Treatment Layout/Design

Dynamic warning signs 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. The 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 should also 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.

2.2.2.3 Speed Effects

Dynamic warning signs reduced speeds significantly at the three high-speed intersection approaches tested through the NCHRP 3-74 project. Speed data was collected at three locations on each intersection approach. A mean speed reduction of 1.7 mph was observed at the sign locations after a three-month acclimation period. At the perception-reaction data collection 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 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 (2003).

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 to 40 percent. Maze concluded that the placement of the signs can impact the effectiveness of this treatment. (Maze, 2000)

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 speed if they had exceeded the maximum safe speed. (CH2M Hill, 2004) (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)

2.2.2.4 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. (CH2M Hill, 2004)

2.2.3 Transverse Pavement Markings

Overview

Documented applications for high-speed intersections	Eight test sites in Oregon
Function	Improve visibility, driver attention
Applicability	Visual cue reinforcing changing conditions and need to reduce speed
Design Variations	Peripheral or full transverse lines
Secondary Effects, Considerations	Long-term effectiveness, driver familiarity

2.2.3.1 Applicability and Considerations

As defined by the *Manual on Uniform Traffic Control Devices* (MUTCD), transverse pavement markings are “pavement markings that are generally placed perpendicular to and across the flow of traffic” (FHWA, MUTCD, 2003). Peripheral transverse lines involve bars only at the edge of 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, 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, 1995). Transverse pavement markings have also been placed at locations where excessive speed was a contributor to crashes and other speed reduction treatments had not been effective (Agent, 1980).

Exhibit 2-7 Peripheral Transverse pavement markings

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.

2.2.3.2 Treatment Layout/Design

Transverse pavement markings should be placed in a location that provides adequate advance warning time for drivers to reduce their speed appropriately. The placement of transverse pavement markings that is optimal to reduce speeds on intersection approaches has not been quantified. The *AASHTO Green Book* 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, MUTCD, 2003). 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, lane-use legends, stop lines, crosswalks 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.

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 is no data to support this claim (Agent, 1980).

2.2.3.3 Speed Effects

After a 90 day acclimation period, transverse pavement markings were found to reduce speed marginally at the four high-speed intersection approaches tested through the NCHRP 3-74 project. 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 to 30 percent. (Katz, 2003) (Griffin, 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 percent, and the overall 85th percentile speed throughout the day was reduced by approximately 30 percent. (Katz, 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 (optical speed bars) reduced 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.

2.2.3.4 Safety Effects

No published data was 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 study referenced below.

In 1993, a study in Osaka, Japan, reported that converging chevron pavement markings placed on the Yodogawa Bridge was 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, 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, 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 that reduced crashes, transverse lines were applied at 42 approaches to roundabouts. Each approach had a minimum of 3.2 km (2 miles) 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, speed were reduced by 57 percent. 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)

2.2.4 Transverse Rumble Strips

Overview

Documented applications for high-speed intersections	Five test sites in Texas
Function	Provide audible and tactile warning to encourage deceleration and reduce comfortable speed
Applicability	Generally STOP-controlled approaches; also toll plazas, horizontal curves, and work zones
Design Variations	Paved, rolled, or milled; raised or depressed; painted or not; cluster spacing
Secondary Effects, Considerations	Noise, motorcycle and bike impacts

2.2.4.1 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 Research and Tech., 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 a motorist with an audible and tactile warning that their vehicle is approaching a decision point of critical importance to safety.

While 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 Research and Tech., 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 varies by state and depends on the type of facility to which the treatment is being applied

Exhibit 2-8 Transverse Rumble Strips in Wheel Path (TTI)

Exhibit 2-9 Transverse Rumble Strips

Exhibit 2-10 Transverse Rumble Strips Across the Entire Travel Lane (Photo: Corkle et al.)

2.2.4.2 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. 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 *AASHTO Green Book* provide a starting point for locating the strips.

Transverse rumble strips can be installed to cover either the entire width of the travel lane or just the width of a vehicle's wheel path (Corkle et al., 2001). Exhibit 2-10 shows transverse rumble strips that stretch across the entire width of the driving lane. Exhibit 2-8 illustrates transverse rumble strips that only cover a vehicle's wheel path, enabling drivers familiar with the area to straddle the rumble strips to avoid driving over them.

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 combination of 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 types 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, 1997). Some agencies paint over rumble strips to make them more visible (FHWA Research and Tech., 2004). 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, 2004).

2.2.4.3 Speed Effects

At the high-speed intersection approaches tested through NCHRP 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 feet 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 feet 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 percent (Kermit and Hein, 1962) (Owens, 1967) (Khotari, 1992) (Zaidel et al., 1986) (Harder et al., 2001). However, it has also increased speed variance. (Morgan, 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. found that transverse rumble strips produce 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 (2005).

2.2.4.4 Safety Effects

NCHRP Synthesis 191 (Harwood, 1993) summarized ten 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 2005 TTI study found that transverse rumble strips produced marginal safety benefits at best, only slightly reducing erratic lane movements (Miles, 2005).

2.2.5 Longitudinal Rumble Strips

Overview

Documented applications for high-speed intersections	None
Function	Provide audible and tactile warning to reduce comfortable speed and minimize off-the-road and crossover crashes
Applicability	Rural undivided highways
Design Variations	Paved, rolled, or milled; raised or depressed; painted or not; cluster spacing
Secondary Effects, Considerations	Noise, motorcycle and bike impacts

2.2.5.1 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, 2004). 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 generally located either are placed on either side of the centerline (Exhibit 2-11), along the width of the centerline pavement markings (Exhibit 2-12), or extend slightly into the travel lane (Exhibit 2-13). 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.

Exhibit 2-11 Centerline Rumble strips (Photo: MnDOT)

Exhibit 2-12 Centerline Rumble Strips on the Centerline Pavement Markings (Photo: Torbic et al.)

Exhibit 2-13 Centerline Rumble Strips Extending into the Travel Lane (Photo: Torbic et al.)

2.2.5.2 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.

2.2.5.3 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. The Federal Highway Administration is currently 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-foot lanes (Porter et al, 2004).

2.2.5.4 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 shown to be a very inexpensive and effective treatment for reducing the number of run-off-the-road crashes. Reports from Maine, New York, and California have reported run-off-road crash reductions of 20 to 72 percent 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-percent reduction for all injury crashes combined, as well as a 25-percent reduction for frontal and opposing-direction sideswipe injury crashes (Persaud et al., 2004).

2.2.6 Wider Longitudinal Pavement Markings

Overview

Documented applications for high-speed intersections	None
Function	Increase intersection visibility, attract driver attention to intersection ahead
Applicability	Older drivers, lack of driver expectancy
Design Variations	Width, length, reflectivity
Secondary Effects, Considerations	Speed may increase with increased visibility

2.2.6.1 Applicability and Considerations

Many departments of transportation increase the width of pavement markings to improve the visibility of centerline, lane line, and edge line striping and can provide added guidance to drivers from greater distances (Gates and Hawkins, 2002) (Hutchins, email). 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 they in the roadway segment.

The most common reasons that jurisdictions apply wider longitudinal pavement markings are to improve visibility, to assist older drivers, and to reduce crashes. Many departments of transportation 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 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, whose 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.

Exhibit 2-14 Examples of wider longitudinal pavement markings in France

2.2.6.2 Treatment Layout/Design

The placement and dimensions of wider longitudinal pavement markings on high-speed intersection approaches should be determined through a combination of a 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 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.

2.2.6.3 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. While 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.

The Federal Highway Administration is conducting demonstration projects in Alaska and Tennessee to evaluate the impacts and effectiveness of increasing the width of pavement marking edge lines from 4 inches to 6 inches. The report is due by June 30, 2009.

2.2.6.4 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 from their use.

There has been conclusive evidence to suggest that wider longitudinal pavement markings are easier for drivers to see, which can contribute to roadway safety (Gates, Chrysler, and Hawkins, 2002). The greatest improvement in visibility is achieved at night.

2.2.7 Roundabouts

Overview

Documented applications for high-speed intersections	Widely used throughout US, UK, France, and Australia
Function	Intersection geometry reduces speeds and conflict points
Applicability	Many types for varying applications
Design Variations	Type, size, lanes, geometry
Secondary Effects, Considerations	Operations, right-of-way, access, horizontal and vertical geometry, driver expectancy

2.2.7.1 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, *Roundabouts: An Informational Guide*, 2000). 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
- 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 speed reduction and the number and severity of collisions.

Exhibit 2-15 Single-lane roundabout (Photo: Oregon DOT)

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 have potential to be difficult for visually impaired pedestrians to navigate. NCHRP 3-78, "Crossing Solutions at Roundabouts and Channelized Turn Lanes for Pedestrians with Vision Disabilities," will provide additional information on the impacts roundabouts have on visually impaired pedestrians.

At single-lane roundabouts, bicyclists have the option to mix with traffic or use the pedestrian crossings. At multi-lane 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, *Roundabouts: An Informational Guide*, 2000).

2.2.7.2 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 key design features, including an appropriate design vehicle, is critical to ensure proper operations and safety for all users at roundabouts (FHWA, *Roundabouts: An Informational Guide*, 2000).

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 2-16.

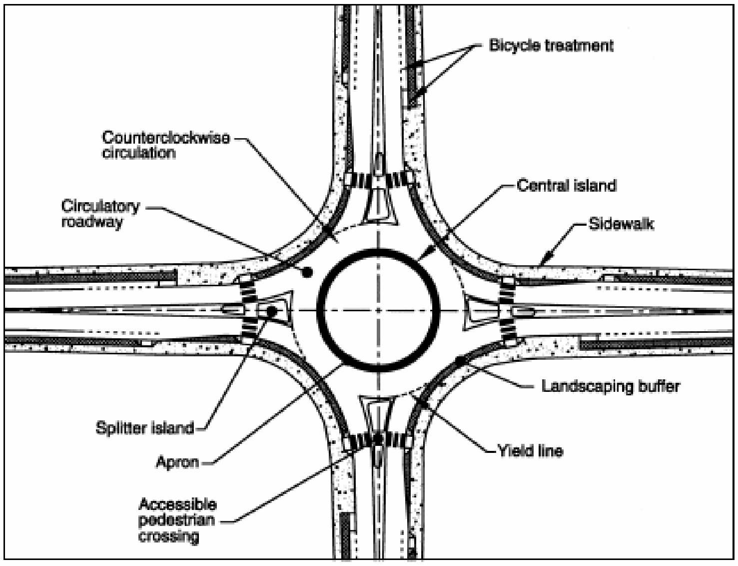


Exhibit 2-16 Key Roundabout Design Features (FHWA, *Roundabouts: An Informational Guide*, 2000)

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, *Roundabouts: An Informational Guide*, 2000).

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, *Roundabouts: An Informational Guide*, 2000).

2.2.7.3 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 to between 13 and 17 mph (NCHRP 572).

2.2.7.4 Safety Effects

One of the largest benefits of roundabout installation is the overall improvement to intersection safety. Research on crash reduction for conversions of all types of intersections to roundabouts (55 sites studied) found a 35-percent reduction in all crashes and 76-percent 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-percent reduction in all crashes and 87-percent reduction in injury crashes (NCHRP 572). The crash reduction is achieved because there are fewer conflict points at roundabouts than at conventional intersections and because speeds are reduced (FHWA, *Roundabouts: An Informational Guide*, 2000).

Single-lane and multi-lane 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 multi-lane roundabouts, a smaller reduction in total crashes was observed at the multi-lane roundabouts. Both single-lane and multi-lane roundabouts exhibit similar reductions in injury crashes (NCHRP 572).

Roundabouts improve the safety of bicyclists by slowing automobiles to speeds closer to bicycle speeds (thus reducing high-speed conflicts) and by simplifying turning movements for bicycles (FHWA, Roundabouts: *An Informational Guide*, 2000). Crashes involving bicycles comprise approximately 1 percent of all reported crashes at roundabouts (NCHRP 572).

Roundabouts also decrease the risk of severe pedestrian collisions, due to the reduced vehicle speeds and a reduced number of conflict points for pedestrians. A Dutch study conducted at 181 roundabouts found a 73-percent reduction in all pedestrian crashes and an 89-percent reduction in injury crashes for pedestrians (FHWA, *Roundabouts: An Informational Guide,* 2000). Crashes involving pedestrians comprise approximately 1 percent of all reported crashes at roundabouts (NCHRP 572).

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, *Roundabouts: An Informational Guide*, 2000).

2.2.8 Approach Curvature

Overview

Documented applications for high-speed intersections	Roundabout approaches only
Function	Introduce geometry to induce slower speeds
Applicability	New facilities, rural highways
Design Variations	Curve geometry
Secondary Effects, Considerations	Right-of-way, grading, driver workload, truck movements

2.2.8.2 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 2-17, approach reverse curvature consists of successive curves with progressively smaller radii. Research and applications of approach curvature have focused on roundabouts. However, this geometric design treatment has potential to be applied to conventional intersections.

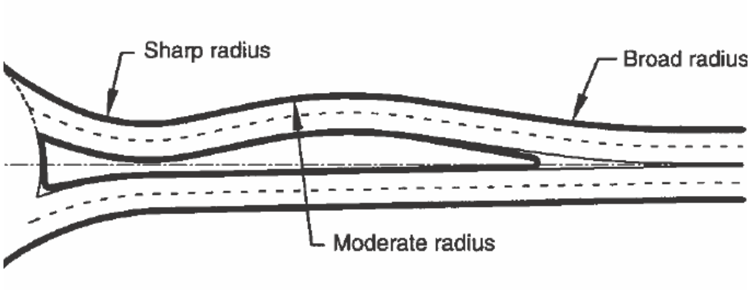


Exhibit 2-17 Approach Reverse Curvature (FHWA, *Roundabouts: An Informational Guide*, 2000).

Approach curvature consists of successive curves with progressively smaller radii. 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 reverse 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.

2.2.8.3 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 *AASHTO Green Book* joined with published documentation from Australian applications at roundabouts 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 reverse curves, each curve must be visible before the next curve to allow drivers adequate time to adjust speeds (Arndt, email). 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 (Arndt, email).

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.

2.2.8.4 Speed Effects

Current information about approach reverse 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 2-18 shows the speed-radius relationship for curves with +0.02 and –0.02 super-elevations.

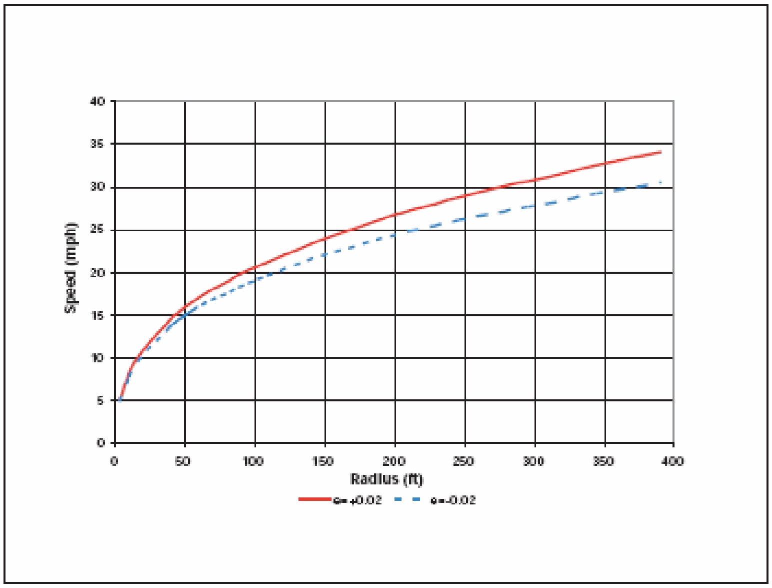


Exhibit 2-18 Speed-Radius Relationship (FHWA, *Roundabouts: An Informational Guide*, 2000).

2.2.8.5 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, *Roundabouts: An*

Informational Guide, 2000)

2.2.9 Splitter Islands

Overview

Documented applications for high-speed intersections	Roundabout intersection approaches and conventional intersection approaches in New Zealand and France
Function	Slow, direct, and separate conflicting traffic
Applicability	Stop- or yield-controlled approaches
Design Variations	Length, geometry, landscaping
Secondary Effects, Considerations	Splitter islands can provide refuge for pedestrians crossing at the intersection

2.2.9.1 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, *Roundabouts: An Informational Guide*, 2000). These islands can increase driver awareness by channelizing the traffic on the minor approaches.

In some cases, these treatments are called throat or fishtail islands; these are shown in Exhibit 2-19. The geometry of fishtail islands introduces deflection at the approach, thereby reducing vehicle speeds at the intersection.

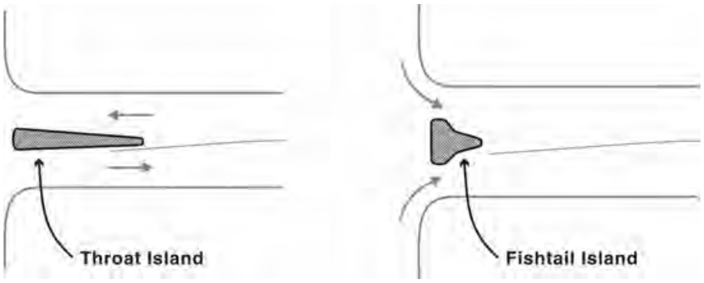


Exhibit 2-19 Throat and fishtail islands

While 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 2-20 depicts a photo of 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.

Exhibit 2-20 Splitter Island at a T-intersection in France

2.2.9.2 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 creating horizontal deflection. In Exhibit 2-21, 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 clue to drivers to slow before the intersection. Form B could potentially reduce speed by creating a deflected path, similar to a roundabout through movement.

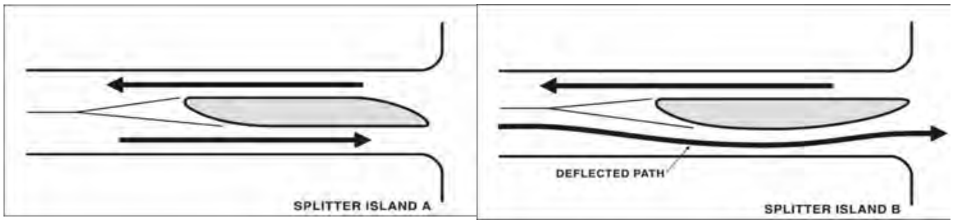


Exhibit 2-21 Splitter Islands

Exhibits 2-22 and 2-23 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 visibility of the intersection.

This splitter island can be mountable to allow larger vehicles to maneuver through the intersection. UK 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 US applications, a sign is usually mounted on the splitter island to increase its visibility

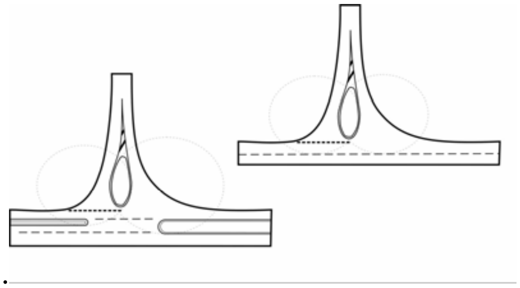


Exhibit 2-22 Example layout of a splitter island at a T-intersection

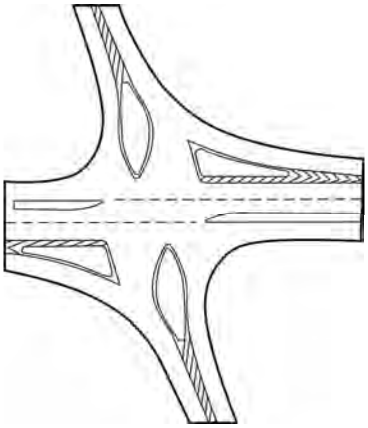


Exhibit 2-23 Example layout of a splitter island at a 4-legged intersection

2.2.9.3 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.

2.2.9.4 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 to 60 percent for fatal, injury, and pedestrian crashes during both the daytime and nighttime. 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) (FHWA, 2006).

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

2.2.10 Speed Tables and Plateaus

Overview

Documented applications for high-speed intersections	None
Function	Create vertical deflection, Alert drivers of the need to slow down
Applicability	Stop-controlled approaches
Design Variations	Geometry, materials
Secondary Effects, Considerations	Snow removal, driver expectancy

2.2.10.1 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 with decorative surface material or constructed with brick or other textured materials. Speed tables have gently sloped ramps on both ends, which allows slightly higher vehicle speeds and a smoother transition than speed humps (ITE, 2007).

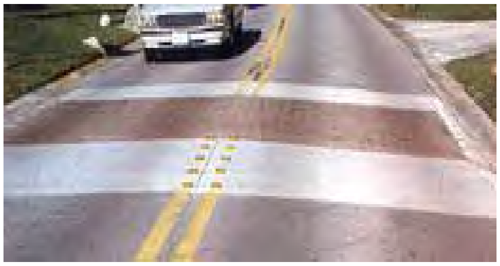


Exhibit 2-24 Speed table combined with textured pavement in Naples, FL (Photo: Fehr & Peers)

Exhibit 2-25 Speed table combined with striping and colored concrete in Charlotte, NC (Photo: Fehr & Peers)

A plateau is an alternative speed table design that has been used in the Netherlands and installed on facilities with speeds ranging from 60 km/h (35mph) to 80km/h (50mph). 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 et al., 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.

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.

2.2.10.2 Treatment Layout/Design

Speed tables and plateaus should be placed at a location where vehicles will not abruptly encounter the speed table at a high speed. The 1993 *ITE Guidelines for the Design and Application of Speed Humps* suggests that the first speed table in a series be placed no more than 200 feet from a stop sign or horizontal curve, and not within 250 feet 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, 2002).

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 feet long in the direction of travel, with a 10-foot flat section in the middle and six-foot 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 meters (165 to 325 feet) from the intersection and designed for a 40 km/h (25 mph) design speed (Schermers et al., 2001).

2.2.10.3 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-percent decrease in the 85th-percentile travel speeds for a sample of 58 test sites (Fehr & Peers, 2004). 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 Traffic Calming, 2007). When designed to the typical dimensions, speed tables have an 85th-percentile speed of 25 to 30 mph (ITE, 1999).

While the speed reduction potential of speed tables is not well known, the ITE 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 lower traffic volumes.

2.2.10.4 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 percent on streets treated with speed tables at particular test sites (ITE, 2007; Fehr & Peers, 2004).

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-percent reduction in traffic volumes based on 24-hour traffic counts collected on 18 streets before and after the speed tables were installed (Bretherton, 2003). ITE reported a 12-percent reduction in traffic volumes on roadways with speed table applications, depending on the availability of alternative routes (ITE, 2007).

2.2.11 Reduced Lane Width

Overview

Documented applications for high-speed intersections	None
Function	Heighten driver attention, narrow the available lane width
Applicability	Expect that narrowing the lane width on the intersection approach will produce similar effects to segment applications
Design Variations	Can involve re-striping only, or narrowing the paved section
Secondary Effects, Considerations	Use with caution with heavy truck traffic, multilane facilities, and curvilinear alignments

2.2.11.1 Applicability and Considerations

Reduced lane width could come in two basic forms: lanes narrowed with paint or a physically reduced roadbed width. 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 feet.

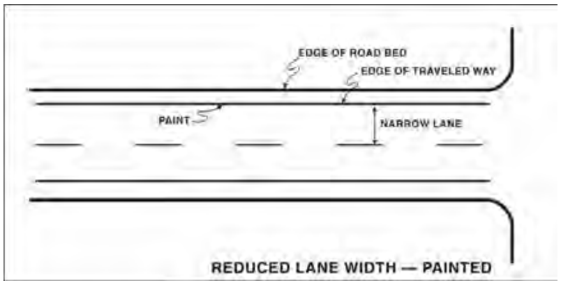


Exhibit 2-26 Reduced Lane Width – Painted

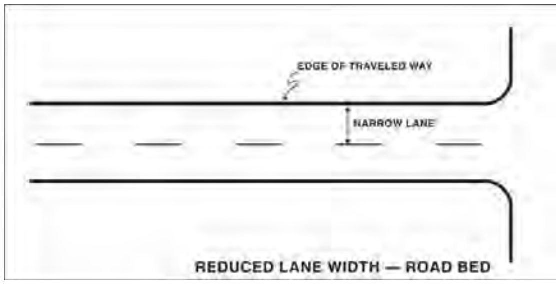


Exhibit 2-27 Reduced Lane Width – Road Bed

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 multi-lane 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 other positive effects such as space for other roadway features (such as medians, and curbside parking), space for roadside features (such as sidewalks and clear zones), and reduced interference with existing roadside development (Zegeer, 2002).

Reduced lane widths improve pedestrian conditions at intersections by reducing crossing distances and exposure time. Excessive crossing distances increase pedestrian exposure time, increase the potential of 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.

2.2.11.2 Treatment Layout/Design

NCHRP 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 feet 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 feet on four-lane divided arterials. These findings are consistent with the *AASHTO Policy on Geometric Design of Highways and Streets*, which recommends lane widths of 10 to 12 feet 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.

2.2.11.3 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 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 feet 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 HCM
- 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-percent reduction in speed was achieved by reducing lane widths to 11.5 and to 12.5 feet (Benekohal, 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 *Highway Capacity Manua*l (HCM) suggested that wider lanes on multi-lane highways also increase capacity and, therefore, reduce following distances (TRB, 1985). However, HCM editions since 1985 have indicated that wider lanes, up to 12 feet, on multi-lane highways increase free-flow speeds but do not increase capacity and, therefore, do not reduce vehicle headways (TRB, 1994; TRB, 2000).

2.2.11.4 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:

- 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 3-72 found no decrease in safety at mid-block locations or intersection approaches with narrow lanes except in these limited cases:

- Four-lane undivided arterials with lane widths less than 10 feet
- Four-lane divided arterials with lane widths less than 9 feet
- Four-leg stop-controlled intersections with lane widths less than 10 feet

Research by Harwood et al. developed accident modification factors (AMFs) for accident 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-foot lanes compared to 12-foot 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 accidents as a roadway with 12-ft lanes. However, some studies indicate that lanes wider than 12 feet may also be associated with higher crash frequencies.

2.2.12 Visible Shoulder Treatments

Overview

Documented applications for high-speed intersections	None
Function	Heighten driver attention, narrow the visual width of the roadway
Applicability	Transition areas, roadways with existing shoulders, roadways in rural areas with no sight line limitations
Design Variations	Many
Secondary Effects, Considerations	Depending on the materials, bicyclists using the shoulder may be impacted

2.2.12.1 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 2-28 shows an example of a visible shoulder treatment that used brick.

Exhibit 2-28 Example of a shoulder composition application (Photo: Dan Burden)

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. Shoulders colored black 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, 1969).

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

2.2.12.2 Treatment Layout/Design

Shoulder dimensions are typically 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.

2.2.12.3 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.

2.2.12.4 Safety Effects

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

2.2.13 Roadside Design Features

Overview

Documented applications for high-speed intersections	None
Function	Reinforce transitioning environment, draw attention to multimodal users, reduce comfortable approach speeds
Applicability	Many applications
Design Variations	Roadside design features, gateways, and landscaping
Secondary Effects, Considerations	Sight distance

2.2.13.1 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. Landscape improvements should not be planted in an area that obstructs signs, sightlines, 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 are prominent physical features that inform drivers they are transitioning into a new roadway environment and can include landscaping, lighting, signage, or physical structures.

Exhibit 2-29 Landscaped median treatment (Photo: FHWA FHD)

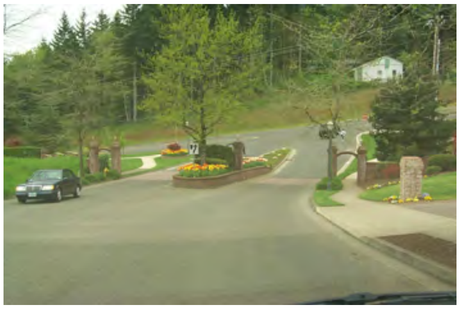


Exhibit 2-30 Gateway

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 feet from the edge of a travel lane to allow maintenance crews to work without being in danger of passing vehicles (Mok, 2006).

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.

2.2.13.2 Treatment Layout/Design

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

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

2.2.13.3 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, McDowell, and Rockwell (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)

2.2.13.4 Safety Effects

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

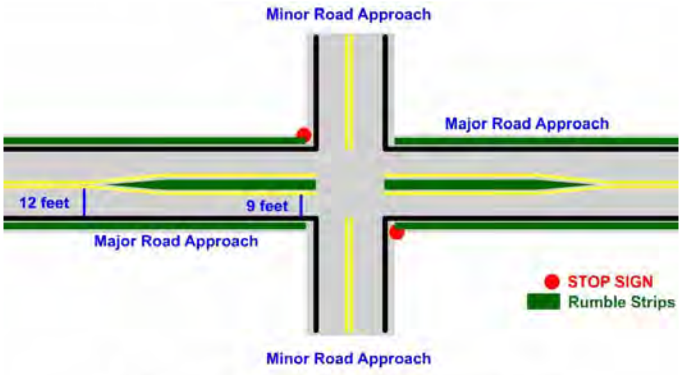
Landscaping can be a significant safety hazard when placed within the clear zone or when it obstructs sight distance for drivers pulling out into the roadway. However, when implemented appropriately, it can provide a safety benefit.

A before-and-after study conducted by Texas Transportation Institute (TTI) implemented landscape improvements to ten selected Texas Department of Transportation projects. After the landscaping was in place for three years, the mean crash rate per 1 million vehicle miles traveled (VMT) decreased approximately 20 percent. (Mok, 2006)

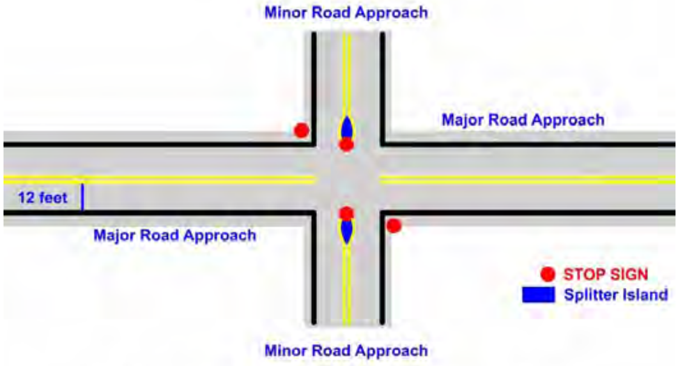
2.3 COMBINING TREATMENTS

Intuition suggests that combining treatments will increase the potential to reduce speed. While 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 studied by the Federal Highway Administration (FHWA). 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.



Concept 1 - Major Road Approaches



Concept 2 - Minor Road Approaches

Exhibit 2-31 FHWA Low-Cost Treatment Concepts (FHWA, 2006)

The objectives of the FHWA Low-Cost Intersection Treatments on High-Speed Rural Roads 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 reduced the lane width, added rumble strips, and added pavement markings on the major road. The second concept was to install a mountable splitter island with stop signs on the minor road approaches. Exhibit 3-4 shows the proposed concepts (FHWA, 2006).

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 miles per hour, and reduced the 85th percentile speeds by 4 miles per hour. In addition, testing results for trucks revealed an average speed reduction of 5 miles per hour and a reduction in the 85th percentile speeds of 4 to 5 miles per hour. (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 several years of data are needed to determine the potential effects the treatments had on roadway safety. (FHWA, 2006)

2.4 SPEED ENFORCEMENT

2.4.1 Overview

Enforcement is critical to achieving compliance with speed limits (TRB Special Report 254, 1998). There are perceived advantages and disadvantages to exceeding the posted speed. Perceived advantages may include saving time or having a thrilling driving experience, while disadvantages include the increased risk of a crash or the possibility of being caught. Whether using traditional officer-based enforcement or automated enforcement techniques, the goal of enforcement is to deter drivers from driving over the speed limit by increasing the disadvantages of being caught speeding (ACC and LTSA, 2000). The following discussion summarizes principles of speed enforcement in general and highlights advantages and disadvantages of automated enforcement.

2.4.2 Speed Enforcement Principles

Police enforcement mechanisms include specific deterrence and general deterrence. Specific deterrence focuses on an individual driver who is speeding and is intended to influence that individual's behavior by catching and punishing them. This assumes that once a driver is caught and punished for speeding, that driver will be less likely to speed in the future. General deterrence is focused on the entire driving population. Whether or not there are actual increased enforcement activities, this type of deterrence strives to influence the overall driving population by increasing the public perception that drivers who speed will be caught (ACC and LTSA, 2000). Studies have shown that actual enforcement and deterrence from speeding is most effective when combined with public information campaigns (TRB Special Report 254, 1998). Deterrence is also affected by punishment factors such as the perceived certainty, severity, and immediacy of the punishment (ACC and LTSA, 2000).

Traditional speed enforcement involves catching the speeding driver and applying a punishment at the site where speeding occurred. In many cases, speeding drivers are detected with a radar device from a police officer adjacent to the road. The speeding driver is then stopped and issued a penalty depending on the severity of the offence (ACC and LTSA, 2000). This enforcement approach has a short-lived effect in deterring speeding (TRB Special Report 254, 1998). The time or distance that a driver is affected and deterred due to enforcement is referred to as the "halo" effect. The distance halo effect is the distance on either side of the enforcement site over which there is a reduction in speeding behavior. The time halo effect is the amount of time from enforcement activity during which speeds at the enforcement site are reduced. Various studies have determined that the distance and time halo effects are dependent on the enforcement strategy. When enforcement is of high intensity and randomly placed the effects can last up to eight weeks and can extend for a distance of 20 kilometers (ACC and LTSA, 2000).

Two approaches of traditional speed enforcement are used: high visibility and low visibility. The high visibility approach aims to increase the overall perceived risk of being caught by deterring drivers from speeding at the enforcement site, whereas the low visibility approach aims to inform drivers that enforcement is unpredictable. Whether to use stationary or moving police enforcement is another decision to make when choosing to use police enforcement. Of the speed enforcement programs conducted throughout the United States, the most successful in deterring speeding were those that:

- Placed enforcement at specific locations and at times when speeding is most likely to occur;
- Made enforcement highly visible to the public; and
- Maintained enforcement for more than a year (ACC and LTSA, 2000).

2.4.3 Automated Speed Enforcement

Automated speed enforcement consists of a detection device (radar device), a processing unit, and an image-recording device (camera). This technology measures vehicle speed and then takes a picture of a speeding vehicle and driver, including the time and date of the incident. A warning letter or citation is mailed to the registered owner of the vehicle, using the vehicle license plate to identify vehicle ownership (ACC and LTSA, 2000).

Some of the advantages to automated speed enforcement are (ACC and LTSA, 2000):

- Increases the probability of detection without overextending police resources;
- Increases road users' perception of the risk of getting caught;
- Increases fairness of enforcement by eliminating "officer discretion;"
- Creates an efficient ticketing process by reducing the number of disputes between motorists and police officers; and
- Enforces speeds in locations where patrol vehicles cannot safely or effectively patrol.

Some disadvantages to automated speed enforcement include (ACC and LTSA, 2000):

- The delay between the offense and the punishment, which is typically two to three weeks.
- The speeding driver does not always immediately realize his or her offense has been detected.
- Community acceptance varies for this type of enforcement technology.

2.4.4 Speed Enforcement Summary

Speed enforcement can be an effective tool for speed management. Automated enforcement has been successfully used in many geographic areas but remains controversial in many communities. Speed enforcement could be used in conjunction with other countermeasures or as a single countermeasure. Funding, resource limitations, and prioritizing enforcement locations are real-world variables that can affect its success. There is varied community acceptance of automated enforcement. This study is focused primarily on physical treatments that might be applied. Further exploration of enforcement as a unique speed reduction treatment will not be conducted as part of this work effort.

2.5 STATE AGENCY SURVEY

2.5.1 Introduction

This section presents a summary of the responses to the survey questionnaire sent to state highway agencies concerning speed reduction treatments on intersection approaches. The survey solicited specific suggestions on potential treatments, and requested expressions of interest in participating in the treatment evaluation process during Phase II of the project. The survey was designed to allow agencies to share their input about what speed reduction treatments they felt were most important to be evaluated when determining a level of effectiveness. To maximize the number of responses, hard copies of the survey were sent via mail and additional survey copies were also emailed to each contact. A copy of the survey distributed to the state highway agencies is shown in *Appendix C*.

2.5.2 Survey Recipients

The mailing list for the survey included the 50 state highway agencies. The questionnaires for state highway agencies were generally sent to the state traffic engineer. Names and addresses of the state traffic engineers were determined from the membership roster of the AASHTO directory, previous mailing lists, and state DOT web pages. The mailing list used for distributing the survey is shown in *Appendix D*.

2.5.3 Response Rate

A total of 38 responses were received out of the 50 questionnaires that were mailed, for a response rate of 76 percent. Exhibit 2-35 presents a list of the state highway agencies that responded to this survey.

Exhibit 2-32 List of Highway Agencies That Responded to Survey

State highway agencies	
Alabama	Mississippi
Arizona	Missouri
California	Montana
Colorado	Nevada
Connecticut	New Hampshire
Delaware	New Jersey
Georgia	New York
Hawaii	North Dakota
Idaho	Oklahoma
Illinois	Oregon
Indiana	Pennsylvania
Iowa	Rhode Island
Kansas	South Carolina
Kentucky	Tennessee
Louisiana	Vermont
Maine	Virginia
Maryland	Washington
Michigan	West Virginia
Minnesota	Wyoming

2.5.4 Summary of Survey Responses

The highway agency responses to each question in the survey are summarized below. Where appropriate, the responses are tabulated.

2.4.4.1 Question 1—Type of Highway Agency Represented

In Question 1, survey respondents were asked to identify what type of agency they worked for (i.e., state, city, county, other). Since the survey was eventually mailed only to state agencies, 100 percent of the respondents answered accordingly.

2.4.4.2 Question 2—Geometric Speed Reduction Treatments

Highway agencies were asked about the types of geometric speed reduction treatments that they use. For agencies responding to the survey, 71 percent indicated that they incorporated some geometric treatment specifically intended to reduce speeds at at-grade intersections. Agencies indicating that they used a particular treatment were asked whether or not they found it to be effective and also whether it was currently in use. Exhibit 2-36 presents the responses to this question based on a list of typical treatments given in the survey.

In addition to the treatments listed in Exhibit 2-36, one agency currently utilizes curb and gutter cross sections as an alternative treatment to reduce speeds and finds them to be effective.

Exhibit 2-33 Highway Agency Use of Geometric Treatments to Reduce Speeds

Treatment	No. of Agencies		Effective		In current use	
Rumble strips	22	82%	20	91%	19	86%
Roundabouts	16	59%	15	94%	15	94%
Shoulder treatments	9	33%	5	56%	9	100%
Roadside treatments	7	26%	4	57%	6	86%
Reduced lane widths	5	19%	3	60%	5	100%
Reverse horizontal curvature	3	11%	3	100%	3	100%
Speed tables	3	11%	2	67%	3	100%
Horizontal curvature	2	7%	2	100%	1	50%
Roundabout-like treatments	1	4%	1	100%	1	100%

NOTE: The percentage of agencies represents the total number of responding agencies; however, the percentage of responses on whether the treatment is effective or in current use corresponds only to the number of agencies using that particular treatment.

2.4.4.3 Question 3—Signing Intended to Reduce Traffic Speeds

Exhibit 2-37 summarizes the number and percentage of agencies that use dynamic warning signs in order to reduce traffic speeds on intersection approaches. Approximately 45 percent of the responding state agencies have implemented this general type of treatment.

There were several additional signing methods mentioned by respondents beyond those suggested in the survey. These include:

- Advance warning signs with flashers (3 respondents)
- Flashing yellow beacons on W3-3 (Signal Ahead) signs
- Special enforcement area signs
- Stopped traffic ahead warning signs with beacons activated by the red signal phase (2 respondents)
- Brighter colored yellow warning signs
- Intersection warning signs
- Intersection warning signs supplemented with advisory maximum safe speed signs

Four of the nine agencies citing the use of these warning signs also indicated that they were found to be effective and currently in use; except in those cases where they are still being installed on a trial basis and effectiveness data is not available.

Exhibit 2-34 Highway Agency use of Signing to Reduce Speeds

Type of Sign	No. Of Agencies		Effective		In current use	
Speed activated dynamic warning signs	6	35%	2	33%	5	83%
Conflicting vehicles activated dynamic warning signs	3	18%	2	67%	1	33%

NOTE: The percentage of agencies represents the total number of responding agencies; however, the percentage of responses on whether the treatment is effective or in current use corresponds only to the number of agencies using that particular treatment.

2.4.4.4 Question 4—Pavement Markings Intended to Reduce Traffic Speeds

Question 4 asked highway agencies about their policies for the use of pavement markings in order to reduce traffic speeds. Twenty-nine percent of the responding agencies indicated a use of at least one of the treatments listed in Exhibit 2-38. Only two agencies gave information on other types of pavement markings used in their jurisdiction that were not mentioned in the survey. Both agencies stated that pavement markings were used to adjust the lane width on intersection approaches; however, neither has found any effectiveness in this method.

Exhibit 2-35 Highway Agency use of Pavement Markings to Reduce Speeds

Type of Sign	No. Of Agencies		Effective		In current use	
Transverse pavement markings on the roadway	7	64%	5	71%	7	100%
Wider edge line markings	4	36%	0	0%	4	100%
Transverse pavement markings on the shoulder	3	27%	2	67%	3	100%
Wider centerline markings	3	27%	0	0%	2	67%

NOTE: The percentage of agencies represents the total number of responding agencies; however, the percentage of responses on whether the treatment is effective or in current use corresponds only to the number of agencies using that particular treatment.

2.4.4.5 Question 5

Question 5 asked respondents to forward any written policies, specifications, or typical drawings associated with their answers to Questions 2, 3, & 4. One respondent (Maryland) provided the following:

- Speed reduction specifications with diagrams for their recommended placement along the roadway

- Speed reduction sign specifications
- Cost estimate table for speed reduction treatments for a specific project they have completed
- Report on a study they published, entitled "Optical Speed Bar Application"

Another respondent (Virginia) provided a one-page document with the specifications for signing and placing rumble strips on an intersection approach.

2.4.4.6 Question 6—Prior Research on Vehicle Speeds and Geometric Treatments

Question 6 asked highway agencies to indicate whether they have conducted formal research on the effects on vehicles speeds of treatments that they identified in Questions 2, 3, and 4. Seven agencies (18 percent) responded affirmatively:

- *Maine* – No specific details were provided.
- *Maryland* – Maryland State Highway Administration conducted a before-and-after study on speed measurements to test the effectiveness of optical speed bars installed at two locations on a test roadway segment. They found that, depending on the time of day, the 85th percentile running speed was reduced by 2.4 to 9 percent.
- *Minnesota* – In 2003, MnDOT performed an evaluation of a rural unsignalized intersection before and after the installation of improved pavement markings that were intended to accentuate the presence of the intersection. The immediate impacts of the study showed no reduction in vehicle speed, but it is yet to be determined if there are fewer crashes in the long-term.
- *Mississippi* – MDOT participated in the NCHRP Pooled Fund Study on Novel Traffic Control Devices. No specific details were provided.
- *New Hampshire* – NHDOT performed before-and-after studies for driver feedback signs (i.e., "Your Speed Is ___"). In addition, they have plans to compare before-and-after crash data for sites where "Stopped Traffic Ahead" signs have been applied. No specific details were provided.
- *New York* – NYSDOT is involved in an FHWA Pooled Fund Study along with Texas and Mississippi to study the effects of pavement markings. The survey respondent was uncertain whether the markings were on the traveled way or on the shoulder, but indicated that all sites were freeway off-ramp approaches. It was noted that MS and TX might be using conventional highways.
- *Virginia* – VDOT conducted research as a part of an evaluation for their Traffic Calming Guide. No specific details were provided.

2.4.4.7 Question 7—Potential Importance of an Effectiveness Evaluation

Question 7 was designed to allow agencies to share their input about what speed reduction treatments they felt were most important to be evaluated to determine a level of effectiveness. This was accomplished by asking respondents to assign a numerical value to each treatment corresponding to its importance on a scale from 1 to 5. A numerical value of 5 corresponded to the "greatest need for evaluation" and a value of 1 corresponded to the "least need for evaluation." Exhibit 2-39 presents the results in descending order of importance, as ranked by highway agencies. In addition to the average value assigned to each treatment, minimum and maximum value columns are included for each treatment.

Exhibit 2-36 Intersection Speed reduction Treatment Importance Rankings

Intersection Speed reduction Treatment	Average Value	Min Value	Max Value
Rumble Strips in Traveled Way on Approach	3.5	1	5
Dynamic-warning Speed Activated Signs	3.4	1	5
Roundabouts	3.4	1	5
Dynamic-warning Signs Activated by Potentially Conflicting Veh.	3.3	1	5
Transverse Pavement Markings on Roadway	3.1	1	5
Transverse Pavement Markings on Shoulder	2.9	1	5
Wider Edge line Markings	2.6	1	5
Roundabout-like Treatments	2.5	1	5
Shoulder Treatments	2.5	1	5
Reduced Lane Widths	2.4	1	5
Roadside Treatments	2.4	1	5
Wider Centerline Markings	2.3	1	5
Horizontal Curvature on Approach	2.0	1	5
Reverse Horizontal Curvature on Approach	1.9	1	5
Speed Tables	1.7	1	4
Other – Advanced Warning Signs, Flashers (one respondent)	5.0	5	5

2.4.4.8 Question 8—Speed Reduction Treatment Evaluation Criterion

Question 8 asked respondents to rank a list of possible criteria for a speed reduction treatment evaluation, according to how important the results obtained by incorporating each criterion would be to their agency. As in the previous question, a response of 5 indicates a "very important" status and a response of 1 indicates that the criterion is "not important." Exhibit 2-40 presents the results in descending order of importance as ranked by responding agencies. In addition to the average value assigned to each treatment, minimum and maximum value columns are included for each treatment.

Exhibit 2-37 Intersection Speed reduction Treatment Evaluation Criteria Rankings

Intersection Speed reduction Treatment	Average Value	Min Value	Max Value
Mean or 85th percentile vehicle speed before vs. after treatment	4.5	1	5
Accident frequency or severity before vs. after treatment	4.4	1	5
Vehicle speed profile	3.9	1	5
Vehicle lateral position	2.2	1	5

2.4.4.9 Question 9—Additional Evaluation Criterion

Question 9 asked respondents whether their agency considered any other criteria important enough to be included in an evaluation study of speed reduction treatments at unsignalized intersections. Twelve agencies (32 percent of respondents) provided additional criteria for consideration, including:

- Cost of treatments (Benefit/Cost analysis) (3 respondents)
- Rural vs. urban locations (2 respondents)
- Type of roadway (2 respondents)
- Community and political fallout
- High vs. low speed intersections
- Approach grade
- Reduction in the high end of the speed profile; "We've seen no change in the 85th percentile speeds but a reduction in the numbers of vehicles traveling 10+ mph above the speed limit."
- Weather effects
- Traffic volume effects
- Vehicle type effects
- 10 mph pace
- Effectiveness over extended time periods

2.4.4.10 Question 10—Recently Installed Speed Reduction Treatments

Question 10 asked highway agencies to provide a description of any treatments that have been installed in their jurisdiction in the last three years that they would be willing to have included in a future evaluation. Six agencies (16 percent of respondents) indicated that they have installed such treatments and would be willing to participate in this research. Exhibit 2-41 provides a list of states with the corresponding treatments that they have installed.

Exhibit 2-38 Possible Evaluation Locations and Treatments

State	Treatment(s)
Arizona	Advance warning signs and flashers
Colorado	Roundabouts (4 locations)
Kansas	Wide edge lines Narrow lanes Speed trailers Lane shift
Maryland	Rumble strips Transverse shoulder markings Wide edge lines Special enforcement area
Missouri	Flashers activated by vehicle presence
Oregon	Rumble strips in traveled way

2.4.4.11 Question 11—Speed Reduction Treatments Available for 2005 Study

Question 11 asked highway agencies to indicate their interest in participating in an effectiveness evaluation of speed reduction treatments at intersection approaches to be installed in 2005. Exhibit 2-42 presents the treatments that are being sought for study along with those states indicating a willingness to cooperate in such a study. Rumble strips on the traveled way was the treatment most often sited by states as being of interest for the evaluation. Kansas indicated in their response that they would be interested in participating but did not include any specific treatments. Agencies were asked if there were any other treatments that they thought would be worthwhile to consider. In response to this Arizona expressed an interest in having their advance warning signs and flashers studied. Maryland indicated they may have another treatment for consideration, but only provided a contact person.

Exhibit 2-39 Potential Speed Reduction Treatment Study Locations

Treatments	Total	Pct (%)	AZ	CO	LA	IA	MD	MI	MS	MO	NH	NY	PA	VA	WA	WY
Rumble strips in traveled way	11	73	X	X	X	X	X		X	X			X	X	X	X
Wider centerline markings	7	47		X	X	X			X	X			X	X		
Wider edge line markings	7	47		X	X	X			X	X			X	X		
Dynamic warning signs activated by speed of vehicle	6	40				X	X		X	X	X			X		
Transverse pavement markings on roadway	6	40				X	X		X	X			X		X	
Reduced lane widths	5	33				X	X		X		X					X
Roadside treatments	5	33		X		X	X		X		X					
Roundabouts	5	33	X	X				X		X		X				
Shoulder treatments	5	33			X	X	X		X		X					
Transverse pavement markings on shoulder	5	33		X		X			X	X			X			
Dynamic warning signs activated by conflicting vehicles	4	27				X			X	X	X					
Roundabout-like Treatments	3	20	X				X								X	
Horizontal curvature on approach	2	13					X				X					
Reverse horizontal curvature on approach	1	7					X									
Other	2	13	X				X									

2.4.4.12 Question 12—Comments

Question 12 asked highway agencies to provide additional comments, if desired. Several agencies expressed an interest in this study and reaffirmed the necessity of such research. Those agencies include:

- *Kansas* – "I think that this is very important research as communities want traffic going through their town to go slower. We are looking for good ways to do this."
- *Maryland* – "This is needed research – the goal is to favorably alter driver behavior, without them consciously knowing it!"

- *Oregon* – "Oregon is interested in the results of this study, however to date we have little experience with many of the treatments mentioned above. Our most relevant experience is with the installation of a couple of roundabouts in Bend and Astoria as an alternative to signalization."

- *California* – "We are starting a research effort regarding potentially assessing approaching vehicle speeds and adjusting signal time to reduce or eliminate dilemma zones."

- *Missouri* – "We are bound by budget when agreeing to participate with (projects). We can only participate within budgetary constraints. Our budget for 2005 has not been completed at this time."

- *Vermont* – "We will be doing a 3 year study on Dynamic Pavement Marking starting in the spring next year."

2.4.4.13 Question 13

Question 13 asked the survey respondent to provide their contact information.

2.4.4.14 Question 14—Other Agencies Possibly Interested in the Project

In Question 14, respondents were asked to identify other agencies in their state, including cities and counties, they think may be interested in participating in an effectiveness evaluation of speed reduction treatments. Six agencies responded to this question. The additional agencies identified in this question will be contacted in Phase II of the research. A list of responding state agencies along with the recommended local agency is provided below:

- Alabama – City of Auburn

- Hawaii – City and County of Honolulu

- Maryland – City of Trappe Landing

- Missouri – Mid-America Regional Council (Kansas City, MO)

- Montana – "most cities in Montana"

- Oklahoma – Cities of Oklahoma City and Tulsa

2.5.5 Conclusions

The 38 responding state agencies provided insight into the current practices being utilized in speed reduction on high-speed intersection approaches. It was reported that geometric treatments (71 percent) are more often used as a speed reduction measure than dynamic signing (45 percent) or pavement marking (29 percent) by state highway agencies. The necessity of this type of research became evident as only 18 percent of reporting agencies indicated that any prior research on the topic had been undertaken. Rumble strips were identified as having the greatest need for evaluation based on their potential effectiveness. While a wide range of speed reduction criteria were offered by the agencies for an effectiveness evaluation, the mean or 85th percentile vehicle speed, before and after a treatment is installed, was noted most often as an important criterion.

3 Testing Plan

3.1 OVERVIEW

This section contains the testing plan for speed reduction treatments investigated during Phase II of this project. The results of the literature review, state highway agency survey responses, and other testing considerations were assessed to establish priority treatments. The testing plan considered a variety of parameters and needs as well.

3.2 FOCUS OF TESTING PLAN

The overall objectives of this research are to (1) identify or develop treatments and (2) develop guidelines for their selection to reduce the operating speed of vehicles approaching intersections, thereby reducing the frequency and severity of crashes.

The Phase II testing quantified the speed effects of three treatments. This testing did not attempt to determine whether speed reduction treatments actually decrease the frequency and severity of crashes. It can take many years of measuring safety effects and conducting safety evaluations to adequately assess the short-, mid-, and long-term effects of a treatment. Such opportunities for analysis are not available within the limitations of this study.

3.3 RECOMMENDED TREATMENTS

The research team ranked and prioritized the treatments based on published results and professional judgment. In addition, the research team evaluated the results of state highway agency surveys to understand each agency’s recommendations and priorities for implementing treatments. The research team correlated its treatment ranking with the survey results to develop primary, secondary, and alternative choices for treatments. With a primary list established, each treatment was further evaluated to determine which specific treatments to recommend for testing. The process the research team used to identify recommended treatments is summarized in Appendix “E”.

The treatments recommended for testing in Phase II were:

- **Rumble Strips**

Rumble strips are raised or grooved patterns installed on travel lanes or shoulder pavement. The texture differs from pavement to produce both an audible warning and physical vibration when a vehicle’s tires pass over them (FHWA Research and Tech., 2004). Rumble strips can be installed to warn drivers of an upcoming need to act, such as stop at a traffic signal, slow down at an intersection, change lanes in a work zone, or steer back into the roadway. Rumble strips often are installed in the travel lane prior to intersections that have high speeds or high potential for vehicle crashes (FHWA Safety, 2004). Some agencies paint over rumble strips to make them more visible (FHWA Research and Tech., 2004).

- **Transverse Pavement Markings**

Transverse pavement markings are placed perpendicular to the flow of traffic and appear as full transverse bars, peripheral transverse bars, or transverse chevrons. Transverse pavement markings are thought to potentially reduce vehicle speeds by giving drivers the perception that they are traveling faster than they really are or creating the perception of a narrowing roadway.

- **Approach Reverse Curvature**

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 geometric curvature. Approach reverse curvature consists of successive curves with progressively smaller radii. Research and applications of approach curvature have focused on roundabouts; however, this geometric design treatment could potentially be applied to conventional intersections.

- **Dynamic Warning Signs**

Dynamic warning signs are placed near the roadway prior to a location that requires a warning or speed reduction. The messages are activated by approaching vehicles traveling a pre-determined speed (i.e. 5 mph above the posted speed). Typically, this type of system combines a radar device or pavement loop detectors with a variable message sign. The system measures the speed of the approaching vehicle and then provides a message to drivers who are traveling above pre-determined speeds. Examples of the messages displayed include, “Slow Down,” “XX mph Curve Ahead,” “Your Speed XX mph” or “Traffic Ahead.”

3.4 EXPERIMENTAL PLAN

A “before-and-after” approach was used to evaluate the effect each treatment has on speed. Speeds were measured at selected locations on the intersection approach before and after the subject treatments were implemented.

The “after” measurements were taken a minimum of three months following a treatment’s installation. This acclimation period allowed the novelty of the treatments to subside and motorists to adjust to their presence.

3.5 SITE SELECTION

This research project funded the treatment tests; however, the cost to install the treatment was the responsibility of the state or county agency involved. Therefore, the research team contacted various individuals and groups to identify states or counties that were interested in participating in the research and/or had plans to install a speed reduction treatment. These included:

- State agencies from the survey conducted during Phase I of the research
- Transportation agency colleagues of the research team
- Members of the NCHRP Panel
- Transportation professors
- Treatment vendors

The research team first contacted the state agencies that participated in the survey. However, the team found that many of the agency staff listed on the survey were not aware of treatments being installed or of projects whose construction was going to correspond with the timeline of this research project.

The team found the most effective way to identify potential treatment locations was to speak with a state's regional or district staff most familiar with specific intersections and roadways in their area. In some cases, the agency staff did not have plans to install a treatment, but knew of "problem" intersections where they would be willing to test a treatment. In those cases, the research team worked with agencies to suggest potential treatments to reduce speeds. The research team also worked with agencies to help identify other high-speed intersections that might benefit from speed reduction and at which the agency was willing to install the subject treatment.

When initial contact was made with agencies regarding possible treatments, the research team requested the following information to become familiar with the agencies' policies, potential sites, and speed and/or safety issues they were experiencing:

- The agency's interest in participating in NCHRP 3-74 testing
- Specific treatments the agency was willing to install and test
- Intersections with known speed or safety issues
- Specific project or intersection information
- Project type
- Location
- Documented problems (crashes, speed, complaints from neighbors, etc.)
- Construction season and installation schedule

The extensive coordination effort identified 16 potential sites in five states and counties around the United States. Exhibit 3-1 shows the list of candidate sites identified.

Exhibit 3-1 Preliminary List of Treatment Sites

State/County Agency	Contact	Site	
Clackamas County	Joe Marek	1	Whiskey Hill Road/Meridian Road (south of Aurora, OR)
		2	Canby-Marquam Highway/Lone Elder Road (south of Canby, OR)
		3	Redland Road/Bradley Road (east of Oregon City, OR)
		4	Redland Road/Ferguson Road (east of Oregon City, OR)
		5	Canby-Marquam Highway/Barnards Road (west of Molalla, OR)
		6	Canby-Marquam Highway/Macksburg Road (south of Canby, OR)
Oregon DOT	Bruce Erickson Angela Kargel	7	OR 6/Wilson River Loop Road (near Tillamook, OR)
Washington DOT	George Stuart	8	US 2/School Street (west of Wenatchee, WA)
		9	SR 26/SR 24/1st Street (near Othello, WA)
Caltrans	Gary Dossey	10	SR 20/Marysville Road (near Marysville, CA)
		11	SR 12/Terminous Road
		12	SR12/Brannan Island Road
Texas DOT	Carlos Ibarra	13	US82 @ SH98 (Bowie County)
		14	US271 @ FM726 (Upshur County)
		15	US271 @ FM593 (Upshur County)
		16	US271 @ FM2088 (Upshur County)

Once an agency identified one or more potential sites, the research team requested additional information to assess whether the sites were appropriate to test, what type of safety or speed issues existed, what type of treatment might be most effective, and where the treatment could be installed. The following information was requested for each potential testing location:

- Intersection and roadway as-builts or layouts that illustrated the plan and profile of the facilities
- Aerial photos of the intersection and surrounding area
- Crash data
- Speed data (e.g. spot speed studies, 85th Percentile speed, Posted Speed)
- Traffic volume data (e.g. ADT or intersection turning movement counts)

After reviewing the information, the research team also found it helpful to speak directly with a state or county staff member to discuss the issues impacting each location. When feasible, the research team conducted site visits to collect additional data and take pictures to help determine the most effective testing plan. This site screening process refined the list of potential sites and screened sites that did not seem to meet the research objectives. Some potential sites were removed for the following reasons:

- Canby-Marquam Highway/Macksburg Road - This site was identified because of frequent run-off-the-road crashes. Therefore, Clackamas County was interested in installing a treatment to reduce vehicle speeds prior to the intersection. However, a closer review of the roadway geometry revealed that the crashes were most likely due to a curvature at the intersection rather than high speeds. The road’s alignment makes it difficult for drivers to observe the impending curve, and the presence of an intersection may not impact the number of crashes. Although a speed reduction treatment may help slow vehicles as they approach the intersection, the team decided not to include this site because speed is not the primary problem.
- Canby-Marquam Highway/Barnards Road - This site experiences frequent crashes due to vehicles violating the stop sign on the minor approach. The research team worked with Clackamas County to identify treatments that may reduce speeds at this intersection. However, a fatal crash occurred during the coordination process, which led to the installation of an immediate treatment. Therefore, the research team was unable to include this site because the treatment’s implementation did not coincide with the testing timeline.
- SR 12/Terminous Road and SR 12/Brannan Island Road - Caltrans identified these intersections as potential treatment sites due to high speeds and crash frequency. However, when the research team reviewed the intersection characteristics and aerials, it appeared that the issues affecting this intersection were most likely due to the unique intersection geometry. Therefore, the team decided not to include these sites in the testing.

- SR 20/Marysville Road - The research team and Caltrans worked together to identify this candidate site, conduct "before" testing, and select and design an appropriate treatment. However, Caltrans was not able to purchase and install the treatment in time to be included in our testing. Therefore, the team was not able to include this site.

- US 2/School Street - The Washington Department of Transportation identified this site due to frequent crashes and a high percentage of drivers exceeding the posted speed limits. The research team coordinated closely with WSDOT to identify appropriate treatments and designs. However, WSDOT also was modifying the speed limit signs and locations near this intersection. The signs were not installed soon enough for us to provide the appropriate acclimation period prior to the research testing. Therefore, the team was not able to include this site.

After the candidate site screening process, the research team was able to confirm 10 testing sites in Oregon, Washington, and Texas. Exhibit 3-2 shows the final list of testing sites.

Exhibit 3-2 Final List of Treatment Sites

State/County Agency	Contact	Site	
Clackamas County, Oregon	Joe Marek	1	Whiskey Hill Road/Meridian Road (south of Aurora, OR)
		2	Canby-Marquam Highway/Lone Elder Road (south of Canby, OR)
		3	Redland Road/Bradley Road (east of Oregon City, OR)
		4	Redland Road/Ferguson Road (east of Oregon City, OR)
Oregon DOT	Bruce Erickson Angela Kargel	5	OR 6/Wilson River Loop Road (near Tillamook, OR)
Washington DOT	Robert Stull	6	SR 26/SR 24/1st Street (near Othello, WA)
Texas DOT	Carlos Ibarra	7	US82 @ SH98 (Bowie County)
		8	US271 @ FM726 (Upshur County)
		9	US271 @ FM593 (Upshur County)
		10	US271 @ FM2088 (Upshur County)

3.6 TREATMENT SELECTION

Once the sites were chosen, the research team worked closely with the respective state or county agencies and used the information gathered during the site selection process to identify appropriate treatments for each site. The following section provides an overview of the treatment selection process.

3.6.1. Pre-Screening

As part of the pre-screening process, gathering data such as crash history, speed study results and aerial images can be helpful in gaining an understanding of the site context. This includes the relationships between the segment and intersection as well as the influence of the geometry and environment. An understanding of these elements can help determine whether speed is the primary cause of problems experienced at a particular location.

STEP 1. Identify intersection in need of improvement

- Crashes (number)
- Crashes (severity)
- Crashes (type)
  - Rear-end crashes may indicate a need for separate left-turn or right-turn lanes on the main line
  - Angle crashes may indicate gap acceptance or intersection sight-distance issues
  - Single-vehicle crashes, including those involving a traffic-control violation, may indicate speed adaptation or intersection-awareness issues
  - Crashes at night may indicate a need for illumination
- Reports of high speed
- Near misses (operations)

STEP 2. Gather intersection information

- Intersection features
- Crash history
- Speed data
- Traffic volumes
- Traffic composition

- Aerial images
- Site visit

STEP 3. Assess Data

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

3.6.2. Treatment Screening

After the pre-screening process verifies that speed is a primary cause, the treatment screening process can help identify "fatal flaws" to eliminate candidate treatments. In some cases, "fatal flaw" treatments may be identified because of cost reasons, agency policies, or existing intersection characteristics.

STEP 4. Identify Fatal Flaws

- *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 due to noise.
- *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 vs. recreational), some treatments are more prone to having novelty effects.

STEP 5. Evaluate Potential Treatments — What are the objectives?

After the list of treatments has been defined, the next step is to gain additional information regarding the remaining potential treatments and determine their objectives. These objectives can include where speeds should be reduced and by how much.

- **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?
  - Does the agency have experience with installing this type of treatment?
- **How much speed reduction is desired?**
  - What is the target speed?
  - Extensively reducing speeds may require more prominent treatments such as an approach curvature, a dynamic warning sign or rumble strips. Other treatments may have a lesser impact on speeds.
- **Where should speed be reduced?**
  - If speed reduction is only needed at the intersection, an approach curvature may be implemented. However, transverse pavement markings may require a longer distance to reduce speeds.

3.6.3. Candidate Site Treatments

This treatment selection process was conducted at all of the sites in Oregon and Washington. For the site in Texas, the research team collaborated with TXDOT staff to determine appropriate treatments based on the agency’s interest and the needs of the research project. Exhibit 3-3 shows the final list of candidate sites and the treatments that were selected for each site

Exhibit 3-3 Candidate Sites and Treatment Selections

State/County Agency	Site		Treatment
Clackamas County, Oregon	1	Whiskey Hill Road/Meridian Road (south of Aurora, OR)	Transverse Pavement Markings
	2	Canby-Marquam Highway/Lone Elder Road (south of Canby, OR)	Transverse Pavement Markings
	3	Redland Road/Bradley Road (east of Oregon City, OR)	Transverse Pavement Markings
	4	Redland Road/Ferguson Road (east of Oregon City, OR)	Transverse Pavement Markings
Oregon DOT	5	OR 6/Wilson River Loop Road (near Tillamook, OR)	Transverse Pavement Marking
Washington DOT	6	SR 26/SR 24/1st Street (near Othello, WA)	Dynamic Warning Sign
Texas DOT	7	US82 @ SH98 (Bowie County)	Dynamic Warning Sign
	8	US271 @ FM726 (Upshur County)	Rumble Strips
	9	US271 @ FM593 (Upshur County)	Rumble Strips
	10	US271 @ FM2088 (Upshur County)	Rumble Strips

The research team made extensive efforts to identify sites that would allow testing of an even mix of treatments. However, based on the agencies' preference for treatments, funding issues, and/or construction abilities, the research team had to adapt to each agency's needs and installation plans when selecting each site's treatments. Exhibit 3-4 shows the mix of treatments that were installed and tested for this research project.

Exhibit 3-4 Mix of Treatments

Treatment	Number of Testing Sites
Transverse Pavement Markings	5
Dynamic Warning Signs	2
Rumble Strips	3
Approach Curvature	0

Transverse pavement markings were the most popular treatment tested because of their low cost, low maintenance requirements, and ease of installation. Some states were hesitant to install rumble strips because of potential noise impacts on adjacent properties. Dynamic warning signs received a high level of interest from state and county agencies. However, their cost - $18,000 to

$20,000 - deterred many states from pursuing this treatment.

Approach curvature also was prohibitive as a treatment because it requires construction and is more costly than other treatments, based on the need for roadway widening and partial roadway reconstruction in some cases. In collaboration with Clackamas County, the research team identified that approach curvature could be an appropriate treatment to install at a site south of Canby, Oregon. Clackamas County surveyed the intersection to provide the research team with detailed intersection and roadway information to allow the research team to finalize the approach curvature design.

However, upon reviewing the survey, the research team and Clackamas County determined that there was a significant amount of right-of-way that would need to be acquired to install this type of treatment. Due to the county's inability to acquire the right-of-way and the high installation costs, the county could not install this treatment. The research team was not able to identify any other candidate sites for approach curvature, so this treatment was not included in the testing.

3.7 TREATMENT LAYOUTS

After the treatment selection process was completed and a treatment was identified for each site, the team used aerial images and the existing roadway and intersection features to identify appropriate locations for the treatment installations.

3.7.1. Implementing Treatments

- **Identify existing roadway features** — existing signs, pavement markings, driveways, and curvature may affect treatments and treatment configurations

- **Apply treatments to roadway** — how well do they match the existing features?

    - Placing a treatment near an existing sign, such as an "intersection ahead" sign, could provide another visual cue to drivers to reduce their speeds and increase driver awareness of the impending intersection.

    - Placing a treatment at a location where the roadway changes, such as the point of tangency, may provide a cue to the driver that the roadway environment is changing and a speed reduction is necessary.

- **Adapt and customize**

    - If adequate stopping sight distance (SSD) and an upstream "intersection ahead" sign are present, treatments may be applied at both locations. However, if the SSD is at the same location as the "intersection ahead" sign, then one set of treatments may be sufficient.

For the majority of the sites, treatment schematics were developed to illustrate the appropriate treatment implementation locations. Exhibits 3-5 to 3-9 contain the treatment schematics for each site in Oregon and Washington. These figures were submitted to each agency for consideration.

Exhibit 3-5

POTENTIAL TRANSVERSE PAVEMENT MARKING LAYOUT
WHISKEY HILL ROAD/MERIDIAN ROAD
CLACKAMAS COUNTY, OREGON

Exhibit 3-6


NCHRP 3-74: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections
December 2007
N
POINT OF CURVATURE APPROX. M.P. 5.77
LONE ELDER ROAD SIGN M.P. 5.68
CANBY-MARQUAM HWY
LONE ELDER ROAD
LONE ELDER ROAD @ M.P. 5.60
LONE ELDER ROAD SIGN M.P. 5.50 (S.S.D. @ 55 MPH M.P. 5.51)
POINT OF TANGENCY APPROX. M.P. 5.42
SCALE
0
200
400
H:\projfile\6284\Task 7\Clackamas County\Canby-Marquam_Lone Elder Road\CM_Lone Elder Aerial.dwg Mar 13, 2006 - 9:42am - jham Layout Tab: Layout1
| | | | | POTENTIAL TREATMENT LOCATION
POTENTIAL TRANSVERSE PAVEMENT MARKING LAYOUT
CANBY-MARQUAM HIGHWAY/LONE ELDER ROAD
CLACKAMAS COUNTY, OREGON
EXHIBIT
3-6
KITTELSON & ASSOCIATES, INC.
TRANSPORTATION ENGINEERING/PLANNING

Exhibit 3-7

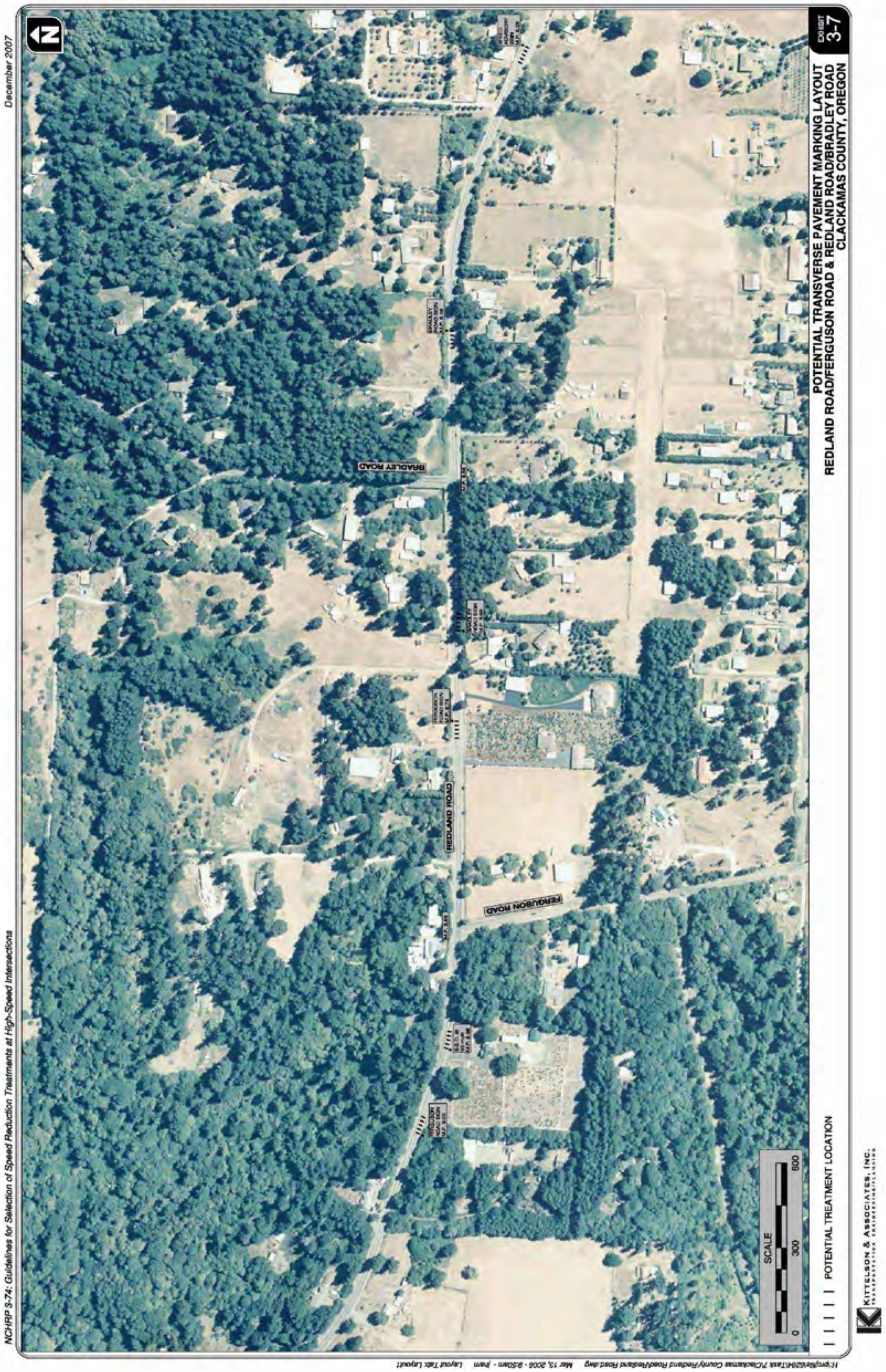
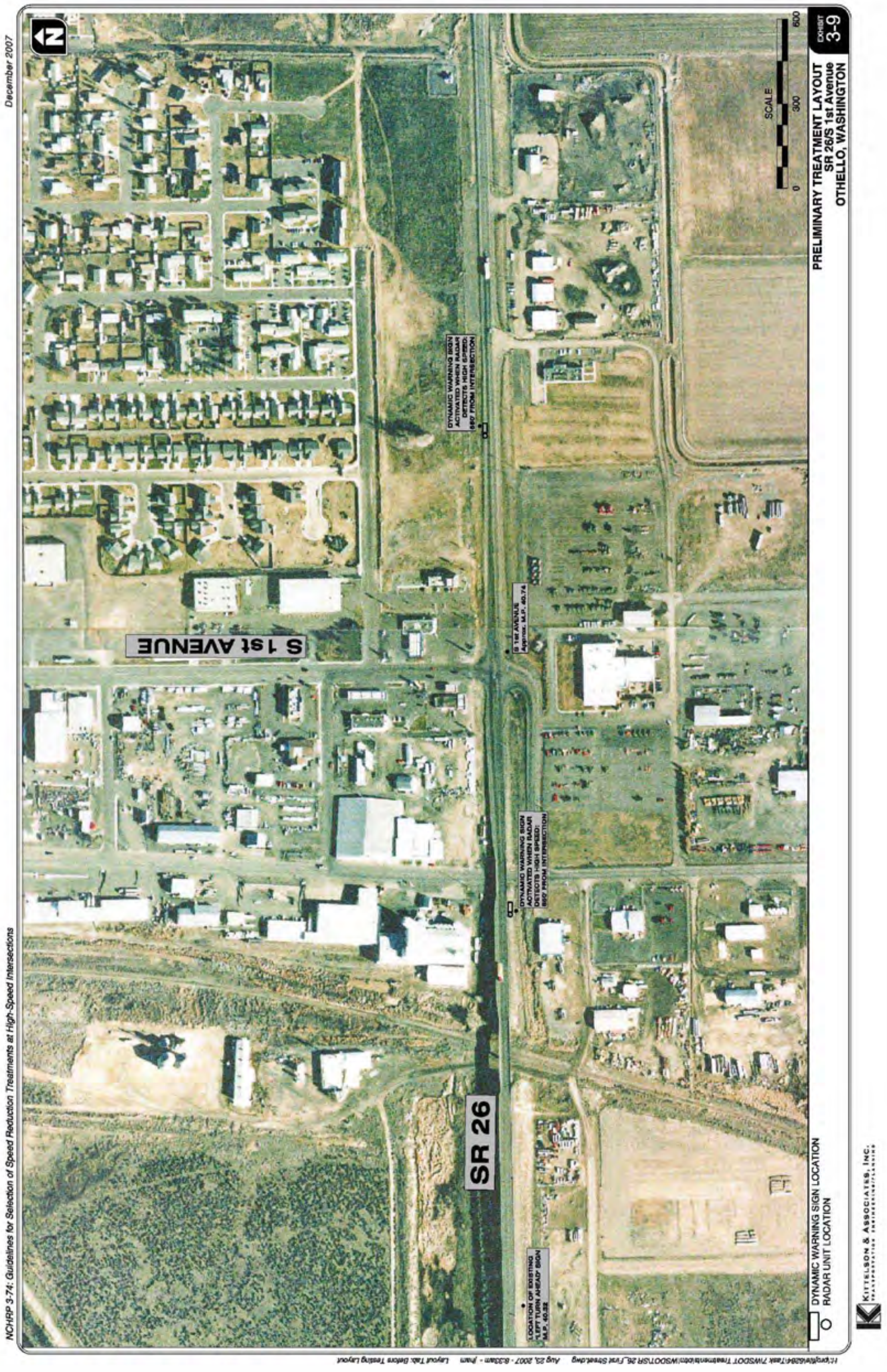


EXHIBIT 3-7
POTENTIAL TRANSVERSE PAVEMENT MARKING LAYOUT
REDLAND ROAD/FERGUSON ROAD & REDLAND ROAD/BRADLEY ROAD
CLACKAMAS COUNTY, OREGON
December 2007
NCHRP 3-74: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections
BRADLEY ROAD
REDLAND ROAD
FERGUSON ROAD
POTENTIAL TREATMENT LOCATION
SCALE
0
300
600
KITTELSON & ASSOCIATES, INC.

Exhibit 3-8


NCHRP 3-74: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections
December 2007
N
WILSON RIVER LOOP ROAD
"WILSON RIVER LOOP ¼ MILE" SIGN @ M.P. 2.05
"FAIRGROUNDS STATE OFFICES NEXT RIGHT" SIGN @ M.P. 1.92
WILSON RIVER LOOP ROAD @ M.P. 1.80
OR 6
"FAIRGROUNDS STATE OFFICES NEXT LEFT" SIGN @ M.P. 1.70
M.P. 1.55 (¼ MILE FROM WILSON RIVER LOOP ROAD)
PROPOSED TREATMENT LOCATION (SEE FIGURE 1 FOR TREATMENT DESIGN)
SCALE
0
200
400
PROPOSED TREATMENT LAYOUT
OR 6/WILSON RIVER LOOP ROAD
TILLAMOOK, OREGON
EXHIBIT
3-8
KITTELSON & ASSOCIATES, INC.
TRANSPORTATION ENGINEERING/PLANNING

Exhibit 3-9


PRELIMINARY TREATMENT LAYOUT
SR 26/S 1st Avenue
OTHELLO, WASHINGTON
EXHIBIT 3-9
SCALE
0
300
600
S 1st AVENUE
SR 26
DYNAMIC WARNING SIGN ACTIVATED WHEN RADAR DETECTS HIGH SPEED: 860' FROM INTERSECTION
S 1st AVENUE Approx. M.P. 40.74
DYNAMIC WARNING SIGN ACTIVATED WHEN RADAR DETECTS HIGH SPEED: 860' FROM INTERSECTION
LOCATION OF EXISTING "LEFT TURN AHEAD" SIGN M.P. 40.32
DYNAMIC WARNING SIGN LOCATION
RADAR UNIT LOCATION
KITTELSON & ASSOCIATES, INC.
December 2007
NCHRP 3-74: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections

For the sites in Texas, TXDOT took an active role in determining the treatment placements by incorporating its standard policies for installing rumble strips and dynamic warning signs. Therefore, the research team did not develop treatment schematics for these intersections. Exhibits 3-10 and 3-11 contain a schematic of the rumble strip and dynamic warning sign layout used at the site in Texas.

In all cases, the research team adapted to the specific needs of the agencies. For example, ODOT and WSDOT preferred that the research team provide treatment installation recommendations for review. Clackamas County and TXDOT staff showed an interest in being more engaged and took a more active role in determining potential treatment types and placements. Overall, the research team's collaborative and adaptive approach to each agency's needs provided a positive testing program.

3.8 TREATMENT DESIGNS

In addition to the treatment layout schematics, the research team also designed some of the treatments for specific sites. The following section describes the treatment designs for the transverse pavement markings, dynamic warning signs, and rumble strips.

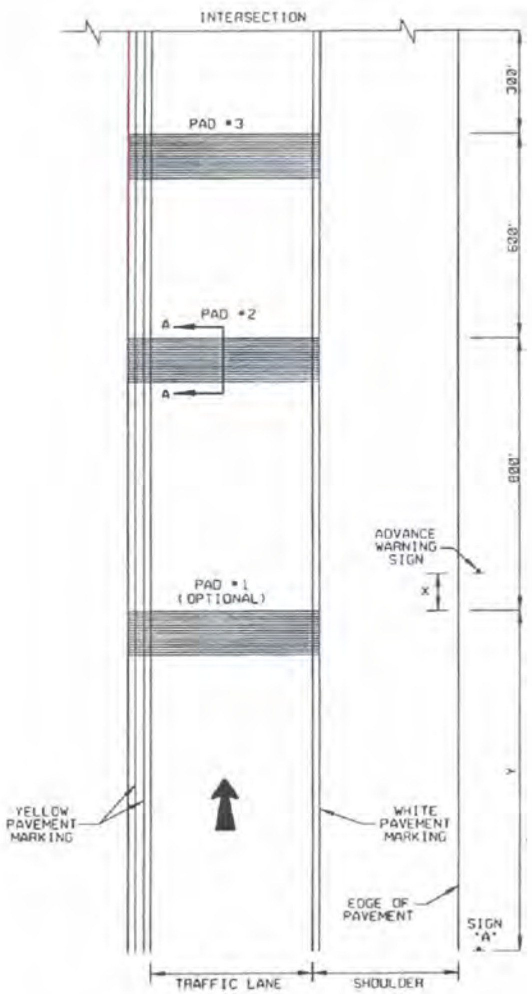
3.8.1. Transverse Pavement Markings

Exhibit 3-12 illustrates the peripheral transverse pavement marking design proposed for the sites. As shown in this figure, the design includes five pavement markings placed in a series and spaced approximately 15 feet apart. Each marking is approximately 12 to 24 inches wide and between 18 to 33 inches long. The length of each peripheral bar depended on the existing lane width and the width of the wheel base for vehicles that commonly travel through the area. The peripheral bars were designed to extend perpendicularly into travel lanes from the edge and center lines, but not to extend into the vehicles' wheel path. For example, peripheral bars placed on a roadway with a 12-foot travel lane that serves trucks with a 9-foot wheel base were designed to be 18 inches long. The actual treatment applications were defined and implemented based on the site specific conditions.

Because the pavement markings did not extend into the wheel path, there is less maintenance, material, and expense, and the markings do not create a slick surface when wet. This type of pavement marking is intended to give drivers the perception that they are traveling faster than they are or that the travel lane is narrowing, thereby promoting speed reduction. In addition, this type of treatment also can supplement existing signs to help drivers be aware that an intersection is ahead.

Exhibit 3-10

NCHRP 3-74: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections ***December 2007***



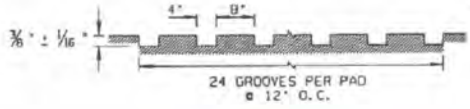
NOTES

1. THIS DESIGN SHOULD ONLY BE USED ON ROADWAYS WITH PAVED SHOULDERS MEETING FULL DESIGN STANDARDS AND IN GOOD CONDITION.
2. A WARNING SIGN GIVING NOTICE TO THE ADVANCE CONDITIONS IS REQUIRED BEYOND PAD •1 AS INDICATED.
3. WHEN A TWO PAD DESIGN IS TO BE USED PAD •1 SHOULD BE EXCLUDED AND THE SIGNS SHOULD BE PLACED AROUND PAD •2 AT THE DISTANCES GIVEN BELOW.
4. THIS DESIGN SHOULD NOT BE PLACED IN ADVANCE OF A CURVE.

85TH % OR POSTED SPEED	MINIMUM DISTANCE X	MINIMUM DISTANCE Y
30	100'	325'
35	120'	400'
40	135'	475'
45	150'	550'
50	165'	625'
55	180'	700'
60	195'	775'
65	215'	850'

X SHOULD NOT EXCEED 250'. AN EXCEPTION MAY BE GIVEN FOR X IF THE SIGN HAS A FLASHING BEACON AND THE DISTANCE IS APPROVED BY THE ENGINEER.

Y SHOULD NOT EXCEED 1000'.



SECTION A-A

RUMBLE STRIPS IN THE TRAVELED WAY
NOT OBSTRUCTING THE SHOULDER

NOT TO SCALE

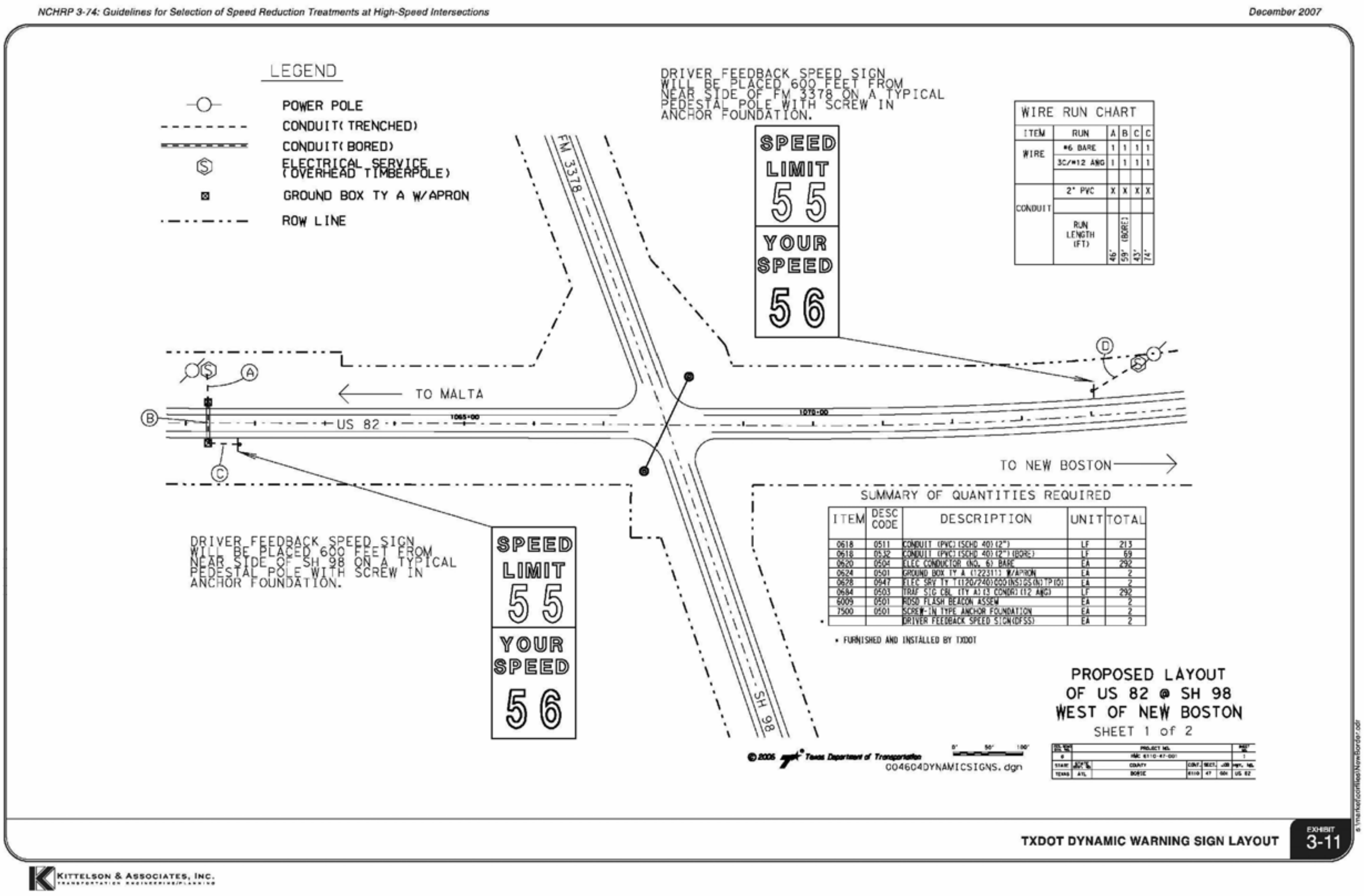
REVISED 2-3-95

s:\market\cdrfiles\NewBorder.cdr

TXDOT RUMBLE STRIP LAYOUT EXHIBIT **3-10**

KITTELSON & ASSOCIATES, INC.
TRANSPORTATION ENGINEERING/PLANNING

Exhibit 3-11



DRIVER FEEDBACK SPEED SIGN WILL BE PLACED 600 FEET FROM NEAR SIDE OF FM 3378 ON A TYPICAL PEDESTAL POLE WITH SCREW IN ANCHOR FOUNDATION.

DRIVER FEEDBACK SPEED SIGN WILL BE PLACED 600 FEET FROM NEAR SIDE OF SH 98 ON A TYPICAL PEDESTAL POLE WITH SCREW IN ANCHOR FOUNDATION.

WIRE RUN CHART

ITEM	RUN	A	B	C	C
WIRE	#6 BARE	1	1	1	1
	3C/#12 AWG	1	1	1	1
CONDUIT	2" PVC	X	X	X	X
	RUN LENGTH (FT)	46'	59' (BORE)	43'	74'

SUMMARY OF QUANTITIES REQUIRED

ITEM	DESC CODE	DESCRIPTION	UNIT	TOTAL
0618	0511	CONDUIT (PVC) (SCHD 40) (2")	LF	213
0618	0532	CONDUIT (PVC) (SCHD 40) (2") (BORE)	LF	69
0620	0504	ELEC CONDUCTOR (NO. 6) BARE	EA	292
0624	0501	GROUND BOX TY A (122311) W/APRON	EA	2
0628	0947	ELEC SRV TY T (120/240) 000 (NS) GS (N) TP (O)	EA	2
0684	0503	TRAF SIG CBL (TY A) (3 CONDR) (12 AWG)	LF	292
6009	0501	RDSD FLASH BEACON ASSEM	EA	2
7500	0501	SCREW-IN TYPE ANCHOR FOUNDATION	EA	2
•		DRIVER FEEDBACK SPEED SIGN(DFSS)	EA	2

• FURNISHED AND INSTALLED BY TXDOT

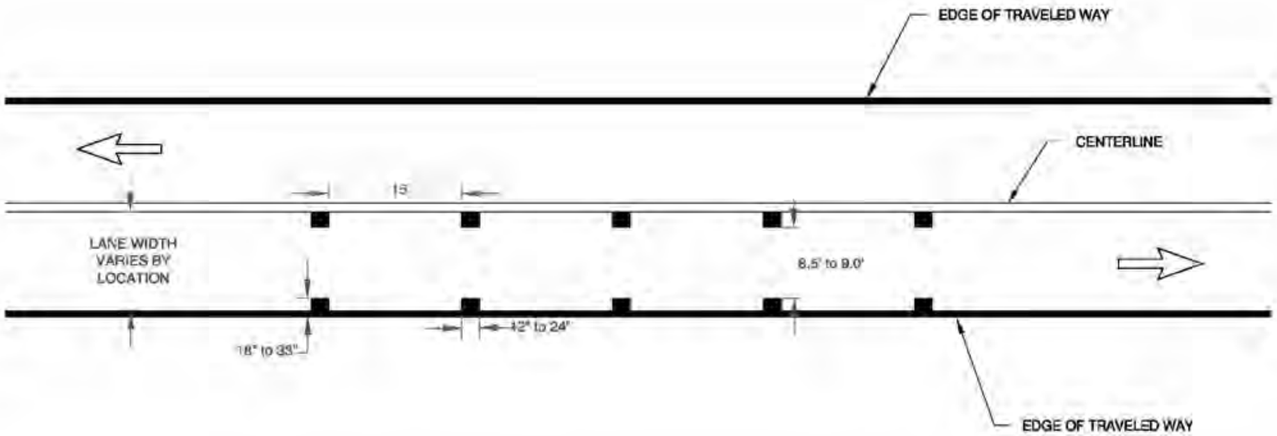
PROPOSED LAYOUT
OF US 82 @ SH 98
WEST OF NEW BOSTON
SHEET 1 of 2

© 2006 Texas Department of Transportation
004604DYNAMICSIGNS.dgn

Exhibit 3-12

NCHRP 3-74: Guidelines for Selection of Speed Reduction Treatments at High Speed Intersections

December 2007



PROTOTYPICAL PERIPHERAL TRANSVERSE PAVEMENT MARKING DESIGN

EXHIBIT
3-12

H:\projfile\6284\Task 7\Clackamas County\Transverse Pavement Markings.dwg   Mar 13, 2006 - 9:34am - jham   Layout Tab: FIG 3

KITTELSON & ASSOCIATES, INC.

A dynamic warning sign was chosen for the SR 26/SR 24/1st Street intersection near Othello, Washington. The research team provided WSDOT with a variety of possible designs that showed various display messages, sizes, and costs. WSDOT chose to design its own dynamic warning sign, which included the following features:

- "Speed Limit 50" sign
- "Intersection Ahead" symbol
- Dynamic message that flashes "SLOW" (1.5 seconds), "DOWN" (1.5 seconds) and then is blank for 1.5 seconds.

Exhibits 3-13 to 3-16 illustrate the dynamic warning sign designed by WSDOT.

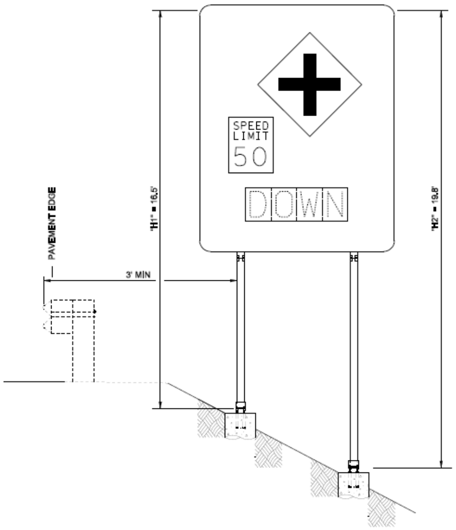


Exhibit 3-13 Dynamic Warning Sign Design

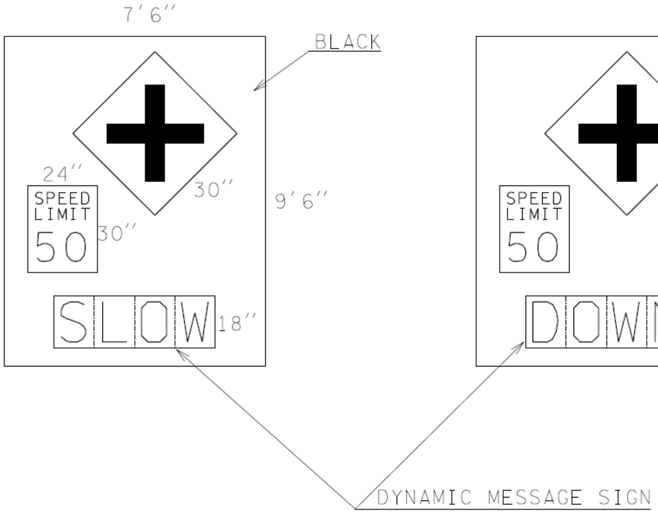


Exhibit 3-14 Dynamic Warning Sign Design

Exhibit 3-15 Dynamic warning sign installed by WSDOT.

Dynamic warning signs are activated by a maximum or target speed that is established in a radar unit or loop detector. WSDOT chose to use a radar unit that was attached to the sign, as shown in Exhibit 3-16. WSDOT, in coordination with the research team, chose a target speed of 54 mph to alert drivers that they are approaching a posted speed limit of 55 mph. This dynamic warning sign does not display the running speed of passing vehicles.

Exhibit 3-16 Radar Unit

A dynamic warning sign also was chosen for the US82/SH98 intersection in Bowie County, Texas, and is illustrated in Exhibit 3-17.

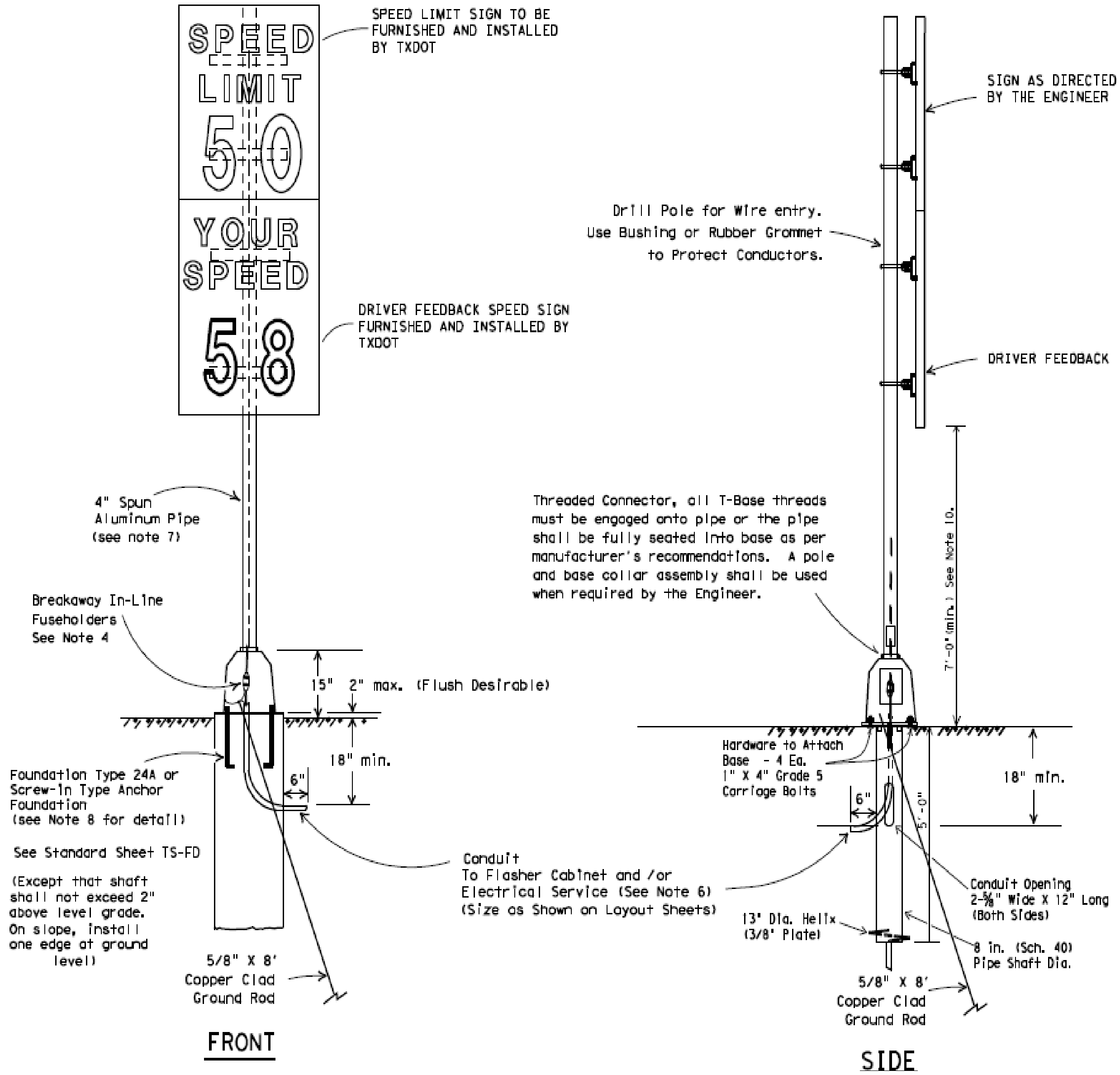


Exhibit 3-17 TXDOT Dynamic Warning Sign Design

As shown here, the TXDOT treatment consisted of a posted speed limit sign and a dynamic sign below that displays the speeds of vehicles as they pass. The speeds were measured using a built-in radar detector and a built-in processor within the radar unit.

3.8.1. Rumble Strips

Rumble strip treatments were selected for three sites in Upshur County, Texas:

- US 271/FM726
- US271/FM593
- US271/FM2088

Exhibit 3-18 illustrates the design that was incorporated based on TXDOT's policy for installing rumble strips on state roads.

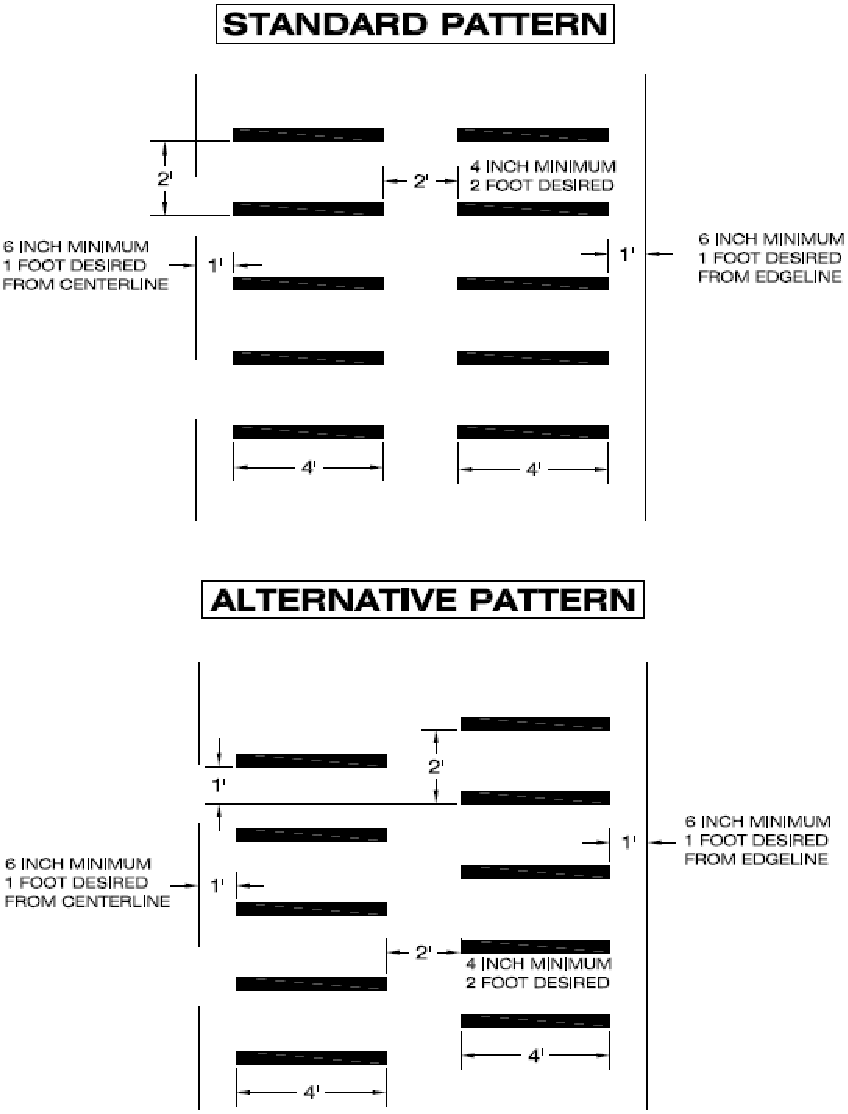


Exhibit 3-18 Rumble Strip Design

The rumble strip design included raised strips of plastic that were attached to the roadway. In addition, these strips were white to add a visual affect. Exhibit 3-19 shows the rumble strip design at one of the Texas sites.

Exhibit 3-19 Rumble Strip Design

The following case study, which describes how a specific speed reduction treatment was chosen to improve the Whiskey Hill Road/Meridian Road site in Clackamas County, Oregon, further illustrates the treatment selection and implementation process.

CASE STUDY

Whiskey Hill Road/Meridian Road

Clackamas County, Oregon

PRE-SCREENING

3.9.1.1. STEP 1. Identify intersection in need of improvement

- Clackamas County identified this intersection because of speed and safety concerns.
- **Meridian Road** - Complaints of 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 the intersection, which motorists also had difficulty anticipating.

Author's 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.

3.9.1.2. STEP 2. Gather intersection information

Traffic Volumes

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

Traffic Composition

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

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.

Speed Data

- Speed is defined according to the "basic rule" *(See "Author's Note" below)*
- 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%
- There are 25 mph school zones on the north approach of Meridian Road and the east approach of Whiskey Hill Road.

Author's Note: Basic Rule = "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."

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

Crash Records

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

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

3.9.1.3. STEP 3. 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.

- **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 prior to the intersection and school.

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

TREATMENT SCREENING

POTENTIAL TREATMENTS

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

3.9.1.4.

3.9.1.5. STEP 4. Identify Fatal Flaws

- **Reduced Lane Width**: Existing lane width is 11-feet.

- **Visible Shoulder Treatment**: Existing study roadways have no shoulders.

Exhibit 3-20 illustrates the limited shoulder and narrow cross-section on Meridian and Whiskey Hill roads.

Exhibit 3-20 Limited Shoulder and Narrow Cross-Section

- **Speed Tables**: 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.

Exhibit 3-21 illustrates the existing residences near Whiskey Hill and Meridian roads.

Exhibit 3-21 Existing Residences near Study Area

- **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 3-22 illustrates the existing roadway vegetation on Meridian and Whiskey Hill roads.

Exhibit 3-22 Existing Roadway Vegetation

- **Approach Curvature**: The 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.
- **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.

Author's 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.

3.9.1.6. STEP 5. Evaluate Potential Treatments

Remaining Potential Treatments

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

After the research team identified the "fatal flaw" treatments that were not feasible to install at this intersection, 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 their effectiveness and determine which was the most appropriate.

Longitudinal Pavement Markings

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

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 manoeuvre 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 feet (SSD) from the intersection.

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

TREATMENT IMPLEMENTATION

As shown previously, Exhibit 3-5 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 milepost 4.12
    - Stopping sight distance at 55 mph is also near milepost 4.12 (approximately 500 feet from the intersection)
- **Treatment Location #2**: 400 feet 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 milepost 1.41
- **Treatment Location #2**: Approximate point of curvature at milepost 1.47
    - The installation points closest to the intersection (mileposts 4.12 and 1.41) were chosen because of the existing signs at those location and because the signs are near the stopping sight distance for 55 mph (495 feet, Exhibit 3-1 in AASHTO). 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 speed 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, milepost 1.47) or presence of driveways (Meridian Road, milepost 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.

3.10. DATA COLLECTION METHODOLOGY

3.10.1. Overview

The research team considered a variety of testing methodologies, including field testing, controlled off-road testing, and driving simulators. The primary objective of any testing methodology is to get meaningful data on the speed reduction capabilities of potential treatments. The research team contacted driving simulator operators and requested information on those facilities' ability to conduct meaningful tests on the four recommended treatments. The responses supported the promise of potential simulator applications but also described limitations in testing some treatments.

Field tests would yield results from real-world drivers with real-world trip purposes, driving a variety of vehicle types. These drivers will generally be unaware that a test is being conducted. Driving simulators would use drivers in a lab with no trip purpose, and those drivers are aware that some sort of test is being conducted (although they should not know what specifically is being tested). These participants would be "driving" a single vehicle type versus the variety of vehicles in applied field tests. It is intuitive that some participants in the driver simulators would pay more attention to the task of driving than would real-world drivers.

Simulator participants would encounter the treatments for the first time and may react more cautiously than if they encountered them at the same location on a regular basis. The research team expected to get more data points from field tests and have the ability to adapt the tests to site-specific needs. Finally, field tests could be implemented and monitored after motorists acclimated to the treatments. This research approach would provide opportunities to understand the long-term speed reduction implications and conduct before-and-after evaluations at a specific site.

The research team recognized the value and potential application of driver simulators, but determined field tests would provide the most meaningful data.

3.10.2. Equipment

The research team investigated various data collection equipment and procedures to determine the most comprehensive and effective means of collecting speed data during field testing. The methodologies that were investigated are: Hi-Star devices, tape switches, and video photography. Prior to the investigation, the team identified three key features that must be achieved by the device to produce the type of data required for this research:

- It must be possible to establish a common time base for data collected by different units along the intersection approach so that speed profiles of individual vehicles could be determined.

- Speed and headway data must be collected and stored for each individual vehicle detected, not placed in "bins" by speed or headway category.

- Each device must have speed and headway data accuracies to ensure that even minimal speed effects of various treatments are recorded.

Based on conversations with many other researchers and the team's own investigation, tape switches were ultimately determined to be the most appropriate device for the speed data collection. Tape switches can achieve the appropriate accuracy desired and have fairly simple set-up and data post processing compared to the other methods. The following sections summarize each of the data collection devices and the reasoning behind choosing tape switches for collecting data.

3.10.2.1. Hi-Star Traffic Analyzers

In the Phase I Interim Report, the research team recommended collecting speed data through the use of traffic classifiers with sensors temporarily placed on the pavement surface. The Nu-Metrics Hi-Star Portable Traffic Analyzer was recommended. This self-contained unit monitors traffic flow conditions by using Vehicle Magnetic Imaging technology to continuously record volume, speed, and vehicle classification data. The benefits of this device are simple equipment installation and user-friendly post processed data that can be easily manipulated. The devices are relatively inconspicuous to drivers, rendering them less likely to influence data integrity.

To ensure the Hi-Star Traffic Analyzer met the above criteria, the research team contacted various state agencies, university professors, and equipment vendors to discuss their experience with it.

At the request of the research team, Coral Sales Company, a vendor for Hi-Star equipment, conducted a presentation at Kittelson & Associates, Inc. about the equipment capabilities, installation, and accuracy. Coral Sales Company brought samples of the device and output data. From this presentation, the research team determined that this device was not likely to record data with the level of accuracy needed for this research. As stated by Coral Sales Company, each individual device is accurate within 2 to 3 mph; therefore, two devices in series have the potential to be only accurate within 4 to 6 mph. The team also learned that, although it is possible to collect data of individual vehicles, the device and data software is set up to place vehicles in "speed bins." Data memory limitations may make it impossible to adequately assess the full range of speeds (say 60 mph to stop) in suitable speed gradations. Collecting speed data of individual vehicles also requires additional post-processing of the data.

The research team also contacted professors at the University of Nebraska, Oregon State University, and Pennsylvania State University to discuss their experience with the Hi-Star devices on other research projects. Conversations with these professors confirmed that the accuracy of these devices in series may not be sufficient for this research and that collecting speed data for individual vehicles would require additional efforts.

3.10.2.2. Video Photography

Based on the concerns with the accuracy of the Hi-Star devices, the research team also began investigating video photography as a potential data collection methodology. Video photography uses digital video cameras that can record at 30 frames per second. Because of this recording speed and estimated vehicle speeds during data collection, a large speed trap would be required to achieve an appropriate level of accuracy. For example, measuring vehicle speeds at 60 mph and using a speed trap of 44 feet, the video cameras can only provide accuracy within approximately 4 mph. As the speeds go down, the accuracy increases with the 44-foot trap; however, at slower speeds this distance no longer provides spot speed data. A larger speed trap provides more accuracy at higher speeds; however, the larger trap creates greater time for vehicles to change speeds within the speed trap and no longer provides spot speed data. The appropriate and desired speed trap needed to be calculated for each site and, in some cases, the most desired length of the speed trap may not have been identified until after the speed data was collected.

Video photography requires extensive post-processing that can induce error due to the subjectivity of the data recording. Video photography requires a post-processor to identify the point at which a vehicle passes a line on the pavement. In some cases, the video frame could show the front of the tire passing the roadway mark. In other cases, the video frame could show the middle of the tire passing the line. Due to the inaccuracy of the video camera, the vehicle could be anywhere from 0 to 3 feet beyond the mark, but still recorded as the beginning of the speed trap. In addition, video detection requires the post-processor to identify vehicles traveling within a platoon by manually measuring gaps in traffic.

The visibility of the cameras and researchers also is a concern when using this device. For security reasons, a researcher would have to remain at the site to watch the camera and, due to limited recording time, replace the camera tapes every two hours. This increases the chance of researchers being visible to passing vehicles. At some locations, the scenery would allow cameras to be placed out of view of drivers, such as near a utility pole or tree. However, in some desert or rural areas, cameras would have to be placed in more visible areas such as on a tripod or fence post near the edge of the roadway.

3.10.2.3. Tape Switches and Traffic Classifiers

In addition to Hi-Star devices and video photography, tape switches also were investigated. Tape switches include two switch wires spaced 10 feet apart connected to a traffic classifier that records speed data between the wires to the nearest 1/10th mile per hour. Speed data is recorded for individual vehicles, and platooned vehicle data can be removed by evaluating the vehicle headways during post-processing. Data from the traffic classifier can be imported into Excel and post-processed to provide speed profile data.

Although this type of device meets the criteria required to collect the appropriate type of data for testing, the research team identified concerns with the tape switches being visible to drivers. This device requires that the tape switches be taped to the pavement with gray tape. Therefore, the potential exists for these tapes to be visible to drivers as they pass over them or to create a slight vibration that drivers might feel when they pass over the tapes.

To resolve this concern, the research team contacted various researchers experienced with this type of device. During one of these discussions, a researcher explained that, in a recent study using tape switches, he and the other researchers were not able to see the tape switches when they drove through the study area, even when they knew the locations of each tape switch. Other researchers confirmed that they did not typically have issues with the tapes being visible to drivers and that the visibility of the tape switches depends on the pavement type.

To ensure that the actual traffic classifier on the side of the roadway is not visible to passing drivers, the connected wires have a 30-foot lead to the classifier. This allows the classifiers to be placed out of view.

An additional concern about the use of tape switches is the potential for them to break or be torn from the pavement under high-volume traffic conditions, in areas with heavy vehicles, or when left in place for a long period of time. This is particularly prominent when tape switches are placed at an intersection approach where drivers will be braking or stopping on the tape switches.

Therefore, to further investigate these data collection devices and the concerns raised by other researchers, the team conducted a pilot study at one of the treatment sites in Clackamas County, Oregon. Based on this pilot study, the research team did not observe any driver impact as a result of the visibility of the tapes switches and had little difficulty with the tape switches being removed from the roadway, even with heavy vehicle volumes. The speed data collected from this pilot study was accurate, precise, time stamped, and able to track the speed profiles of individual vehicles.

In summary, Hi-Star devices have accuracy limitations that may exceed what could be subtle speed changes with the proposed treatments. Video photography appears to have accuracy limitations in high-speed locations and could require more extensive and subjective data reduction efforts. Therefore, based on the investigations conducted for the three potential data collection devices and methodologies, tape switches were selected as the most appropriate device to collect speed data. Although some concerns were raised about these devices, the pilot study helped confirm that this device can achieve the appropriate accuracy desired and had fairly simple set-up and data post-processing compared to the other methods.

3.11. DATA COLLECTION

For the subject treatment to be effective, it must get the attention of drivers and appropriately reduce speed in time for an emergency stop, if necessary, prior to reaching the intersection. Therefore, speed data collection points on the approach to the intersection were designated based on drivers' ability to perceive the intersection and sufficiently decelerate in time for an emergency stop. The proposed field data collection scheme consists of an intersection-approach speed profile based on the four speed collection points noted below.

3.11.1. Advance Speed Location for Control Purposes

A valid before-and-after experimental design must include "control" speed data collection to account for extraneous non-treatment effects (e.g., seasonal differences). A speed data collection location placed significantly in advance (e.g., ¼ mile) of the treatment application was proposed for this purpose. Such a location would yield vehicle speeds unaffected by the presence of the intersection.

3.11.2. Intersection Perception/Response Speed

Intersection design principles require that the intersection be visible to an approaching driver at a sufficient distance to come to a complete stop, following 2.5 seconds of perception-response time (PRT). Therefore, a data collection point was established at the 2.5-second PRT stopping distance at the posted speed limit. Assuming that data collection would be conducted during dry pavement conditions, the research team selected applied data collection locations based on an estimated dry pavement friction (e.g., 0.65) stopping requirement to ensure that measured speeds reflected actual perceivable conditions.

3.11.3. Accident Avoidance Speed

A driver's "last chance" (or emergency opportunity) to avoid an accident in response to a surprise or unexpected hazard requires an instantaneous perception-reaction-time response (e.g., 1.0 second, followed by skidding to a stop just short of the collision point). For example, assuming a 45-mph approach speed and a dry pavement friction coefficient of 0.65, the advance data collection location is 170 feet from the intersection. Exhibit 3-23 displays the advance distances for the driver perception-response and accident-avoidance data-collection points.

Exhibit 3-23 Human-Factors-Based Speed Data Collection Distances Advance of Intersection

Speed Data	**Operating speed (mph)**			
	45	50	55	60
Intersection Perception/Response	269′	312′	357′	405′
Accident-avoidance	170′	202′	236′	273′

3.11.4. Intersection Entry Speed

The speed at which vehicles enter the intersection was measured in close proximity (e.g., at or near the stop bar) to the intersection.

This data collection scheme considered drivers' ability to detect the intersection and, if necessary, to stop in time to avoid an unexpected hazard, thereby preventing an accident. A significant advantage of this data collection scheme is the sensitivity of measures of effectiveness to driver responses without confounding effects of differing approach speed limits. That is, the placement of speed collection points is based on available driver information processing time, thus avoiding the potential error effect of shorter driver response time associated with a higher approach speed limit.

The sensors were positioned at the same locations before and after the subject treatments were installed to ensure direct comparisons between vehicle speeds at the same locations on the intersection approach. However, in addition to such comparisons between speeds at one location before and after the treatment was installed, speed profiles for individual vehicles were established so that vehicle speeds at any point on the intersection approach could be determined in the before-and-after condition.

3.12. ADDITIONAL DATA COLLECTION

In addition to speed data collection, the research team used one or two video cameras at each site during the data collection period. The field of view for each camera was:

- Camera 1 — at the intersection, directed toward the paved intersection area and the stop line or curb line of the approach being studied.

- Camera 2 — upstream of the intersection and directed along the approach being studied.

The video recording from Camera 1 was used to observe whether each vehicle made a full stop, a partial stop, or no stop at the intersection. The video recording from Camera 2 documented any undesirable driver behavior such as hard braking near the treatment or encroachment on the shoulder or an adjacent lane to avoid the treatment.

3.12.1. Data Collection Layouts

Based on this data collection scheme, the research team prepared treatment layouts for all testing sites. The research team prepared data collection plans for each of the sites, identifying the appropriate locations to collect speed data during “before” and “after” data collection.

Based on the number of traffic classifiers available for data collection, the team collected data at eight to ten spot speed locations at a given time. In most cases, the research team collected data at eight points to allow for at least one spare classifier to be available if any of the other devices malfunctioned. At an intersection with treatments on two approaches, data was collected at four points on each approach. Exhibit 3-24 shows a data collection plan developed for the Whiskey Hill Road/Meridian Road site in Clackamas County, Oregon.

At the site shown in Exhibit 3-24, the research team designed peripheral transverse pavement markings to be installed on the northbound and eastbound approaches. Four data collection points were identified on each approach:

- *Advance Speed Control Location*. The location of this data collection point was determined based on the location of the treatment farthest from the intersection. At each location, the research team verified that the treatment could not be visible from this data collection point to ensure that speeds at this location were not affected by the presence of the treatment.
    - Eastbound Direction — 1,300 feet from the intersection
    - Northbound Direction — 1,800 feet from the intersection
- *Intermediate Treatment Location*. At least two sets of treatments were installed on a given intersection approach at all transverse pavement marking and rumble strip treatment locations. This data collection point measured the speed of vehicles traveling between the two treatments, showing the effects of the first treatment.
    - Eastbound and Northbound Directions — 600 feet from the intersection
- *Accident Avoidance Speed.* At both approaches in Exhibit 3-24, the speed was “basic rule.” Therefore, an estimated speed of 55 mph was used to measure the approximate accident avoidance distance of 250 feet.

Exhibit 3-24


NCHRP 3-74: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections
December 2007
N
1300'
APPROX. M.P. 1.47
600'
ADVANCE INTERSECTION SIGN M.P. 1.41
250'
100'
MERIDIAN ROAD
WHISKEY HILL ROAD
165'
250'
SCHOOL ADVANCE SIGN M.P. 4.12 (S.S.D. @ M.P. 4.13)
600'
400' BEYOND UPSTREAM MARKING M.P. 4.21
1800'
SCALE
0
200
400
POTENTIAL TREATMENT LOCATION
TAPE SWITCH DATA COLLECTION POINT
TUBE COUNTER DATA COLLECTION POINT
POTENTIAL TRANSVERSE PAVEMENT MARKING LAYOUT
WHISKEY HILL ROAD/MERIDIAN ROAD
CLACKAMAS COUNTY, OREGON
EXHIBIT
3-24
H:\projfile\6284\Task 7\Clackamas County\Whiskey Hill Road\Whiskey Hill_Meridian Data collection plan.dwg Jun 30, 2006 - 2:32pm - jham Layout Tab: Layout1
KITTELSON & ASSOCIATES, INC.
TRANSPORTATION ENGINEERING/PLANNING

Intersection Entry Speed. The research team collected intersection entry speeds 100 feet from the intersection at most locations.

- Eastbound Direction — 100 feet from the intersection
- Northbound Direction — 165 feet from the intersection (This distance was extended due to a driveway located approximately 100 feet from the intersection.)

The data collection points described above were used at most intersection treatment sites. However, in some cases, the data collection points were altered to accommodate different types of treatments or unique site characteristics. For example, the dynamic warning sign sites did not have an "Intermediate Treatment Speed" due to there only being one treatment per approach; instead, another data collection point was identified. Exhibits 3-25 to 3-28 show the data collection layouts for the remaining four sites in Oregon and the site in Washington.

3.12.1.1. Pilot Test

To test the data collection methodology and equipment prior to the "before" testing, the research team conducted a pilot test using tape switches at the Whiskey Hill Road/Meridian Road intersection in Clackamas County, Oregon, during the week of April 17, 2006. The data collection equipment was set up as shown previously in Exhibit 3-24 and speed data were collected from 9 a.m. to 6:30 p.m. The research team that participated in this pilot study included three KAI staff, two MRI staff, and two staff from Quality Counts, LLC (a transportation data collection firm). The intent was to have most of the research team members present at the pilot to learn how to operate the data collection devices, to discuss the data collection plan, and to identify any issues with the proposed testing plan or potential testing sites.

In addition to testing the equipment and methodology for data collection, the pilot study also investigated two concerns associated with using tape switches for data collection: (1) visibility to drivers; and (2) tapes being removed from the pavement by trucks. The "before" testing conducted during the pilot study confirmed that these issues would not affect the research data collection. The tape switches were inconspicuous to drivers, and were even difficult for the research team to see when driving through the site.

Exhibit 3-25


NCHRP 3-74: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections
December 2007
N
1300'
POINT OF CURVATURE APPROX. M.P. 5.77
625'
LONE ELDER ROAD SIGN M.P. 5.68
CANBY-MARQUAM HWY
250'
175'
LONE ELDER ROAD
LONE ELDER ROAD @ M.P. 5.60
100'
275'
LONE ELDER ROAD SIGN M.P. 5.50 (S.S.D. @ 55 MPH M.P. 5.51)
700'
POINT OF TANGENCY APPROX. M.P. 5.42
1500'
SCALE
0
200
400
H:\projfile\6284\Task 7\Clackamas County\Canby-Marquam_Lone Elder Road\CM_Lone Elder Aerial data collection plan.dwg Jun 30, 2006 - 2:36pm - jham Layout Tab: Layout1
| | | | | POTENTIAL TREATMENT LOCATION
| | TAPE SWITCH DATA COLLECTION POINT
POTENTIAL TRANSVERSE PAVEMENT MARKING LAYOUT
CANBY-MARQUAM HIGHWAY/LONE ELDER ROAD
CLACKAMAS COUNTY, OREGON
EXHIBIT 3-25
KITTELSON & ASSOCIATES, INC.
TRANSPORTATION ENGINEERING/PLANNING

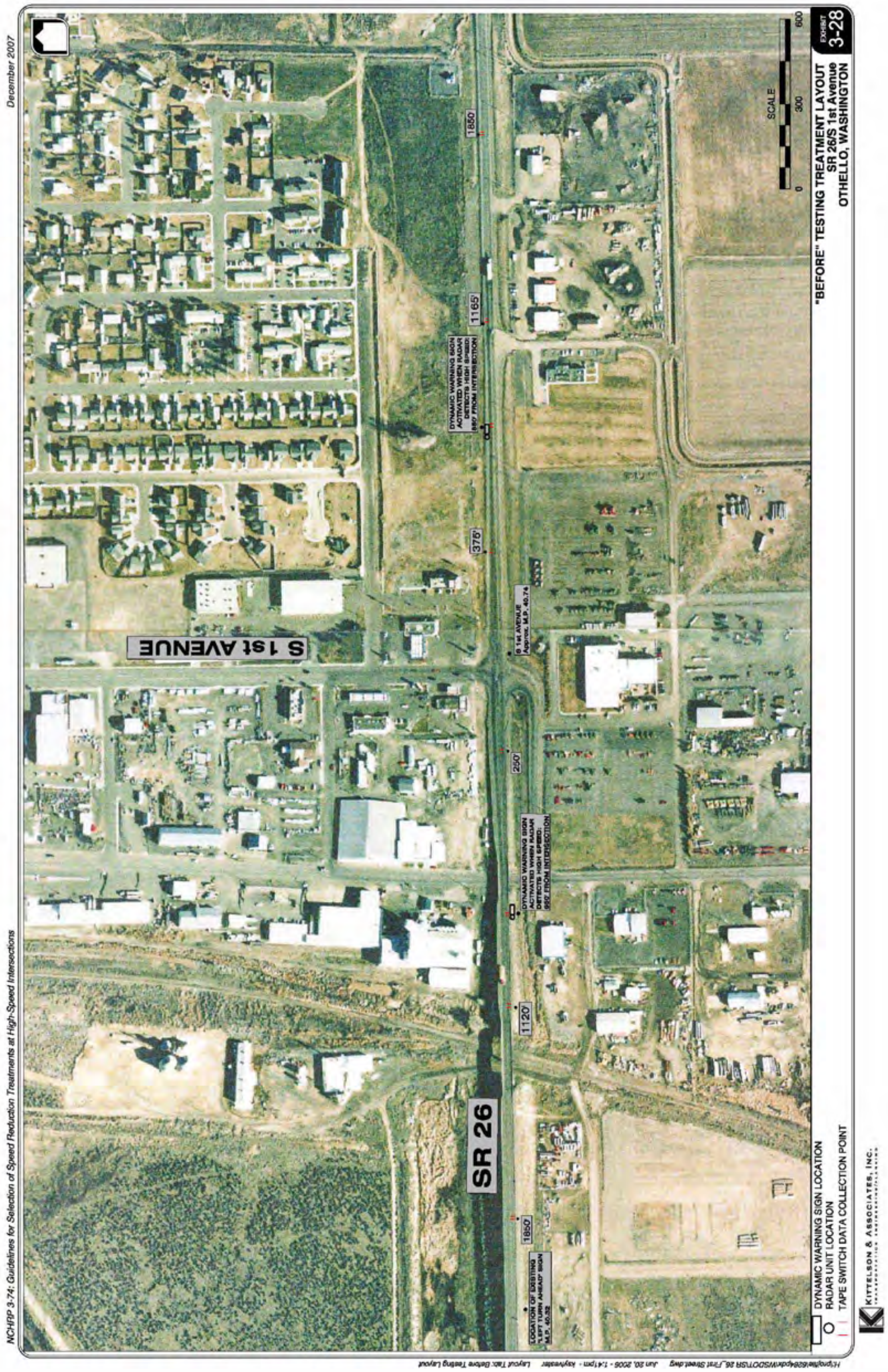
Exhibit 3-26


December 2007
EXHIBIT
3-26
POTENTIAL TRANSVERSE PAVEMENT MARKING LAYOUT
REDLAND ROAD/FERGUSON ROAD & REDLAND ROAD/BRADLEY ROAD
CLACKAMAS COUNTY, OREGON
BRADLEY ROAD
REDLAND ROAD
FERGUSON ROAD
SCALE
0
300
600
POTENTIAL TREATMENT LOCATION
TAPE SWITCH DATA COLLECTION POINT
KITTELSON & ASSOCIATES, INC.
NCHRP 3-74: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections

Exhibit 3-27


NCHRP 3-74: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections
December 2007
N
WILSON RIVER LOOP ROAD
OR 6
1800' WB 4
"WILSON RIVER LOOP ¼ MILE" SIGN @ M.P. 2.05
900' WB 3
"FAIRGROUNDS STATE OFFICES NEXT RIGHT" SIGN @ M.P. 1.92
250' WB 2
100' WB 1
WILSON RIVER LOOP ROAD @ M.P. 1.80
100' EB 1
250' EB 2
"FAIRGROUNDS STATE OFFICES NEXT LEFT" SIGN @ M.P. 1.70
900' EB 3
M.P. 1.56 (¼ MILE FROM WILSON RIVER LOOP ROAD)
1800' EB 4
SCALE
0
300
600
POTENTIAL TREATMENT LOCATION
TAPE SWITCH DATA COLLECTION POINT
PROPOSED TREATMENT LAYOUT & DATA COLLECTION PLAN
OR 6/WILSON RIVER LOOP ROAD
TILLAMOOK, OREGON
EXHIBIT
3-27
H:\projfile\6284\Task 7\ODOT Treatments\6284aerials.dwg May 02, 2006 - 4:23pm - jham Layout Tab: Layout3
KITTELSON & ASSOCIATES, INC.
TRANSPORTATION ENGINEERING/PLANNING

Exhibit 3-28


December 2007
NCHRP 3-74: Guidelines for Selection of Speed Reduction Treatments at High-Speed Intersections
EXHIBIT 3-28
"BEFORE" TESTING TREATMENT LAYOUT
SR 26/S 1st Avenue
OTHELLO, WASHINGTON
SCALE
0
300
600
1850'
1165'
DYNAMIC WARNING SIGN ACTIVATED WHEN RADAR DETECTS HIGH SPEED: 860' FROM INTERSECTION
375'
S 1st AVENUE Approx. M.P. 40.74
S 1st AVENUE
250'
DYNAMIC WARNING SIGN ACTIVATED WHEN RADAR DETECTS HIGH SPEED: 950' FROM INTERSECTION
1120'
SR 26
1850'
LOCATION OF EXISTING "LEFT TURN AHEAD" SIGN M.P. 40.32
DYNAMIC WARNING SIGN LOCATION
RADAR UNIT LOCATION
TAPE SWITCH DATA COLLECTION POINT
KITTELSON & ASSOCIATES, INC.
H:\projfile\6284\pdx\WSDOT\SR 26_First Street.dwg Jun 20, 2006 - 1:41pm - ksylvester Layout Tab: Before Testing Layout

In addition, the team did not have any issues with the tape switches being removed from the pavement during data collection. The tape switches withstood the high percentage of trucks on Meridian Road and Whiskey Hill Road throughout the entire day (a ten-hour period). No switches were damaged, even on the stop-controlled approaches on Meridian Road.

As suggested by one of the NCHRP panel members, the research team used a radar gun to check the speed data being collected from the tape switches. Approximately ten speeds were collected on the northbound approach of Meridian Road using the radar gun and were compared with speeds being recorded on the traffic classifiers. The comparison between the two devices resulted in a difference of less than one mile per hour. Therefore, the research team is confident that the tape switches collected accurate data.

Clackamas County planned to continue monitoring the effectiveness of the treatments installed during this research project beyond this project's timeline. Based on their experience with other treatments in the county, county staff would like to observe the effectiveness of treatments six months and one year after installation. To allow them to compare this study's data to future data they will collect, county staff installed tube counters for a two-hour period with our tape switches to calibrate the data. Tube counters were installed on the northbound approach of Meridian Road from approximately 10 a.m. to noon during the data collection pilot. The research team provided the county with the data collected from the tape switches to compare the speed data from both devices and develop a calibration that can be used for future speed studies beyond this research project. Speed data collected with the tape switches during this time will not be included in the "before" data for this site, to exclude any effects that may have occurred due to the tube counters.

In addition to speed data collection, the research team used three video cameras at the site during the data collection period. The field of view for each camera is described below:

- Camera 1 — at the intersection, directed toward the paved intersection area and the stop line or curb line of the approach being studied.
- Cameras 2 and 3 — upstream of the intersection and directed along each approach being studied (northbound and eastbound approaches).

Overall, the tape switches and video recording provided sufficient data for the pilot test to be used as the "before" testing at this site in Clackamas County.

3.13. BEFORE-AND-AFTER TESTING

After the pilot testing, the research team conducted the "before" testing at all the other candidate sites. The same equipment and methodology described in the pilot test were used at all other sites. Quality Counts (QC) served as the primary staff on-site during all testing. However, the team also ensured that one researcher was on-site during the beginning of each testing period to assist in laying out the data collection points and making decisions if collection points needed to be changed. In most cases, QC and the research team followed the data collection layouts to identify the testing points. However, in some cases, when the team arrived on-site, the points needed to be modified due to existing driveway locations or other complexities not visible on the aerial schematics.

As described previously, after the treatments were installed a three-month acclimation period was used prior to the "after" testing. In most cases, there was an even longer acclimation period, due to the research testing schedule and weather conditions at some sites. The research team made significant efforts during the "after" testing to be consistent with the "before" testing to ensure that the data from each test could be compared to determine the effectiveness of each treatment. The team permanently marked the data collection points with "mag" nails during the "before" testing and used them to identify the exact locations during the "after" testing. In addition, the team also scheduled the "after" testing on days and under weather conditions similar to each "before" test.

Exhibit 3-29 shows the before-and-after testing and treatment installation schedule.

Exhibit 3-29 Treatment Testing and Installation Schedule

State/County Agency	Site		Treatment	Before Testing	Treatment Installation	After Testing
Clackamas County, OR	1	Whiskey Hill Road/Meridian Road (south of Aurora, OR)	Transverse Pavement Markings	April 18, 2006	May 31, 2006	September 26, 2006
	2	Canby-Marquam Highway/Lone Elder Road (south of Canby, OR)	Transverse Pavement Markings	April 27, 2006	May 31, 2006	September 27, 2006
	3	Redland Road/Bradley Road (east of Oregon City, OR)	Transverse Pavement Markings	April 28, 2006	May 31, 2006	September 29, 2006
	4	Redland Road/Ferguson Road (east of Oregon City, OR)	Transverse Pavement Markings	April 28, 2006	May 31, 2006	September 29, 2006
Oregon DOT	6	OR 6/Wilson River Loop Road (near Tillamook, OR)	Transverse Pavement Marking	May 4, 2006	May 19, 2006	September 28, 2006
Washington DOT	8	SR 26/SR 24/1st Street (near Othello, WA)	Dynamic Warning Sign	May 26, 2006	September 1, 2006	March 8, 2007
Texas DOT	10	US82 @ SH98 (Bowie County)	Dynamic Warning Sign	June 13, 2006	August 1, 2006	November 13, 2006
	11	US271 @ FM726 (Upshur County)	Rumble Strips	June 14, 2006	July 26, 2006	November 14, 2006
	12	US271 @ FM593 (Upshur County)	Rumble Strips	June 15, 2006	July 26, 2006	November 15, 2006
	13	US271 @ FM2088 (Upshur County)	Rumble Strips	June 16, 2006	July 26, 2006	November 16, 2006

4 Treatment Installations

Once the before testing was completed, the research team coordinated with each agency to install treatments at each of the testing sites. Due to the three-month acclimation period, installing the treatments in a timely manner was a high priority to meet the overall project timeline. As shown previously, Exhibit 3-30 summarizes the testing and installation dates of each treatment.

Most participating agencies desired treatments that were inexpensive, easy to install, and did not required extensive maintenance. Therefore, in most cases the installation process for each treatment was completed in one day by agency staff.

The transverse pavement markings and rumble strip installations required little time to install. The agencies had the materials in stock and there were not utility impacts. In these cases, the roadway maintenance crews for each agency obtained the material and installed the treatment at the specified location within a few hours. As shown previously in Exhibit 3-30, Clackamas County was able to install transverse pavement markings at four locations in the same day. ODOT and TXDOT were also able to install the transverse pavement markings and rumble strips, respectively, within one day.

The dynamic warning sign installations required more coordination for the agencies due to the sign purchasing and designing, selecting the detection type (i.e. radar or loop detectors), and accessing a power source. The dynamic warning sign installations required power sources to provide power to the electronic sign. Therefore, TXDOT and WSDOT coordinated with the utilities and power in the site vicinity to identify the most appropriate and convenient power source.

The following exhibits illustrate photos of each treatment installed in Oregon, Washington, and Texas.

4.1 CLACKAMAS COUNTY

1.) Whiskey Hill Road/Meridian Road

Exhibit 4-1 Eastbound on Whiskey Hill Road

Exhibit 4-2 Northbound on Meridian Road

2.) Canby-Marquam Highway/Lone Elder Road

Exhibit 4-3 Southbound on Canby-Marquam Highway

Exhibit 4-4 Northbound on Canby-Marquam Highway

3.) Redland Road/Ferguson Road

Exhibit 4-5 Eastbound on Redland Road

Exhibit 4-6 Westbound on Redland Road

4.) Redland Road/Bradley Road

Exhibit 4-7 Eastbound on Redland Road

The transverse pavement markings in Clackamas County were installed with thermoplastic material. After the research team reviewed the treatment installations at these locations, there were two items noted for future consideration which include marking location and visibility.

As shown in the above exhibits, at all of the sites, there were treatments installed downstream of existing signs. The intent of these particular treatment locations were to supplement the existing signing by providing an additional visual cue that the roadway segment was changing and an intersection is ahead. Therefore, in the future the research team would instruct the agency to install the treatments upstream of the existing signs. This would allow a driver to observe the visual treatment prior to observing the "intersection ahead" or other warning sign. Instead, the way the treatments are currently shown may actually distract the driver away from the existing sign by directing their eyes downstream at the markings.

In addition to the marking location upstream of the sign, the research team would also recommend using a more visible pavement marking design. The marking design is based on the existing lane width and the width of the design vehicle wheel base. Due to the narrow lane widths and high volume of truck traffic on the rural two-lane roadways in Clackamas County, the pavement markings shown are approximately 12 inches in length and 8 inches in width. In the future, the research team would recommend extending the pavement marking farther (approximately 18 to 24 inches) into the travel lane and using a pavement marking width of approximately 12 to 18 inches. This would provide a more significant visual treatment and allow drivers to observe the treatment from farther distances.

4.2 OREGON DEPARTMENT OF TRANSPORTATION

5.) OR 6/Wilson River Loop

Exhibit 4-8 Westbound on OR 6

The transverse pavement markings in Tillamook, Oregon were installed with paint. ODOT chose to install the pavement markings as an interim treatment before constructing a future interchange at this location. Therefore, they chose to use material that was less expensive and easier to remove from the pavement.

As shown in the above exhibit, the treatments were installed upstream of the existing sign, as recommended by the research team. However, similar to the transverse pavement marking location in Clackamas County, the research team would also recommend using a more visible pavement marking design that would extend farther into the travelway.

4.3 WASHINGTON DEPARTMENT OF TRANSPORTATION

6.) SR 26/SR 24/1st Street

Exhibit 4-9 Eastbound on SR 26

Exhibit 4-10 Westbound on SR 26

WSDOT chose to design a specific sign for the Othello, Washington site, which required the agency to develop design plans and decide on the type of dynamic message to install. As shown in Exhibit 4-9 and 4-10, this sign included a static "speed limit" and "intersection ahead" sign combined with a dynamic sign that would flash "slow" and "down" when triggered by specific vehicle speeds. WSDOT constructed the static sign board and base, however, the dynamic warning sign and radar was purchased from an outside vendor. Due to the time required for ordering and receiving the dynamic sign and radar, the static sign was installed for a short period of time before the dynamic sign and radar was received and installed.

4.4 TEXAS DEPARTMENT OF TRANSPORTATION

7.) US 82/SH 98

Exhibit 4-11 Westbound on US 82

For the dynamic warning sign installation in Texas, TXDOT used a standard sign and layout for the treatment installation. Therefore, this required less time for designing and obtaining the sign. As shown in Exhibit 4-11, this sign included a speed limit sign and a dynamic sign below that would show the speed of each passing vehicle.

8.) US 271/FM 726

Exhibit 4-12 Southbound on US 271

Exhibit 4-13 Southbound on US 271

9.) US 271/FM 593

Exhibit 4-14 Southbound on US 271

Exhibit 4-15 Northbound on US 271

10.) US 271/FM 2088

Exhibit 4-16 Northbound on US 271

Exhibit 4-17 Northbound on US 271

Exhibit 4-18 Southbound on US 271

As shown in the above exhibits, the rumble strips installed in Texas were installed in two transverse segments in the wheel path of the travel way. The rumble strips consisted of a white plastic material that was adhered to the pavement. Therefore, in addition to the audible and physical vibration of the strips this was also a visual treatment.

As shown in Exhibit 4-12 and 4-18, at some of the locations there was an existing pavement marking legend that illustrated the speed limit of the roadway. In reviewing the treatment installation locations, the research team recommends installing the rumble strips upstream of the existing pavement legend, as shown in Exhibit 18. Similar to the discussions with the transverse pavement markings, installing the rumble strips upstream of the existing markings allows drivers to become more alert from the rumble strips and then more likely to notice the additional speed limit pavement markings. If the rumble strips are installed downstream of the existing pavement markings, the driver may not become aware of the intersection until after experiencing the rumble strips, at which time they have already passed the other pavement markings to illustrate the speed limit.

4.5 SUMMARY

All of the treatments were installed in a timely manner allowing the research team to maintain the project timeline. After the treatment installation the research team did identify some treatment locations and designs that could have been improved. However, the research team is confident that the treatment installations and designs shown provided an appropriate basis for measuring the effectiveness of each treatment type.

5 Testing Results

5.1. EXECUTIVE SUMMARY

Three speed-reduction treatments were tested at 10 intersection sites for a total of 19 intersection approaches. The testing was conducted to determine the effectiveness of each treatment at reducing speeds on high-speed intersection approaches. The treatments included peripheral transverse pavement markings, rumble strips, and dynamic warning signs activated by speed.

Speed data were collected at four locations along each of the 19 intersection approaches 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. The 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.

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
- *Analysis by Treatment Type* – to quantify the effect of each treatment across all intersection approaches at which it was installed

The analysis by location showed that installing treatments generally reduced speeds by as much as 3.2 mph. At a few locations, increases in speed of as much as 1.8 mph were observed. The analysis by intersection approach showed that at most intersection approaches, the treatment installation resulted in a statistically significant speed reduction. At three approaches, there was an increase in speed; however, only one of these was statistically significant. All three intersection approaches on which dynamic warning signs were installed experienced a statistically significant speed reduction. The analysis by treatment type showed that dynamic warning signs and peripheral transverse pavement marking had a statistically significant overall effect in reducing speeds. Dynamic warning signs had a mean speed reduction of 1.7 mph, while peripheral transverse pavement marking had a mean speed reduction of 0.6 mph. Dynamic warning signs resulted in the largest speed reduction compared to the other treatments. Rumble strips did not have a statistically significant overall effect in reducing speeds; however, the results of the analysis by treatment type were based on only three intersection approaches where rumble strips were installed.

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). Of the three treatment types, dynamic warning signs may be the most effective at reducing speeds and may result in the greatest speed reduction. However, this conclusion is based on testing results at three intersection approaches.

5.2. INTRODUCTION

Chapter 5 presents the results of data collection and analyses conducted to evaluate the effectiveness of various treatments intended to reduce vehicle speeds on high-speed intersection approaches.

The research team coordinated with the Oregon Department of Transportation (ODOT), Washington State Department of Transportation (WSDOT), Texas Department of Transportation (TXDOT), and Clackamas County, Oregon, to install treatments at 10 intersections. These treatments included peripheral transverse pavement markings, rumble strips, and dynamic warning signs.

This chapter is organized as follows:

- Data Collection Approach
- Data Analysis Approach
- Data Analysis Results
    - Results of Analysis by Location (Step 1 Analysis)
    - Results of Analysis by Intersection Approach (Step 2 Analysis)
    - Results of Analysis by Treatment Type (Step 3 Analysis)
    - Results of 85th Percentile Speeds
    - Testing Results Summary
- Conclusions

5.3. DATA COLLECTION APPROACH

A total of 19 intersection approaches from 10 intersection sites in Oregon, Texas, and Washington were tested. Exhibit 5-1 presents basic site information, including the type of treatment evaluated, for each intersection site.

The techniques used to collect field data included:

- Automated traffic recorders to count traffic volumes and collect data on the speeds, headways, and lengths of individual vehicles.
- Video recorders to film traffic events at the intersection for later review and data reduction, as needed.

- The automated traffic recorders were Unicorn traffic classifiers manufactured by Diamond Traffic Products. Vehicle axle passages to determine speeds, headways, and vehicle lengths were detected with piezoelectric cables taped to the pavement surface.

Speed data were collected before and after treatment installation to determine the effectiveness of each treatment at reducing speeds on a high-speed intersection approach. After treatment installation, a three-month acclimation period occurred prior to collecting speed data to allow for the novelty of the treatment to subside and for motorists to adjust to the presence of the treatment.

Data were collected under daylight, off-peak, and free-flow conditions in dry weather. With the exception of one intersection approach, speed data were collected at four locations along each intersection approach to obtain the following speeds:

- *Free-Flow Speed (Location D)* - A set of sensors was placed upstream of the treatment in a location where vehicle speeds would not be affected by the presence of the intersection (before treatment installation) or the treatment itself (after treatment installation).

- *Intersection Perception/Response Speed (Location C)* - A set of sensors was placed at the point where the intersection or the treatment (after treatment installation) would first become visible to the driver, i.e., the point at which the driver might first react to the presence of the intersection or treatment.

Exhibit 5-1 Summary of Speed Data Collection Sites

Site No.	Intersection Site	Intersection Approach	Treatment	Through Lanes	STOP Control	Speed Limit (mph)
OR1	Meridian Rd / Whiskey Hill Rd	NB	Peripheral transverse pavement markings	1	Y	55
		EB	Peripheral transverse pavement markings	1	N	55
OR2	Canby-Marquam Hwy / Lone Elder Rd	NB	Peripheral transverse pavement markings	1	N	55
		SB	Peripheral transverse pavement markings	1	N	55
OR3	Redland Rd / Ferguson Rd	EB	Peripheral transverse pavement markings	1	N	55
		WB	Peripheral transverse pavement markings	1	N	50
OR4	Redland Rd / Bradley Rd	EB	Peripheral transverse pavement markings	1	N	55
		WB	Peripheral transverse pavement markings	1	N	55
OR6	SR 6 / Wilson River Loop Rd	EB	Peripheral transverse pavement markings	1	N	55
		WB	Peripheral transverse pavement markings	1	N	55
TX1	US 271 / FM 726	SB	Rumble strips	2	Na	70
TX2	US 271 / FM 2088	NB	Rumble strips	2	Na	70
		SB	Rumble strips	2	Na	70
TX3	US 271 / FM 593	NB	Rumble strips	2	Na	70
		SB	Rumble strips	2	Na	70
TX4	US 82 / SH 98	EB	Dynamic warning sign	1	Na	55
		WB	Dynamic warning sign	1	Na	55
WA1	SR 26 / S 1st Ave	EB	Dynamic warning sign	1	N	50
		WB	Dynamic warning sign	1	N	50b

a The intersection has a flashing-yellow signal on the major road and a flashing-red STOP-control signal on the minor road.
b At 1,850 feet from the intersection, the speed limit is reduced from 60 to 50 mph.

- *Accident Avoidance Speed (Location B)* - A set of sensors was placed at the point that represents a driver's "last chance" (or emergency opportunity) to avoid an accident at the intersection, in response to a surprise or unexpected hazard. Such a maneuver would require an instant perception-reaction-time response.

- *Intersection Entry Speed (Location A)* - A set of sensors was placed close (e.g., at or near the stop bar) to the intersection to measure the speed at which vehicles enter the intersection.

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. The 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. All distances were measured from the point where the roadway approach entered the intersection proper.

As discussed in the following section, three primary types of analyses were conducted in the study: (1) the speed reduction observed at each traffic classifier location; (2) the speed reduction observed along each intersection approach; and (3) the speed reduction effectiveness for each treatment type. A secondary analysis (of 85th-percentile speeds) was conducted for each intersection approach and each treatment type; however, less emphasis is placed on this analysis as explained later. To clarify the terminology used throughout the analysis discussion, a summary of terms is presented below:

- *Location* – A data collection location refers to a single point along an intersection approach at which a traffic classifier and two accompanying sensors were placed to measure speeds before and after treatment installation. Typically, traffic classifiers were placed at four such locations (e.g., Locations A, B, C, and D) along each intersection approach.

- *Intersection Approach* – An intersection approach refers to a single intersection leg (i.e., EB, WB, NB, or SB). As many as four traffic classifiers were placed on an intersection approach to establish a speed profile as drivers approached the intersections.

- *Intersection Site* – An intersection site refers to an entire intersection, including all approaches. At all but one of the intersection sites, speeds were measured at two of the intersection approaches (see Table 5-1).

5.4. DATA ANALYSIS APPROACH

The objective of the speed data analysis was to evaluate the effectiveness of three treatments (peripheral transverse pavement markings, rumble strips, and dynamic warning signs activated by speed) at reducing vehicle speeds on high-speed intersection approaches. The primary analysis consisted of three steps, with each step building upon the previous one. The three steps were:

- *Determine the speed reduction at each data collection location (i.e., A, B, C, and D)* – The speed reduction at an individual location was determined by comparing the speed data at an individual location before and after treatment installation. This approach is perhaps the least meaningful because it estimates treatment effectiveness only at a specific point along the intersection approach. The results do not provide information about speed reduction at any other point along that intersection approach; thus, no information is provided about the treatment's effect on the overall speed profile. However, because individual location speed data might be of interest to the reader, they have been summarized and are presented in *Appendix G*.

- *Determine the speed reduction along each intersection approach* – The effect of a treatment on the speed profile of an intersection approach is determined by comparing speed data, before and after treatment installation, at all locations while accounting for base speed changes along the intersection approach before treatment installation. This analysis should identify, for example, if a treatment causes drivers to begin their deceleration farther upstream of the intersection than before the treatment was installed.

- *Determine the overall effectiveness of a particular treatment type* – The effectiveness of a particular treatment type (i.e., peripheral transverse pavement markings, rumble strips, dynamic warning signs) is determined by comparing speed data, before and after treatment installation, across all intersection approaches at which the treatment was installed while accounting for site-to-site differences.

Each analysis step is described in greater detail below.

5.4.1. Analysis by Location (Step 1 Analysis)

The purpose of the analysis by location is to determine the speed reduction observed at each data collection location on an intersection approach as a result of the treatment installed on that approach. The observed speed reduction provides an estimate of the treatment effectiveness at a given location. This analysis is perhaps the least meaningful of the three analyses because it estimates the effectiveness of the treatment only at a specific point along the intersection approach. The effectiveness of a treatment at reducing the mean or median speed and the speed variability at a specific location were evaluated by comparing the speed data measured at an individual location before and after treatment installation.

The first step of the analysis was to verify that the speed data were normally distributed as many statistical tests are based on this assumption. To accomplish this, histograms of speed data were plotted for each location. A visual inspection of the histograms identified traffic classifiers from which speed data did not appear to be normally distributed. The most common location for this to occur, on a given intersection approach, was the location closest to the intersection (Location A). It appears that turning movements taking place at the intersection created a sufficient number of slower vehicles to result in either skewed or bimodal data and, thus, violate the assumption of normality at that location. Histograms of the speed profile data at all ten sites are shown in *Appendix F*.

The next step of the analysis was to compare speed variability between before and after treatment periods. This was accomplished using the modified Levene's test of homogeneity of variance. This test is less sensitive than the standard Levene's test to the assumption of normally distributed data. In essence, the test is constructed by calculating the absolute deviation from the sample median for each speed measurement, separately for the before and after speed groups, and then using analysis of variance (ANOVA) to test that the means of this quantity are the same for the before and after speed groups. This ANOVA provides an F-test and associated p-value. Small p-values (≤ 0.05) are an indication that the before and after speed variances are unequal at the 95-percent confidence level.

Based on the results of the check of normality and the homogeneity of variance test (i.e., modified Levene's test), either mean or median speeds were compared to determine if the difference between the before and after speeds were significant. The statistical approach was as follows:

- Normally distributed speed data and equal variances: a two-sample t-test with pooled variance was used to compare mean speeds before and after treatment
- Normally distributed speed data and unequal variances: a two-sample t-test with weighted variance (with Satterthwaite's approximation of degrees of freedom) was used to compare mean speeds before and after treatment
- Non-normally distributed (skewed or bimodal) speed data (no test of equal variance is needed): a Wilcoxon rank-sum test was used to compare median speeds before and after treatment

5.4.2. Analysis by Intersection Approach (Step 2 Analysis)

The purpose of the analysis by intersection approach was to determine the overall speed reduction observed along an intersection approach as a result of the treatment installed on that approach. The observed speed reduction provided an estimate of the overall treatment effectiveness along the approach.

The overall effect of the treatment at a particular intersection approach, i.e., the average speed reduction across all data collection locations, was evaluated using a two-way analysis of variance (ANOVA). Two factors were included in the ANOVA model:

- Distance from intersection to data collection location (i.e., A, B, C, or D)
- Data collection period (before or after).

An interaction between data collection location and period is also included to account for differences in the treatment effect by location.

The assumptions made in the ANOVA include:

- The variability in speed measurements was allowed to differ across locations and collection period.
- All data (regardless of data collection location and period) was normally distributed. Although this assumption may not hold for a few of the locations, speed reduction estimates were unaffected by this assumption, and the effect on the overall conclusions was believed minor given the degree of non-normality.

- While speed measurements across data collection locations were likely correlated, due to the same vehicle being measured at each location as it approached the intersection, an assumption of independent measurements across locations was made. The implication of this assumption was considered when evaluating the statistical significance of the overall treatment effect.

For each intersection approach, the overall speed difference (across Locations A, B, C, and D) was estimated and an F-test used to determine if the difference in mean speeds before and after treatment installation was significant. An interaction between treatment and location was also evaluated with an F-test.

5.4.3. Analysis by Treatment Type (Step 3 Analysis)

The purpose of the analysis by treatment type is to determine the overall effectiveness of a particular treatment type (i.e., peripheral transverse pavement markings, rumble strips, dynamic warning signs).

The effect of the three treatment types across all sites was evaluated through ANOVA with random effects. The fixed effects considered in the ANOVA are the data collection period (before/after) and the interaction between data collection period and location. The random effects included in the ANOVA are:

- Intersection approach
- Interaction between data collection period and intersection approach
- Interaction between intersection approach and data collection location
- Three-way interaction between intersection approach, data collection location, and data collection period

The assumptions made in the ANOVA include:

- Equal variance in speed measurements at each site approach and location
- Independence of measurements across locations for a site-approach
- Normal distribution for all random effects and speed measurements.

For each treatment, the overall treatment effect on speeds across intersection approaches and data collection locations was estimated and an F-test used to determine if the difference in mean speeds before and after treatment installation was significant. The data collection period effect (treatment effect) was tested in comparison to the collection period by intersection approach interaction. Thus, the treatment effect was evaluated based on the number of intersection approaches where the treatment was applied. The treatment by location interaction was similarly tested. The collection period by location interaction was tested in comparison to the interaction between intersection approach, data collection location, and data collection period. Thus, the treatment by location was compared to the number of locations for all intersection approaches with the same treatment.

5.4.4. Secondary Analysis of 85th-Percentile Speeds

The statistical analyses discussed in the analyses by location, intersection approach, and treatment type (Step 1, Step 2, and Step 3 analyses) clearly focus on the comparison of speed distributions and their changes due installation of a speed-reduction treatment. In each of these analyses, the entire speed distribution at each individual data collection location is considered when making final estimates of speed differences between the before and after periods due to treatment installation. Although the emphasis in these analyses is placed on differences in mean speeds, the results of these analyses are applicable to the entire speed distribution; that is, to any quantile or percentile of that distribution. As such, the results of analyses of mean speeds may be applied to 85th-percentile speeds as well, assuming that speed distributions are normal.

A rigorous statistical procedure, similar to the comparison of mean speeds as discussed in the Step 1, Step 2, and Step 3 analyses, has not yet been developed for 85th-percentiles (or any other quantile). However, an attempt was made to statistically compare 85th-percentile speeds before and after treatment installation for the analysis by interaction approach (Step 2 analysis) and the analysis by treatment type (Step 3 analysis). In each case, the 85th-percentile speeds were compared using a paired t-test on the differences between before and after 85th-percentile speeds obtained at each site-location with the following caveats:

- The 85th-percentile speed was estimated from the speed distribution at each site and location individually; as a result, the variability in the 85th-percentile speed at each site and location is ignored. This, is turn, reduces the variability in the test statistic and increases the significance of the results (i.e., a difference in 85th-percentile speeds may be significant when it is not, simply because extra variability is ignored.)

- The t-test assumes normal distribution of the 85th-percentile speeds; this assumption could not be checked due to small sample sizes (e.g., between 2 and 4 locations at the intersection approach level); normality was simply assumed in all the t-tests.

- When an intersection has two lanes per approach with unequal traffic volumes (e.g., Texas sites with rumble strips), no weighting by traffic volume could be performed in either the before or after period and across periods.

- The different sample sizes between the before and after treatment periods could not be accounted for in the t-tests; this was done in the more rigorous average speed comparisons since properly weighting by the number of speed measurements affects the data analysis.

5.4.5. Data Preparation

Several steps were taken to prepare the speed data for analysis, including general data cleanup and data selection for a particular analysis.

5.4.5.1. General Data Cleanup

Speed data were carefully reviewed to determine which data to include in the analyses. For example, speed data of the following vehicles were not included in the analyses:

- Vehicles traveling in the opposite direction but traveling over the sensors (assumed to be a vehicle involved in a passing maneuver)

- Vehicles following another vehicle, with a headway less than 3 seconds between the two vehicles (i.e., the speed of the first vehicle was retained but the speed of the closely following second vehicle was not)

In addition, plots of vehicle speed vs. time of day (by traffic classifier) and traffic flow rate vs. time of day (by traffic classifier) were reviewed to identify potential problems such as:

- *Inconsistencies in traffic flow* – Major disruptions in traffic flow could indicate an accident on the roadway. While no major disruptions in traffic flow were identified, the traffic flow plots revealed at least two occasions when one classifier recorded substantially fewer vehicles than the other classifiers on the same approach (and there was no logical explanation, such as a major intersection or driveway between the classifiers).

- *Occasional malfunctioning of traffic classifier or roadway sensors* – Periods of time during which no speeds were recorded or traffic flow rates appeared to be erratic usually indicated that either the traffic classifier was malfunctioning or the roadway sensors had come loose from the roadway.

When a particular classifier recorded substantially fewer vehicles than the other classifiers on the approach, speed data from that classifier were not included in the analysis. When a particular classifier appeared to be malfunctioning or its roadway sensors came loose from the roadway, speed data from that classifier during the time period in question were not included in the analysis. Generally, equipment failure was an infrequent occurrence (site-specific problems with individual classifiers are addressed in the section "Results of Analysis by Intersection Approach"). However, data collection efforts at TX4 experienced substantial equipment problems. As a result, no speed data from TX4 could be included in an analysis.

5.4.5.2. Data Selection for Analyses

Two data selection procedures were implemented to generate datasets that were most appropriate for a particular analysis approach (i.e., analysis by location, intersection approach, or treatment type):

- When conducting the analysis by data collection location (Step 1 above), the most encompassing set of speed data was used. As such, no restrictions were imposed on matching time of day across locations at a particular intersection approach.

- Evaluating the effectiveness of a treatment along an intersection approach (Step 2) or comparing the effectiveness of one treatment type to another (Step 3) involved developing speed profiles for each intersection approach. In this case, great care was taken to consider only those data collection periods during which all traffic classifiers on an intersection approach (Locations A, B, C, and D) were collecting speed data. This permitted the general assumption that the same vehicles traversed all four data collection locations and that the population of vehicles at Location D were generally the same as the population of vehicles at the other locations.

5.5. DATA ANALYSIS RESULTS

5.5.1 Results of Analysis by Location (Step 1 Analysis)

As discussed previously, the analysis of the speed data collected at each individual location (A, B, C, and D) is of minor importance in assessing overall treatment effectiveness. Nonetheless, descriptive summaries and the results from a before-after comparison of either mean or median speeds at each individual location are provided in *Appendix G.*

General observations from the results of the analysis by location are:

- Before-after speed comparisons were made for 51 individual traffic classifier locations (Locations A, B, C, and D)

- At approximately 75 percent of the locations, speeds decreased; the decrease in speeds ranged from 0.1 to 8.7 mph. (It should be noted that the decrease of 8.7 mph – at Location A at WA1 eastbound – is an anomaly. The next largest decrease in speed is 3.2 mph.)

- At approximately 25 percent of the locations, speeds increased; the increase ranged from 0.1 to 1.8 mph.

- Of the 51 before-after speed differences, 34 were statistically significant at the 5-percent level (including a p-value of 0.051). The distribution of the 34 statistically significant speed differences by traffic classifier location was:

    - Location A (8)

    - Location B (10)

    - Location C (10)

    - Location D (6)

5.5.2 Results of Analysis by Intersection Approach (Step 2 Analysis)

This section is organized by site in the order listed in Exhibit 5-1. The discussion of each site begins with a general site description, a summary of the data collection activities conducted at that site, and a site diagram. Next, description summaries of the speed data collected at each site are presented, including separately for the before-and-after treatment periods:

- number of measurements
- speed range (i.e., minimum and maximum speeds)
- mean, median, and 85th-percentile speeds
- speed standard deviation

Next, the ANOVA results from the before-after statistical comparison of speed profile data at a particular intersection approach are presented in a table and subsequently discussed.

- The column “Main Effect or Interaction” in that table refers to either the main treatment effect or the treatment by location interaction (abbreviated as “Treatment x Location”).
- Columns 3 and 4 present the estimated speed difference (between the before and after periods), its standard error, and an estimate of the precision of the speed difference. A negative estimated speed difference indicates a decrease in mean speeds from before to after treatment installation.
- The last three columns show the results of the F-test, with the last column indicating statistical significance of the treatment or the treatment by location interaction: a p-value of 0.05 or less (highlighted in yellow) will indicate a significant effect at that intersection approach at the 5-percent significance level. Thus, a p-value of 0.05 or less in a “Treatment” row will indicate a statistically significant treatment effect on speed profile at that approach. A p-value of 0.05 or less in a “Treatment x Location” row will indicate that the treatment effect on speed profile varies by location.
- To conclude the discussion of each site, speed profile plots are shown separately for each approach. Each figure presents the mean speed profile, separately for the before period (solid blue line) and after period (dashed red line). The vertical dashed lines on each figure represent the locations (A, B, C, or D) on the approach where the speed-reduction treatment was installed. The interval around each estimated mean speed represents the 95-percent confidence bound of the mean.

A summary discussion across all sites follows the presentation of the individual site results.

5.5.2.1 OR1 – Meridian Road/Whiskey Hill Road

The Meridian Road/Whiskey Hill Road intersection is located in Clackamas County, Oregon. Peripheral transverse pavement markings were installed on the northbound approach of Meridian

Road and the eastbound approach of Whiskey Hill Road. The intersection is unsignalized with no control on Whiskey Hill Road and STOP-control on Meridian Road.

The speed data collection sensors on the northbound approach of Meridian Road were placed 165, 265, 600, and 1,800 feet from the intersection. Peripheral transverse pavement markings were installed at two locations on the northbound intersection approach: 265 and 795 feet from the intersection. The speed data collection sensors on Whiskey Hill Road's eastbound approach were placed 100, 250, 600, and 1,300 feet from the intersection. Peripheral transverse pavement markings were installed at two locations on the eastbound intersection approach: 420 and 728 feet from the intersection. Exhibit 5-2 presents a site diagram of the intersection and illustrates the treatment and speed data collection locations.

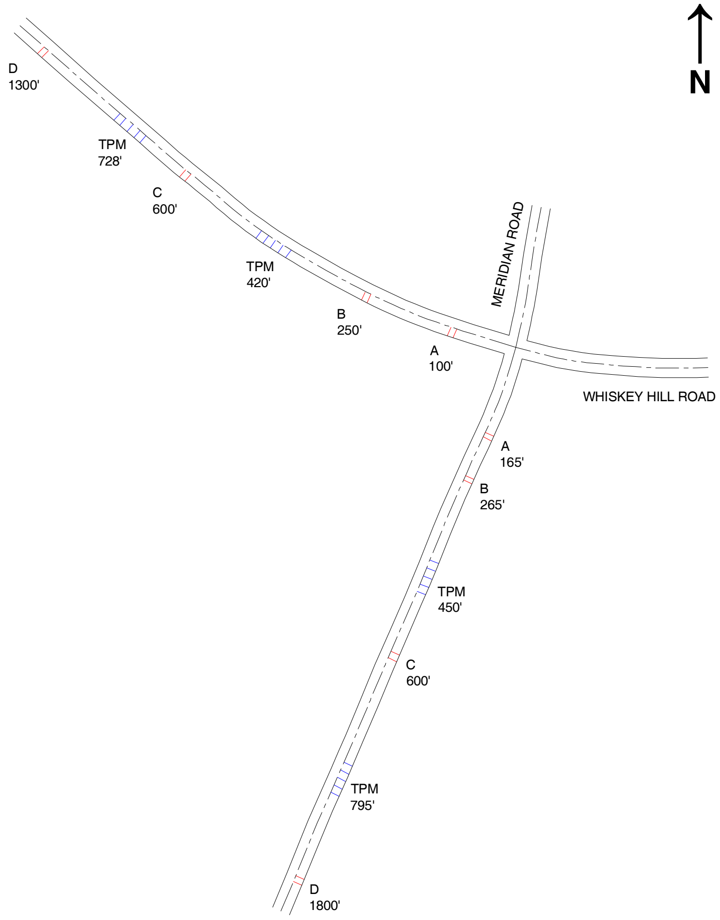


Exhibit 5-2 **Site Diagram for OR1**

Basic descriptive summaries for the before and after speed data at each location are presented in Exhibit 5-3. The comparison of the before and after mean speeds at all locations, while accounting for base speed changes (mostly deceleration) along the intersection approach, is summarized in Exhibit 5-4, separately for each intersection approach. Accounting for changes between segment speeds and intersection speeds before a treatment is implemented is important so as not to confound any potential treatment effect on speed with naturally occurring speed changes as drivers approach an intersection.

Exhibit 5-3 Descriptive Summaries for OR1

Location		Number of Measurements	Speed Statistics (mph)				
			Speed Range (Minimum - Maximum)	Mean	Median	85th Percentile	Standard Deviation
Before Treatment							
NB	A	417	8.3 - 41.5	29.3	29.8	34.2	5.2
	B	410	9.9 - 48.8	35.0	35.2	40.3	5.7
	C	410	8.2 - 64.9	44.7	45.3	52.3	8.0
	D	385	16.4 - 77.8	52.4	53.1	61.2	8.6
EB	A	180	10.7 - 50.4	30.4	29.2	38.8	7.0
	B	177	19.5 - 53.3	37.0	37.3	43.0	5.9
	C	177	27.1 - 59.2	44.3	45.2	50.1	6.0
	D	159	27.5 - 72.2	49.2	49.4	55.5	6.7
After Treatment							
NB	A	235	10.4 - 40.2	27.6	28.1	32.9	5.4
	B	234	4.6 - 50.0	33.5	34.4	39.4	6.3
	C	230	8.6 - 68.3	43.8	44.5	52.1	9.2
	D	234	12.9 - 83.4	51.4	51.9	59.5	9.7
EB	A	437	7.8 - 56.5	28.3	27.4	34.5	6.4
	B	440	6.1 - 58.3	35.0	35.5	40.8	6.6
	C	429	7.2 - 59.0	41.7	42.4	48.1	7.1
	D	432	14.1 - 72.0	47.4	48.5	54.1	8.1

Exhibit 5-4 Treatment Effect on Speed Profile at OR1 Approaches

Approach	Main Effect or Interaction	Estimated Speed Difference (mph)	Standard Error (mph)	F-Statistic	Degrees of Freedom	P-Value
NB	Treatment	-1.2	0.3	15.6	(1, 2547)	<.001
	Treatment x Location			0.35	(3, 2547)	0.786
	Location A	-1.6	0.4			
	Location B	-1.4	0.5			
	Location C	-0.9	0.7			
	Location D	-1.0	0.8			
EB	Treatment	-2.1	0.3	50.87	(1, 2423)	<.001
	Treatment x Location			0.32	(3, 2423)	0.811
	Location A	-2.1	0.6			
	Location B	-2.0	0.5			
	Location C	-2.6	0.6			
	Location D	-1.8	0.7			

Exhibits 5-3 and 5-4 present mean speed profiles for the northbound and eastbound approach, respectively. Both intersection approaches experienced a slight reduction in mean, median, and 85th-percentile speeds after installing the peripheral transverse pavement markings (Exhibit 5-3). The speed reduction appears to be greater on the eastbound approach than on the northbound approach (Exhibit 5-4). The reduction in mean speeds on both intersection approaches (1.2 mph and 2.1 mph) is statistically significant as indicated by the small p-values for treatment in Exhibit 5-4.

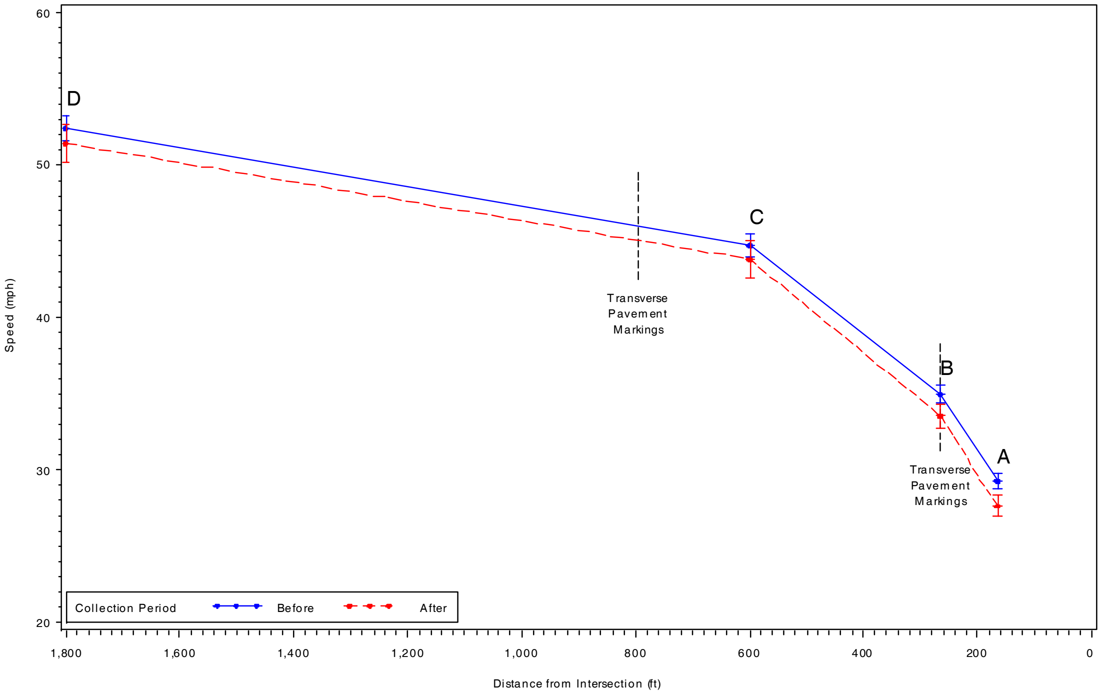


Exhibit 5-5 Mean Speed Profile for NB Traffic at OR1

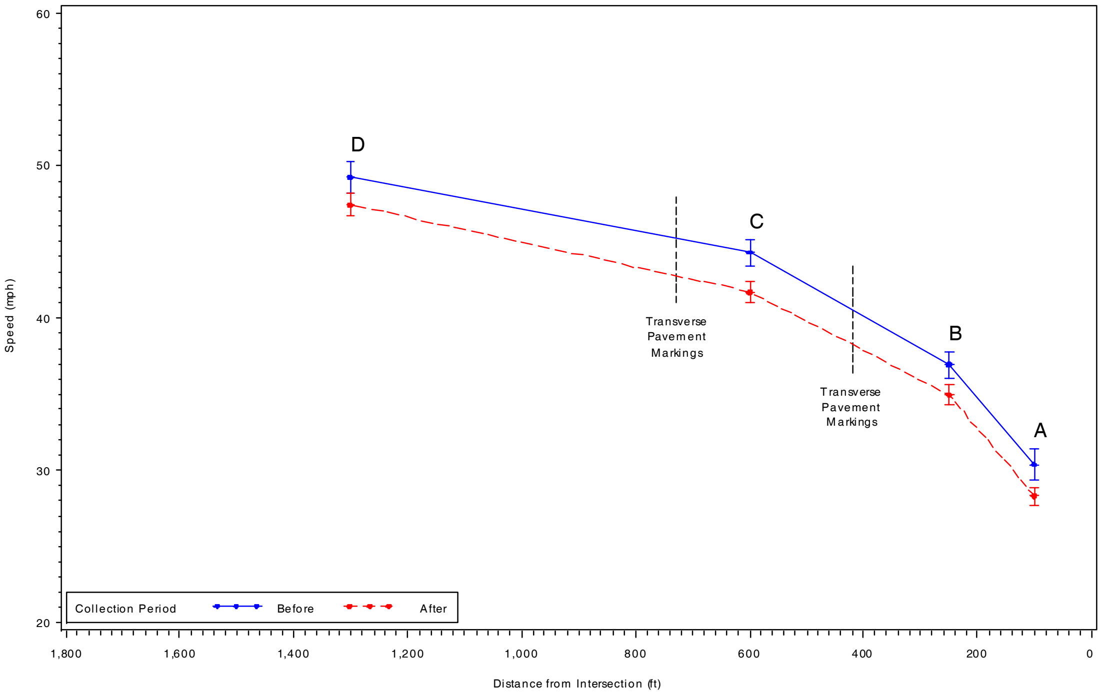


Exhibit 5-6 Mean Speed Profile for EB Traffic at OR1

5.5.2.2 OR2 – Canby-Marquam Highway/Lone Elder Road

The Canby-Marquam Highway/Lone Elder Road intersection is in Clackamas County, Oregon.

Peripheral transverse pavement markings were installed on the northbound and southbound approaches. The intersection is unsignalized with no control on Canby-Marquam Highway and STOP-control on Lone Elder Road.

The speed data collection sensors on the northbound approach of Canby-Marquam Highway were placed 100, 250, 700, and 1,500 feet from the intersection. Peripheral transverse pavement markings were installed at two locations on the intersection approach: 417 and 860 feet from the intersection. The speed data collection sensors on the southbound approach of Canby-Marquam Highway were placed 175, 250, 625, and 1,300 feet from the intersection. Peripheral transverse pavement markings were installed at two locations on the intersection approach: 350 and 854 feet from the intersection. Exhibit 5-7 presents an intersection site diagram and illustrates the treatment and speed data collection locations.

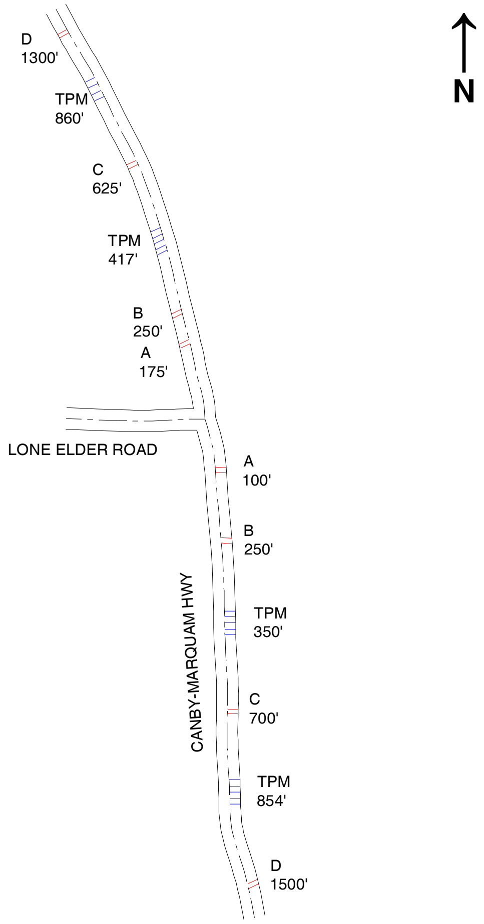


Exhibit 5-7 **Site Diagram for OR2**

Basic descriptive summaries for the before and after speed data at each location are presented in Exhibit 5-8. The comparison of the before and after mean speeds at all locations, while accounting for base speed changes along the intersection approach before treatment implementation, is summarized in Exhibit 5-9, separately for each intersection approach.

Exhibit 5-8 Descriptive Summaries for OR2

Location		Number of Measurements	Speed Statistics (mph)				
			Speed Range (Minimum - Maximum)	Mean	Median	85th Percentile	Standard Deviation
Before Treatment							
NB	A	1,457	4.3 – 65.2	37.6	38.8	49.6	11.4
	C	1,399	16.7 - 66.0	47.4	47.7	53.7	6.3
	D	1,278	10.4 - 65.5	46.8	47.5	52.4	6.3
SB	B	1,307	12.3 - 69.5	42.6	43.5	50.1	7.8
	C	1,302	14.1 - 73.2	48.5	48.8	54.0	6.0
	D	1,264	15.5 - 75.8	49.8	50.0	55.1	5.7
After Treatment							
NB	A	1,023	11.4 - 67.8	38.0	39.5	49.2	10.5
	C	971	10.8 - 72.8	47.2	47.5	53.0	6.4
	D	850	15.3 - 65.1	47.1	47.5	52.1	5.7
SB	B	571	16.2 - 60.6	42.2	42.7	49.1	7.0
	C	576	4.7 – 63.9	47.5	48.1	53.4	6.4
	D	581	21.3 - 66.1	48.7	49.1	54.5	5.9

The traffic classifier at Location B on the northbound approach recorded substantially fewer vehicles in the before period than the other traffic classifiers on the approach. Since there was no logical explanation for this (e.g., major intersection or driveway onto which vehicles would be turning), it was assumed that the classifier was not functioning properly and, therefore, no data from this classifier were included in the analysis of the northbound approach. Also, on the southbound approach, before-period speed data were collected on a different day at Location A than at Locations B, C, and D. Therefore, no data from the traffic classifier at Location A were included in the southbound approach analysis.

Exhibit 5-9 Treatment Effect on Speed Profile at OR2 Approaches

Approach	Main Effect or Interaction	Estimated Speed Difference (mph)	Standard Error (mph)	F-Statistic	Degrees of Freedom	P-Value
NB	Treatment	0.15	0.19	0.59	(1, 6972)	0.443
	Treatment x Location			1.07	(2, 6972)	0.343
	Location A	0.42	0.44			
	Location C	-0.21	0.27			
	Location D	0.24	0.26			
SB	Treatment	-0.83	0.19	19.55	(1, 5595)	<.001
	Treatment x Location			1.31	(2, 5595)	0.269
	Location B	-0.38	0.36			
	Location C	-1.03	0.31			
	Location D	-1.08	0.29			

Exhibits 5-10 and 5-11 present mean speed profiles for the northbound and southbound approaches, respectively. The speed differential on the northbound approach after installing the peripheral transverse pavement markings appears to be negligible; mean and median speeds either slightly increased or decreased depending on the location along the intersection; and all 85th -percentile speeds slightly decreased (Exhibit 5-8). The overall increase of 0.15 mph in mean speeds is not statistically significant as indicated by the large p-value for treatment in Exhibit 5-9. The southbound approach appears to have experienced a slight reduction in mean, median, and 85th-percentile speeds after installing the peripheral transverse pavement markings (Exhibit 5-8). The reduction of 0.83 mph in mean speeds on the southbound approach is statistically significant as shown by the small treatment p-value in Exhibit 5-9.

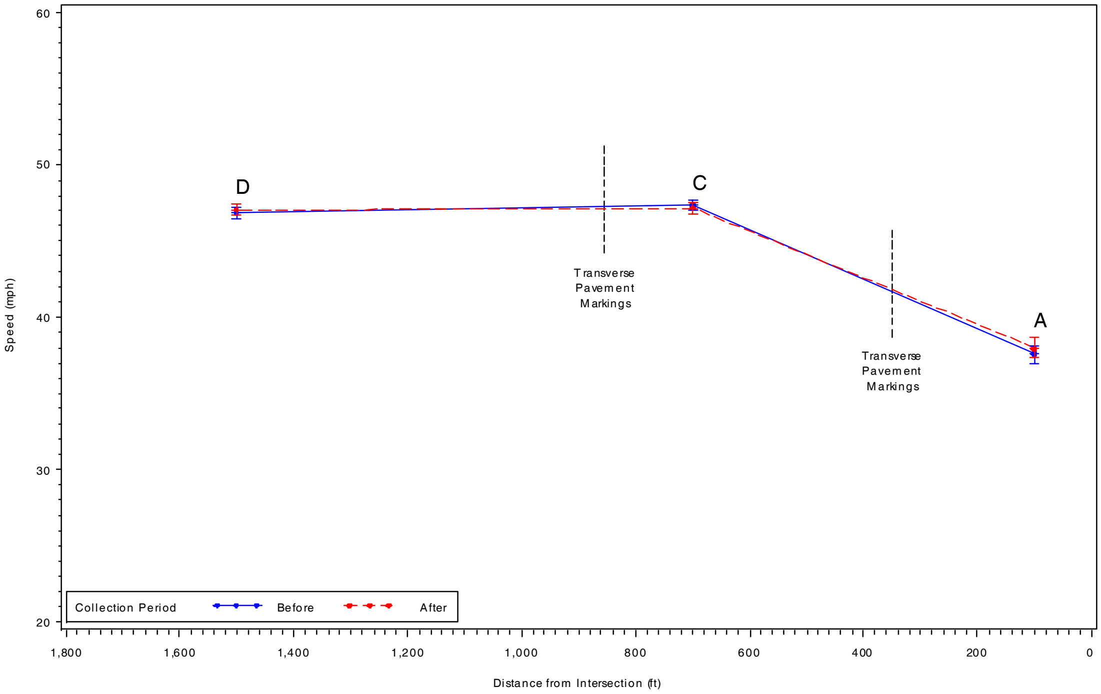


Exhibit 5-10 **Mean Speed Profile for NB Traffic at OR2**

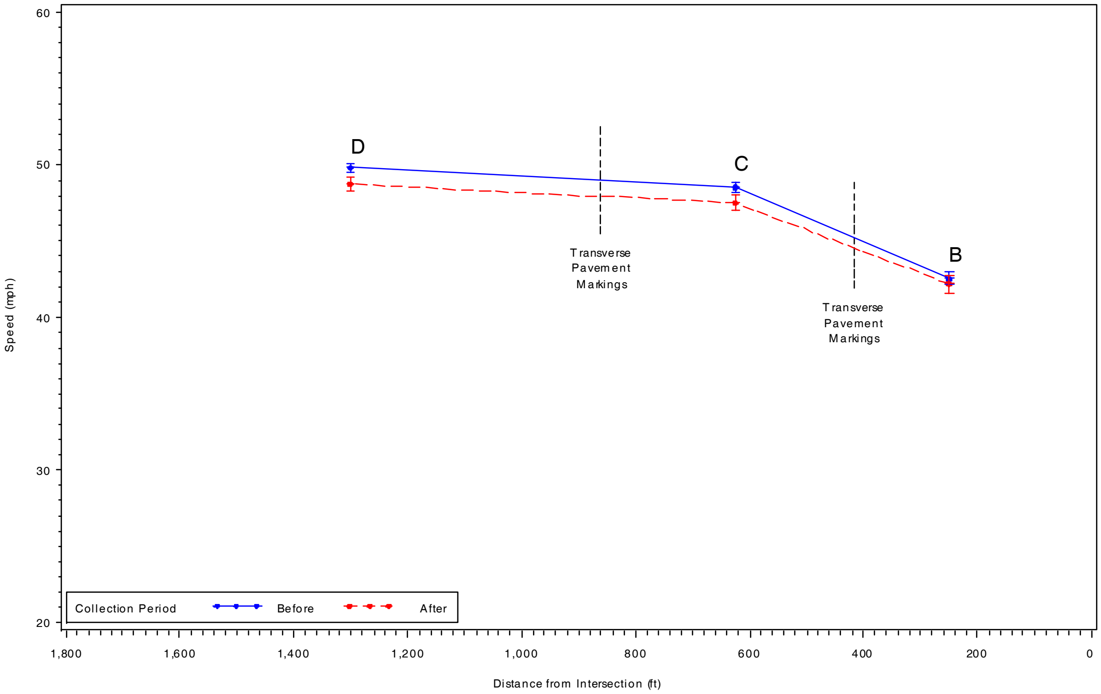


Exhibit 5-11 **Mean Speed Profile for SB Traffic at OR2**

5.5.2.3 OR3 – Redland Road/Ferguson Road

The Redland Road/Ferguson Road intersection is in Clackamas County, Oregon. Peripheral transverse pavement markings were installed on the eastbound and westbound approaches. The intersection immediately east of this site (Redland and Bradley roads) was also a study site (OR4), and speed data were collected at these locations simultaneously. Exhibit 5-12 presents a site diagram of Sites OR3 and OR4 and illustrates the locations of treatment installation and speed data collection for both sites. The close proximity of these intersections did not allow for multiple data collection points between the intersections; only one set of sensors was placed on each approach between the intersections. Therefore, data collection was focused on the eastbound approach at OR3 and the westbound approach at OR4.

The intersection of Redland and Ferguson roads is unsignalized with no control on Redland Road and STOP-control on Ferguson Road. The speed data collection sensors on the eastbound approach were placed 100, 250, 500, and 1,200 feet from the intersection. Peripheral transverse pavement markings were installed at two locations on the eastbound intersection approach: 318 and 550 feet from the intersection. The speed data collection sensors on the westbound approach were placed 275 feet from the intersection and peripheral transverse pavement markings were installed 660 feet from the intersection. Speed data from the traffic classifier on the westbound approach were not included in the analysis since there was only one data collection point and, therefore, no speed profile could be developed.

Basic descriptive summaries for the before and after speed data at each location are presented in Exhibit 5-13. The comparison of the before and after mean speeds at all locations, while accounting for base deceleration along the intersection approach before treatment implementation, is summarized in Exhibit 5-14, separately for each intersection approach.

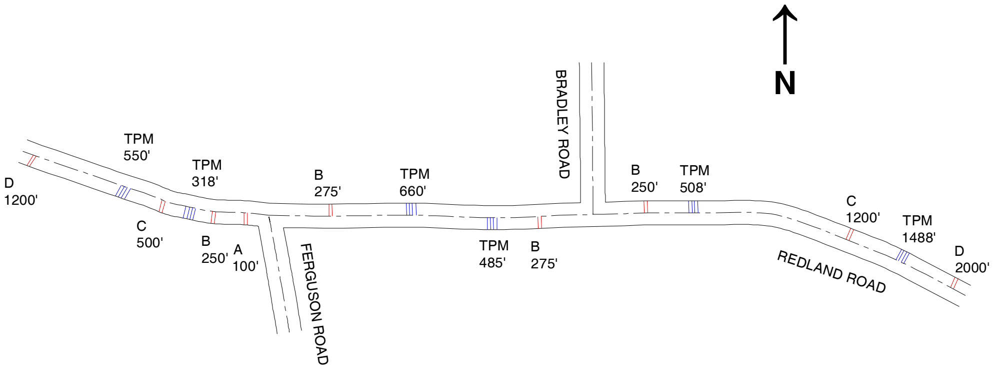


Exhibit 5-12 **Site Diagram for OR3 and OR4**

Exhibit 5-13 Descriptive Summaries for OR3

Location		Number of Measurements	Speed Statistics (mph)				
			Speed Range (Minimum - Maximum)	Mean	Median	85th Percentile	Standard Deviation
Before Treatment							
EB	A	1,381	7.0 - 68.4	45.3	47.7	53.1	9.1
	B	1,351	8.3 - 90.2	47.0	47.9	53.0	7.3
	C	1,356	14.5 - 71.2	48.9	49.1	54.0	5.5
	D	1,336	18.0 - 71.4	49.6	49.8	54.6	5.6
After Treatment							
EB	A	780	8.1 - 67.5	44.9	46.9	52.3	8.5
	B	802	11.6 - 67.0	46.5	47.1	52.4	6.3
	C	777	23.4 - 67.3	48.3	48.5	53.3	5.4
	D	785	5.4 - 74.0	49.2	50.0	54.5	6.8

Exhibit 5-14 Treatment Effect on Speed Profile at OR3 Approach

Approach	Main Effect or Interaction	Estimated Speed Difference (mph)	Standard Error (mph)	F-Statistic	Degrees of Freedom	P-Value
EB	Treatment	-0.44	0.15	8.03	(1, 8560)	0.005
	Treatment x Location			0.15	(3, 8560)	0.932
	Location A	-0.46	0.39			
	Location B	-0.41	0.3			
	Location C	-0.56	0.24			
	Location D	-0.32	0.29			

Exhibit 5-15 presents mean speed profiles for the eastbound approach. The eastbound approach experienced a slight reduction in mean, median, and 85th-percentile speeds after installing the peripheral transverse pavement markings (Exhibit 5-13). The reduction of 0.44 mph in mean speeds is statistically significant as shown by the small treatment p-value in Exhibit 5-14.

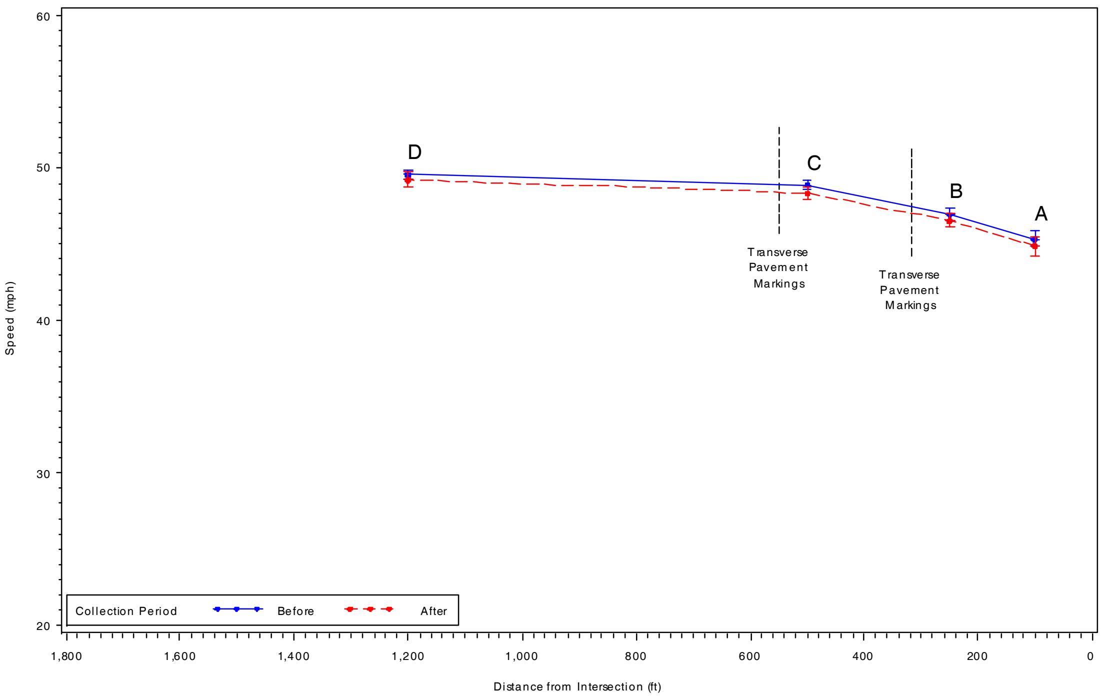


Exhibit 5-15 **Mean Speed Profile for EB Traffic at OR3**

5.5.2.4 OR4 – Redland Road and Bradley Road

The Redland and Bradley road intersection is in Clackamas County, Oregon. Peripheral transverse pavement markings were installed on the eastbound and westbound approaches. The intersection immediately to the east of this site (Redland and Ferguson roads) was also a study site (OR3) and, as mentioned previously, speed data were collected at both locations simultaneously.

The intersection of Redland and Bradley roads is unsignalized with no control on Redland Road and STOP-control on Bradley Road. The speed data collection sensors on the eastbound approach were placed 275 feet from the intersection and peripheral transverse pavement markings were installed 485 feet from the intersection. Speed data from the traffic classifier on the eastbound approach were not included in the analysis since there was only one data collection point and, therefore, no speed profile could be developed. The speed data collection sensors on the westbound approach were placed 250, 1,200, and 2,000 feet from the intersection. Peripheral transverse pavement markings were installed at two locations on the westbound intersection approach: 508 and 1,488 feet from the intersection.

Basic descriptive summaries for the before and after speed data at each location are presented in Exhibit 5-16. The comparison of the before and after mean speeds at all locations, while accounting for base deceleration along the intersection approach before treatment implementation, is summarized in Exhibit 5-17, separately for each intersection approach.

Exhibit 5-16 Descriptive Summaries for OR4

Location		Number of Measurements	Speed Statistics (mph)				
			Speed Range (Minimum - Maximum)	Mean	Median	85th Percentile	Standard Deviation
Before Treatment							
WB	B	1,349	9.6 - 74.3	52.6	53.3	58.2	6.5
	C	1,352	16.0 - 77.4	52.0	52.4	57.5	6.7
	D	1,366	5.0 - 78.5	54.8	55.4	60.5	7.0
After Treatment							
WB	B	1,072	19.6 - 73.0	51.2	51.8	56.7	6.3
	C	1,029	3.9 - 105.0	50.0	51.0	56.7	8.6
	D	1,070	4.6 - 78.5	53.3	54.1	59.2	7.6

Exhibit 5-17 Treatment Effect on Speed Profile at OR4 Approach

Approach	Main Effect or Interaction	Estimated Speed Difference (mph)	Standard Error (mph)	F-Statistic	Degrees of Freedom	P-Value
WB	Treatment	-1.6	0.2	87.56	(1, 7232)	<.001
	Treatment x Location			0.99	(2, 7232)	0.372
	Location B	-1.4	0.3			
	Location C	-2.0	0.3			
	Location D	-1.4	0.3			

Exhibit 5-18 presents mean speed profiles for the westbound approach. The westbound approach experienced a slight reduction in mean, median, and 85th-percentile speeds after installing the peripheral transverse pavement markings (Exhibit 5-16). The reduction of 1.6 mph in mean speeds is statistically significant as indicated by the small p-value for treatment shown in Exhibit 5-17.

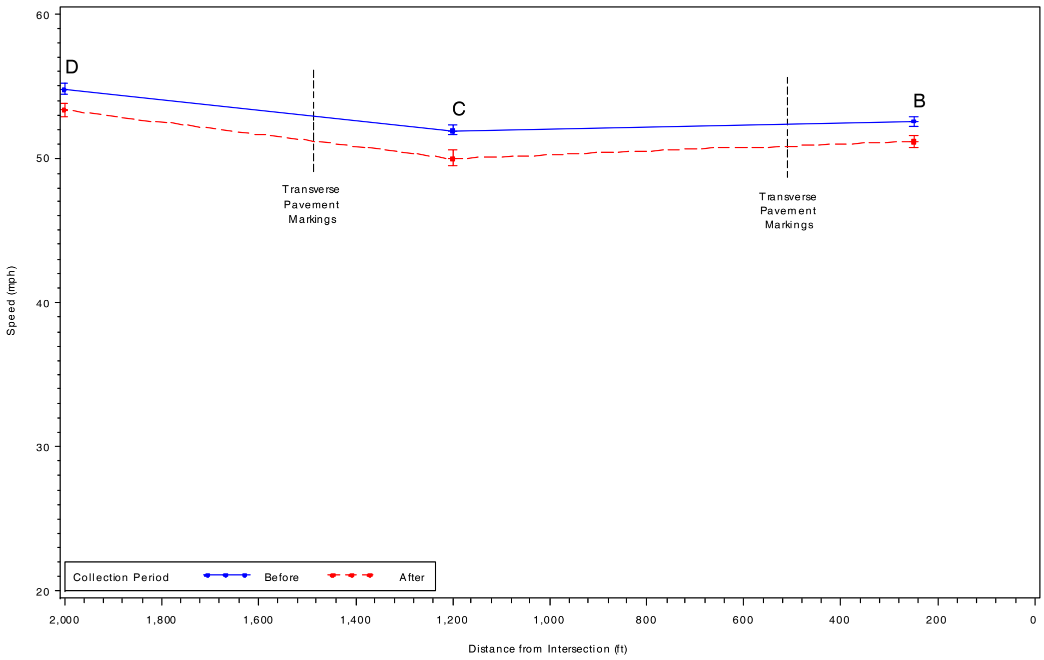


Exhibit 5-18 Mean Speed Profile for WB Traffic at OR4

5.5.2.5 OR6 – OR 6/Wilson River Loop Road

The OR 6/Wilson River Loop Road intersection is in Tillamook County, Oregon. Peripheral transverse pavement markings were installed on the eastbound and westbound approaches. The intersection is unsignalized with no control on OR 6 and STOP-control on Wilson River Loop Road.

The speed data collection sensors on the eastbound approach of OR 6 were placed 100, 250, 900, and 1,700 feet from the intersection. Peripheral transverse pavement markings were installed at approximately 530 and 1,320 feet from the intersection on the approach. The speed data collection sensors on the westbound approach of OR 6 were placed 280, 440, 980, and 1,580 feet from the intersection. Peripheral transverse pavement markings were installed at approximately 630 and 1,320 feet from the intersection on the approach. Exhibit 5-19 presents a site diagram of the intersection and illustrates the projected locations of treatment installation and actual speed data collection locations.

The traffic classifier at Location D on the eastbound approach never functioned properly during the before- and after-period data collection efforts. In fact, from the traffic flow plots that were reviewed during data cleanup, it appeared that this classifier did not record any speeds. Therefore, no speed data from this classifier were available for analysis. Also, it should be noted that there were no data collection time periods at Location D that were common with the other three locations, so data from the classifier at Location D were not included in the analysis.

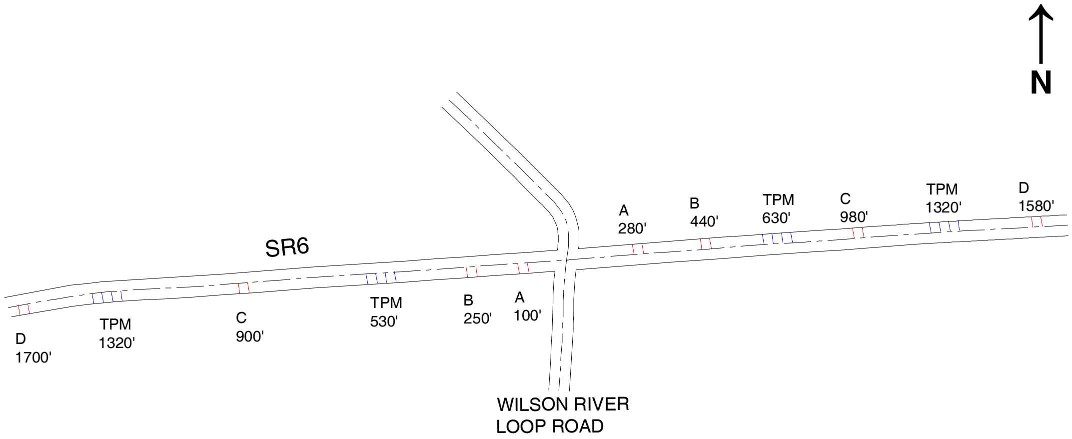


Exhibit 5-19 Site Diagram for OR6

Basic descriptive summaries for the before and after speed data at each location are presented in Exhibit 5-20. The comparison of the before and after mean speeds at all locations, while accounting for base speed changes along the intersection approach before treatment implementation, is summarized in Exhibit 5-21, separately for each intersection approach.

Exhibit 5-20 Descriptive Summaries for OR6

Location		Number of Measurements	Speed Statistics (mph)				
			Speed Range (Minimum - Maximum)	Mean	Median	85th Percentile	Standard Deviation
Before Treatment							
EB	A	822	13.5 – 66.6	51.5	54.0	58.5	9.4
	B	852	23.2 – 66.4	52.7	54.1	58.6	6.8
	C	918	8.9 – 71.6	55.9	56.2	60.4	4.9
WB	A	1,139	4.7 – 69.2	51.0	52.9	58.6	8.3
	B	1,079	13.5 – 74.2	53.3	54.0	59.4	6.4
	C	1,212	7.2 – 73.3	55.5	55.9	60.4	5.7
	D	1,232	15.3 – 76.2	54.5	56.6	61.4	9.6
After Treatment							
EB	A	1,029	15.0 - 74.4	53.1	54.7	59.0	8.2
	B	1,065	5.4 - 76.7	53.6	54.8	59.3	6.9
	C	1,125	14.8 - 76.7	56.3	56.4	60.6	5.0
WB	A	668	12.6 - 68.7	51.8	53.6	59.8	8.0
	B	685	33.6 - 66.7	52.2	53.0	58.2	5.6
	C	687	37.7 - 71.9	55.6	55.8	60.2	5.0
	D	683	17.6 - 76.9	53.3	55.4	59.8	9.7

Exhibit 5-21 Treatment Effect on Speed Profile at OR6 Approaches

Approach	Main Effect or Interaction	Estimated Speed Difference (mph)	Standard Error (mph)	F-Statistic	Degrees of Freedom	P-Value
EB	Treatment	1.0	0.2	27.01	(1, 5805)	<.001
	Treatment x Location			3.22	(2, 5805)	0.04
	Location A	1.6	0.4			
	Location B	0.9	0.3			
	Location C	0.4	0.2			
WB	Treatment	-0.4	0.2	4.03	(1, 7377)	0.045
	Treatment x Location			7.02	(3, 7377)	<.001
	Location A	0.8	0.4			
	Location B	-1.1	0.3			
	Location C	0.1	0.3			
	Location D	-1.2	0.5			

Exhibits 5-22 and 5-23 present mean speed profiles for the eastbound and westbound approaches, respectively. The eastbound approach experienced a slight and unexpected increase in mean, median, and 85th-percentile speeds after installing the peripheral transverse pavement markings (Exhibit 5-20). The overall increase of 1.0 mph in mean speeds was statistically significant as indicated by the small treatment p-value in Exhibit 5-21. In addition, the significant interaction between treatment and location along the intersection approach as shown by the small p-value for interaction in Exhibit 5-21 indicates that the speed increase due to treatment varies from location to location (1.6 mph at Location A; 0.9 mph at Location B; and 0.4 mph at Location C). No explanation for the increase in mean speeds or the varying effect across locations was identified.

In the westbound direction, there was a slight change (increase or decrease) in mean, median, and 85th-percentile speeds after installing treatments, depending on the location along the intersection (Exhibit 5-20). The overall mean speed reduction of 0.4 mph on the westbound approach was statistically significant as shown by the small treatment p-value in Exhibit 5-21. However, it should be noted that the interaction between treatment and location (i.e., increase of 0.8 mph at Location A; decrease of 1.1 mph at Location B; increase of 0.1 mph at Location C; and decrease of 1.2 mph at Location D) was also statistically significant as indicated by the small p-value for interaction in Exhibit 5-21, indicating that the degree of treatment effectiveness was not consistent along the intersection approach.

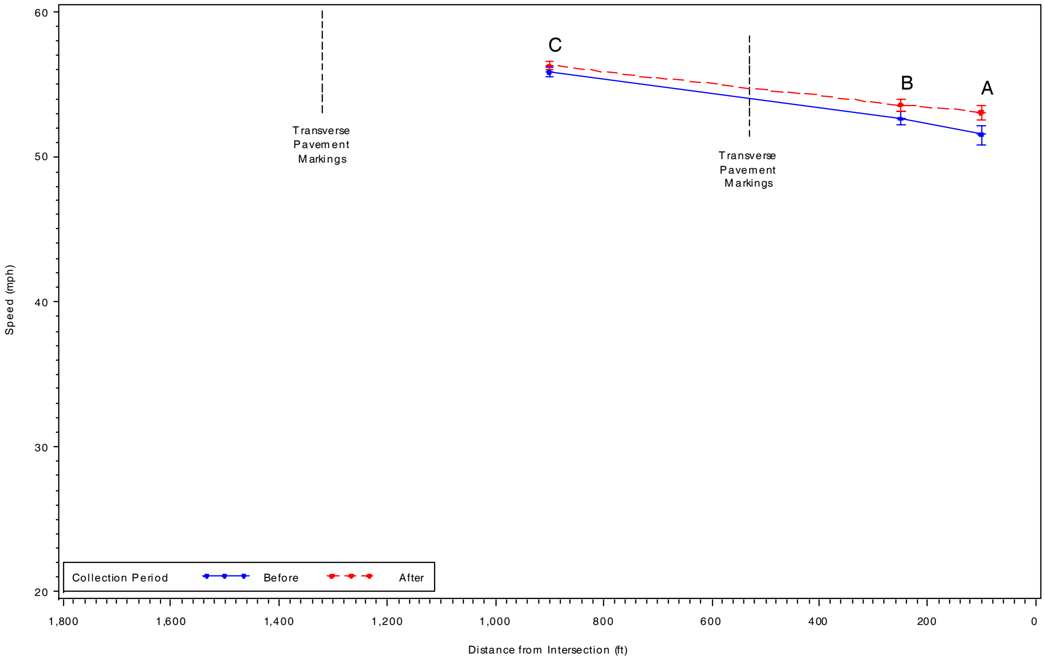


Exhibit 5-22 **Mean Speed Profile for EB Traffic at OR6**

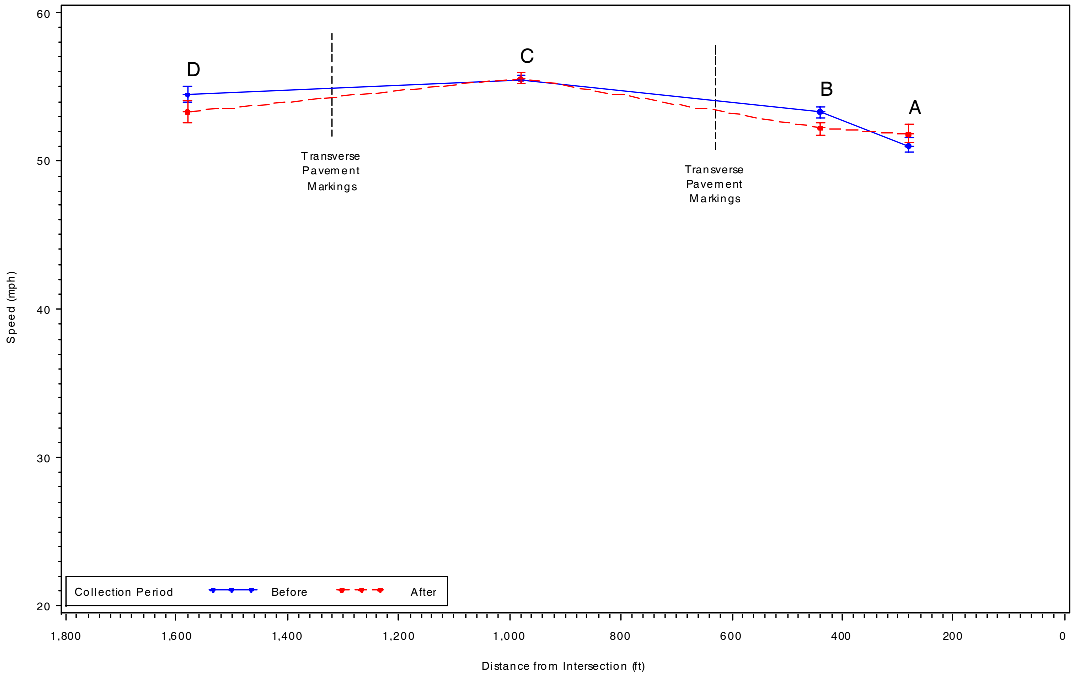


Exhibit 5-23 **Mean Speed Profile for WB Traffic at OR6**

5.5.2.6 TX1 – US 271 and FM 726

The US 271/FM 726 intersection is in Upshur Country, Texas. Rumble strips were installed on the southbound approach (rumble strips were already present on the northbound approach). The intersection has a flashing-yellow signal on US 271 and a flashing-red STOP-control signal on FM 726.

The speed data collection sensors on US 271's southbound approach were placed 100, 200, 600, and 1,800 feet from the intersection. Rumble strips were installed at three locations on the intersection approach: 330, 935, and 1,710 feet from the intersection. Exhibit 5-24 presents a site diagram of the intersection and illustrates the treatment installation and speed data collection locations.

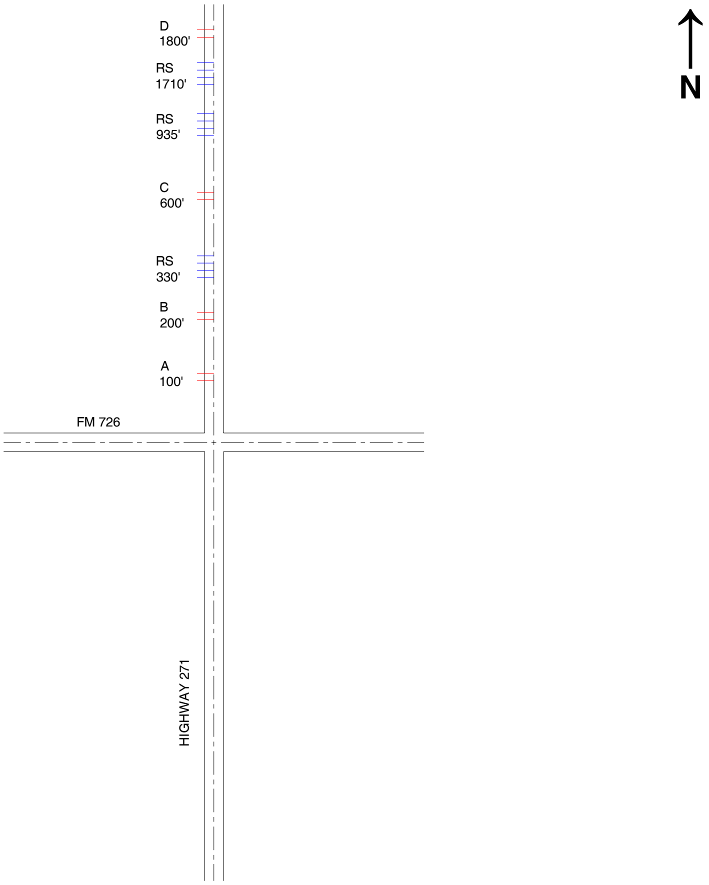


Exhibit 5-24 **Site Diagram for TX1**

Basic descriptive summaries for the before and after speed data at each location are presented in Exhibit 5-25. The comparison of the before and after mean speeds at all locations, while accounting for base speed changes along the intersection approach before treatment implementation, is summarized in Exhibit 5-26, separately for each intersection approach.

Exhibit 5-25 Descriptive Summaries for TX1

Location		**Number of Measurements**	**Speed Statistics (mph)**				
			Speed Range (Minimum – Maximum)	**Mean**	**Median**	**85th Percentile**	**Standard Deviation**
Before Treatment							
SB	A	1,343	19.4 - 78.8	57.1	59.0	67.6	11.1
	B	1,329	16.5 - 79.1	59.3	60.4	68.3	8.7
	C	1,357	20.3 - 80.0	63.4	63.9	69.8	6.5
	D	1,363	35.7 - 85.2	66.0	66.7	71.8	6.2
After Treatment							
SB	A	1,274	24.3 - 80.7	57.2	58.6	67.5	10.7
	B	1,296	35.1 - 81.4	59.0	59.7	68.0	8.5
	C	1,284	30.9 - 89.5	62.7	63.1	70.2	7.1
	D	1,260	22.6 - 110.0	65.9	66.9	71.9	6.5

Exhibit 5-26 Treatment Effect on Speed Profile at TX1 Approach

Approach	**Main Effect or Interaction**	**Estimated Speed Difference (mph)**	**Standard Error (mph)**	**F-Statistic**	**Degrees of Freedom**	**P-Value**
SB	Treatment	-0.3	0.2	4.33	(1, 7883)	0.037
	Treatment x Location			1.55	(2, 7883)	0.212
	Location B	-0.4	0.3			
	Location C	-0.7	0.3			
	Location D	0.0	0.3			

Exhibit 5-27 presents mean speed profiles for the southbound approach. There was a slight, and statistically significant, speed reduction of 0.3 mph on the southbound intersection approach after installing rumble strips.

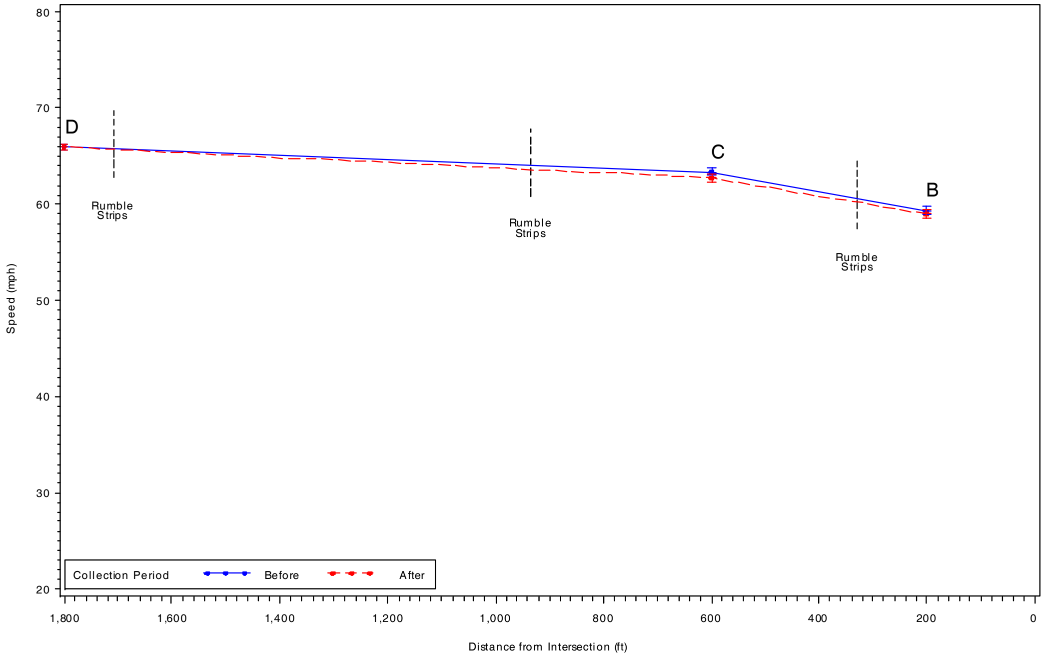


Exhibit 5-27 **Mean Speed Profile for SB Traffic at TX1**

5.5.2.7 TX2 – US 271/FM 2088

The US 271/FM 2088 intersection is in Upshur County, Texas. Rumble strips were installed on the northbound and southbound approaches. The intersection has a flashing-yellow signal on US 271 and a flashing-red STOP-control signal on FM 2088.

The speed data collection sensors on the northbound approach of US 271 were placed 175, 300, 750, and 1,800 feet from the intersection. Rumble strips were installed at two locations on the intersection approach: 700 and 1,080 feet from the intersection. The speed data collection sensors on the southbound approach of US 271 were placed 100, 250, 750, and 1,615 feet from the intersection. Rumble strips were installed at two locations on the intersection approach: 500 and 900 feet from the intersection. Exhibit 5-28 presents a site diagram of the intersection and illustrates the treatment installation and speed data collection locations.

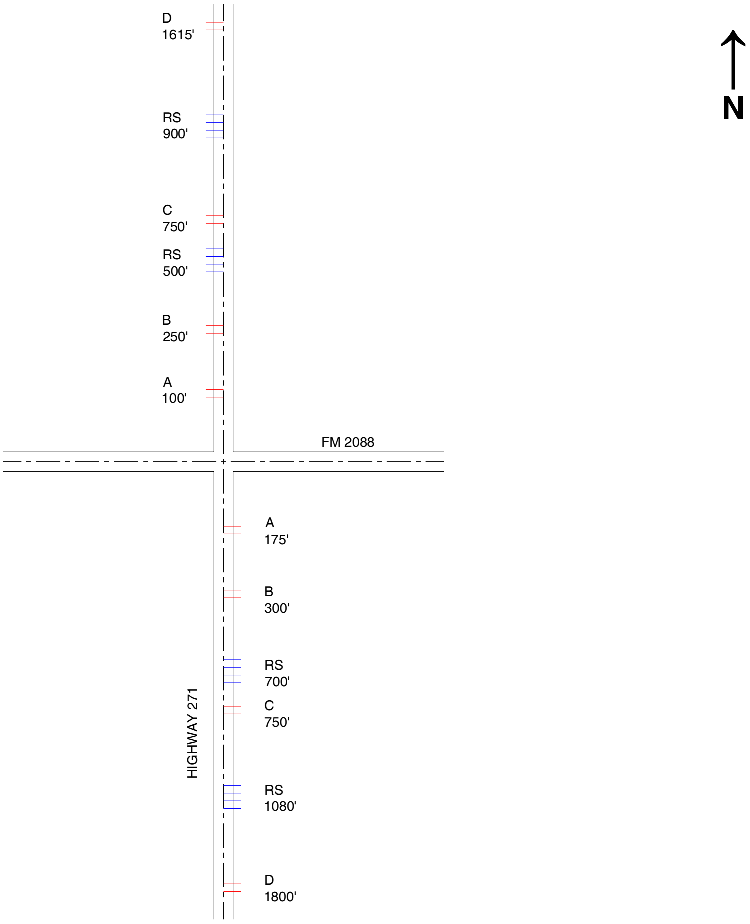


Exhibit 5-28 Site Diagram for TX2

Basic descriptive summaries for the before and after speed data at each location are presented in Exhibit 5-29. The comparison of the before and after mean speeds at all locations, while accounting for base speed changes along the intersection approach before treatment implementation, is summarized in Exhibit 5-30, separately for each intersection approach.

Exhibit 5-29 Descriptive Summaries for TX2

Location		Number of Measurements	Speed Statistics (mph)				
			Speed Range (Minimum - Maximum)	Mean	Median	85th Percentile	Standard Deviation
Before Treatment							
NB	A	353	18.4 - 81.4	56.5	57.3	65.1	8.8
	B	294	12.2 - 81.6	55.5	57.2	63.4	10.4
	C	413	38.1 - 84.5	61.8	62.7	68.2	7.0
	D	100	23.8 - 77.6	65.0	66.8	71.9	8.3
SB	A	48	14.8 - 77.4	56.0	56.7	64.7	10.7
	B	47	26.5 - 78.5	57.8	57.7	65.1	8.9
	C	47	50.7 - 79.5	61.5	60.3	67.0	7.0
	D	43	48.8 - 85.2	67.2	67.5	71.5	6.5
After Treatment							
NB	A	1,172	10.4 - 85.6	56.2	57.0	64.1	9.1
	B	320	18.9 - 74.8	56.3	56.7	63.4	7.8
	C	1,268	16.7 - 87.6	60.4	61.5	67.9	8.5
	D	998	20.9 - 87.4	66.3	67.0	72.1	6.3
SB	A	264	21.6 - 75.6	54.8	55.5	61.3	8.2
	B	230	24.6 - 75.7	55.4	56.4	61.8	8.2
	C	257	20.3 - 76.2	59.1	59.3	65.5	6.7
	D	245	43.0 - 80.4	66.7	67.2	71.6	5.3

Exhibit 5-30 Treatment Effect on Speed Profile at TX2 Approaches

Approach	Main Effect or Interaction	Estimated Speed Difference (mph)	Standard Error (mph)	F-Statistic	Agrees of Freedom	P-Value
NB	Treatment	0.1	0.3	0.05	(1, 4910)	0.83
	Treatment x Location			3.71	(3, 4910)	0.011
	Location A	-0.3	0.5			
	Location B	0.7	0.8			
	Location C	-1.4	0.4			
	Location D	1.2	0.9			
SB	Treatment	-1.6	0.7	5.86	(1, 1173)	0.016
	Treatment x Location			0.63	(3, 1173)	0.595
	Location A	-1.2	1.6			
	Location B	-2.3	1.4			
	Location C	-2.4	1.1			
	Location D	-0.5	1.0			

Exhibits 5-31 and 5-32 present mean speed profiles for the northbound and southbound approaches, respectively. The northbound approach experienced a slight reduction in mean, median, and 85th-percentile speed at all locations except Location D (all three speed statistics) and Location B (mean speed only) (Exhibit 5-29). The overall increase of 0.1 mph in mean speed is not statistically significant as indicated by the large treatment p-value in Exhibit 5-30. However, the extent to which mean speed reduction varied across data collection locations was statistically significant (small interaction p-value in Exhibit 5-30). Looking at Exhibit 5-31, it is apparent that the speed profiles from the before and after data cross each other twice, indicating that the treatment effectiveness on this intersection approach is inconsistent.

The southbound approach overall experienced a reduction in mean, median, and 85th-percentile speeds (Exhibit 5-29). The overall reduction of 1.6 mph in mean speeds was statistically significant (small treatment p-value in Table Exhibit 5-30) and is consistent across locations along the intersection approach (large interaction p-value in Exhibit 5-30).

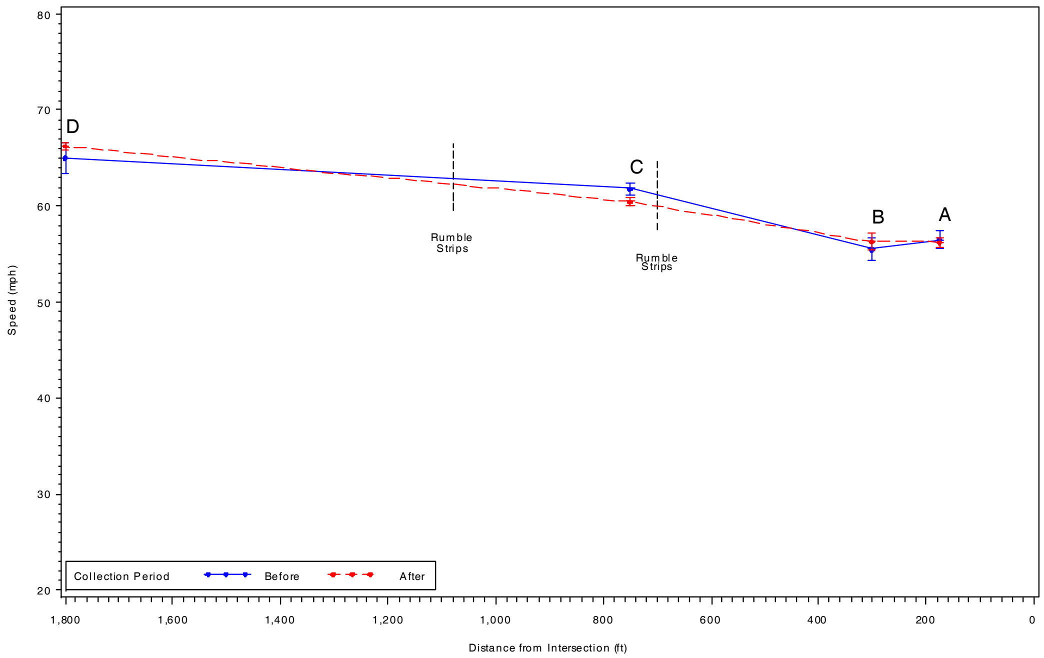


Exhibit 5-31 **Mean Speed Profile for NB Traffic at TX2**

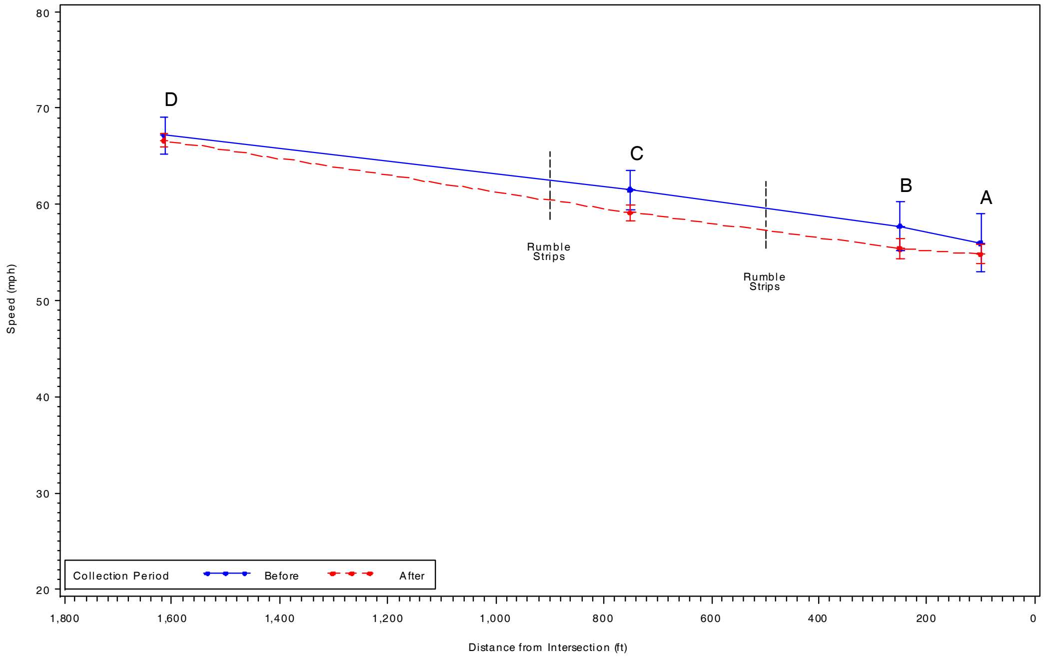


Exhibit 5-32 **Mean Speed Profile for SB Traffic at TX2**

5.5.2.8 TX3 – US 271/FM 593

The US 271/FM 593 intersection is in Upshur County, Texas. Rumble strips were installed on the northbound and southbound approaches. The intersection has a flashing-yellow signal on US 271 and a flashing-red STOP-control signal on FM 593.

The speed data collection sensors on US 271's northbound approach were placed 125, 275, 600, and 1,800 feet from the intersection. Rumble strips were installed at three locations on the intersection approach: 330, 900 and 1,700 feet from the intersection. The speed data collection sensors on US 271's southbound approach were placed 125, 250, 600, and 1800 feet from the intersection. Rumble strips were installed at three locations on the intersection approach: 330, 940, and 1,730 feet from the intersection. Exhibit 5-33 presents a site diagram of the intersection and illustrates the treatment installation and speed data collection locations.

Data collection efforts at this site experienced substantial equipment problems. As a result, no data collection time periods were common across traffic classifiers. Thus, no analysis could be conducted.

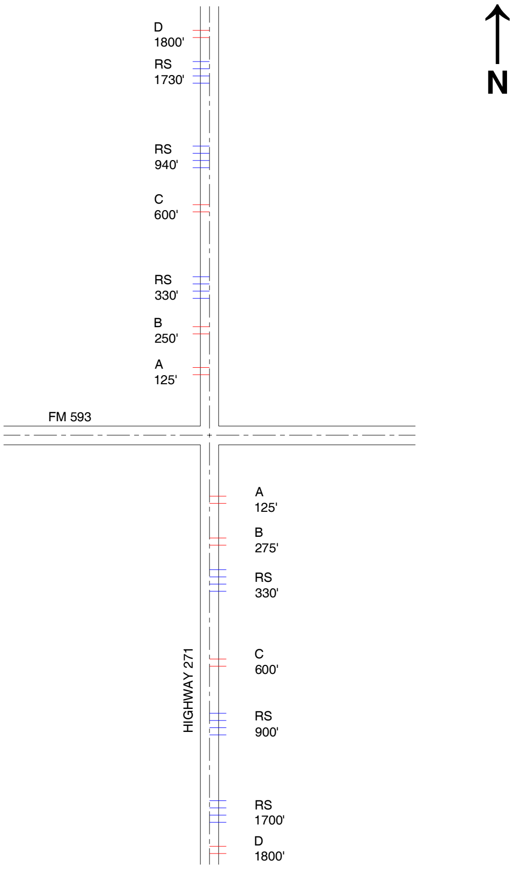


Exhibit 5-33 Site Diagram for TX3

5.5.2.9 TX4 – US 82/SH 98

The US 82/SH 98 intersection is in Bowie County, Texas. Dynamic warning signs activated by speed were installed on the eastbound and westbound approaches. The intersection has a flashing-yellow signal on US 82 and a flashing-red STOP-control signal on SH 98.

The speed data collection sensors on US 82's eastbound approach were placed 100, 250, 600, and 1,300 feet from the intersection. The dynamic warning sign activated by speed was installed 650 feet from the intersection on the approach. The speed data collection sensors on US 82's westbound approach were placed 100, 300, 600, and 1,800 feet from the intersection. The dynamic warning sign was installed 630 feet from the intersection on the approach. Exhibit 5-34 presents an intersection site diagram and illustrates the treatment installation and speed data collection locations.

Basic descriptive summaries for the before and after speed data at each location are presented in Exhibit 5-35. The comparison of the before and after mean speeds at all locations, while accounting for base deceleration along the intersection approach before treatment implementation, is summarized in Exhibit 5-36, separately for each intersection approach.

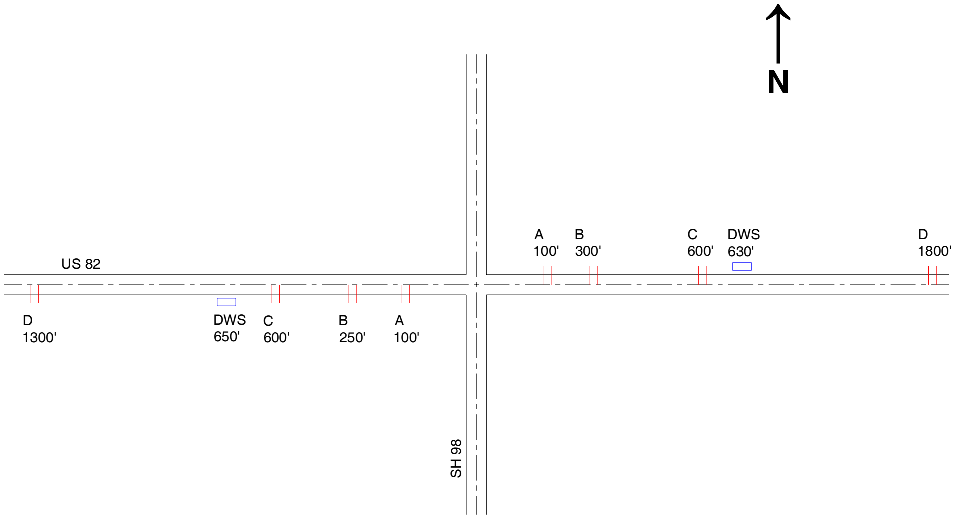


Exhibit 5-34 **Site Diagram for TX4**

Exhibit 5-35 Descriptive Summaries for TX4

Location		Number of Measurements	Speed Statistics (mph)				
			Speed Range (Minimum - Maximum)	Mean	Median	85th Percentile	Standard Deviation
Before Period							
WB	B	389	24.5 - 84.1	52.0	52.4	58.4	7.2
	C	452	23.7 - 67.4	53.7	53.8	58.5	5.2
	D	439	14.7 - 73.9	55.1	55.3	60.4	5.5
After Period							
WB	B	816	12.0 - 67.4	49.1	50.5	55.9	7.1
	C	796	18.0 - 80.7	51.6	52.4	56.9	6.0
	D	781	19.6 - 78.2	54.5	54.7	60.3	6.1

Exhibit 5-36 Treatment Effect on Speed Profile at TX4 Approach

Approach	Main Effect or Interaction	Estimated Speed Difference (mph)	Standard Error (mph)	F-Statistic	Degrees of Freedom	P-Value
WB	Treatment	-1.9	0.2	75.08	(1, 3667)	<.001
	Treatment x Location			9.92	(2, 3667)	<.001
	Location B	-2.9	0.4			
	Location C	-2.1	0.3			
	Location D	-0.6	0.3			

Exhibit 5-37 presents mean speed profiles for the westbound approach. The westbound approach experienced a reduction in mean, median, and 85th-percentile speeds at all locations (Exhibit 5-35). The overall reduction of 1.9 mph in mean speeds was statistically significant (small treatment p-value shown in Exhibit 5-36). The treatment effect in reducing speeds was not consistent along locations as shown by the significant interaction p-value in Exhibit 5-36 (2.9-mph speed reduction at Location B; 2.1-mph speed reduction at Location C; and 0.6-mph speed reduction at Location D).

No analysis was conducted for the eastbound approach due to equipment problems (and resulting inconsistent data collection periods across locations). Also, no data were collected at Location A on the westbound approach due to a malfunctioning traffic classifier.

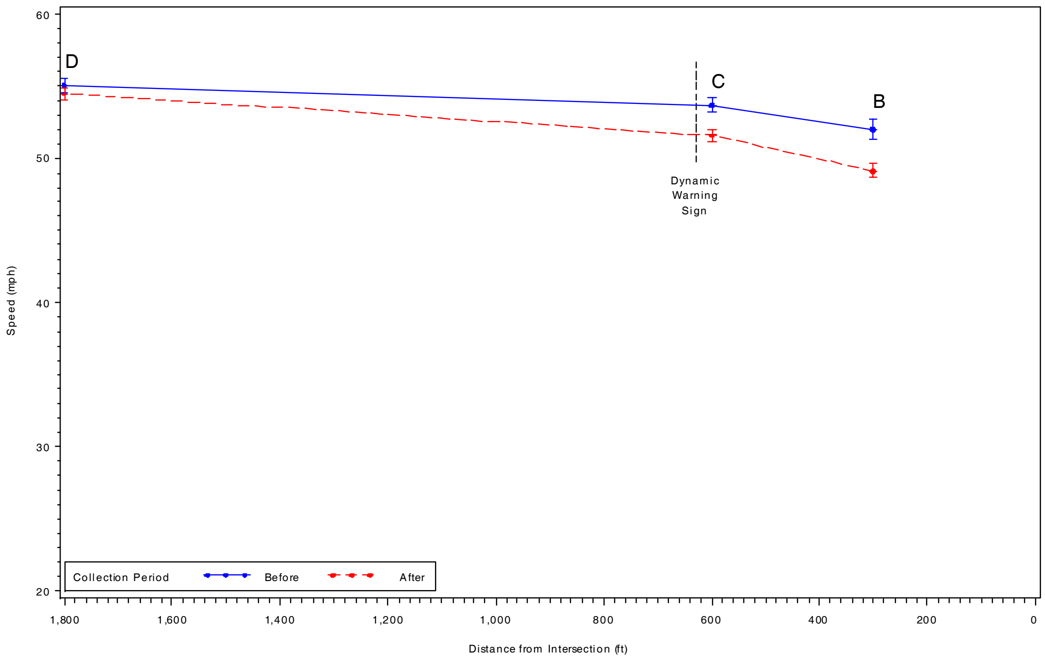


Exhibit 5-37 **Mean Speed Profile for WB Traffic at TX4**

5.5.2.10 WA1 – SR 26/S 1st Ave

The SR 26/S 1st Ave intersection is in Adams County, Washington. Dynamic warning signs activated by speed were installed on the eastbound and westbound approaches. The intersection is unsignalized with no control on SR 26 and STOP-control on S 1st Ave.

The speed data collection sensors on SR 26's eastbound approach were placed 250, 850, 1,120, and 1,850 feet from the intersection. A dynamic warning sign activated by speed was installed 850 feet from the intersection. The speed data collection sensors on the westbound approach of SR 26 were placed 375, 850, 1,150, and 1,850 feet from the intersection. A dynamic warning sign activated by speed was installed 850 feet from the intersection. Exhibit 5-38 presents an intersection site diagram and illustrates the treatment installation and speed data collection locations.

Basic descriptive summaries for the before and after speed data at each location are presented in Exhibit 5-39. The comparison of the before and after mean speeds at all locations, while accounting for base deceleration along the intersection approach before treatment implementation, is summarized in Exhibit 5-40, separately for each intersection approach.

On the eastbound approach, the traffic classifier at Location A recorded substantially fewer speeds than the other three classifiers during the before period; in the after period, it did not function properly until the last hour of the data collection period. Therefore, no speed data from Location A were included in the analysis. The traffic classifier at Location D did not record any speeds in the before and after periods. Therefore, no speed data from Location D were available for analysis.

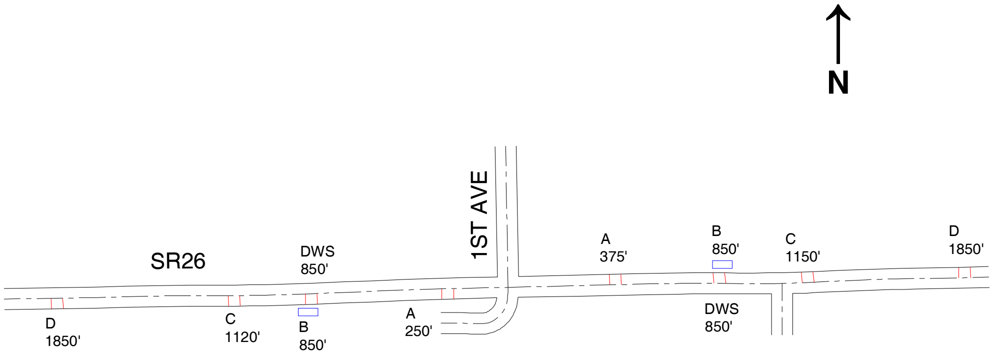


Exhibit 5-38 Site Diagram for WA1

Exhibit 5-39 Descriptive Summaries for WA1

Location		Number of Measurements	Speed Statistics (mph)				
			Speed Range (Minimum - Maximum)	Mean	Median	85th Percentile	Standard Deviation
Before Treatment							
EB	B	1,036	8.5 - 65.9	47.4	47.8	53.2	6.0
	C	959	16.0 - 84.5	48.2	48.4	53.7	6.4
WB	A	390	5.8 - 61.6	43.3	43.6	50.1	7.2
	B	427	10.1 - 85.8	47.4	47.7	52.9	7.2
	C	456	10.3 - 69.8	49.5	49.7	54.4	6.1
	D	478	11.5 - 70.8	51.7	51.8	56.7	6.5
After Treatment							
EB	B	352	9.1 - 64.9	44.2	44.9	51.0	7.1
	C	352	4.5 - 89.6	46.2	46.8	52.3	7.1
WB	A	533	3.4 - 95.4	42.2	42.4	48.7	7.4
	B	480	4.2 - 98.7	45.4	46.0	50.9	6.7
	C	582	4.0 - 67.7	46.7	47.7	52.5	7.4
	D	563	14.4 - 70.5	50.6	50.6	56.0	6.1

Exhibit 5-40 Treatment Effect on Speed Profile at WA1 Approaches

Approach	Main Effect or Interaction	Estimated Speed Difference (mph)	Standard Error (mph)	F-Statistic	Agrees of Freedom	P-Value
EB	Treatment	-2.6	0.3	74.34	(1, 2695)	<.001
	Treatment x Location			3.81	(1, 2695)	0.051
	Location B	-3.2	0.4			
	Location C	-2.0	0.4			
WB	Treatment	-1.8	0.2	62.67	(1, 3901)	<.001
	Treatment x Location			3.51	(3, 3901)	0.015
	Location A	-1.1	0.5			
	Location B	-2.0	0.5			
	Location C	-2.8	0.4			
	Location D	-1.2	0.4			

Exhibits 5-41 and 5-42 present mean speed profiles for the eastbound and westbound approaches, respectively. Both the eastbound and westbound intersection approaches experienced a reduction in mean, median, and 85th-percentile speeds (Exhibit 5-39). The reductions in mean speeds of 2.6 mph at the eastbound approach and 1.8 mph at the westbound approach are both statistically significant as indicated by the significant treatment p-values in Exhibit 5-40. The difference in effectiveness across locations was also statistically significant in both directions as shown by the significant interaction p-values in Exhibit 5-40.

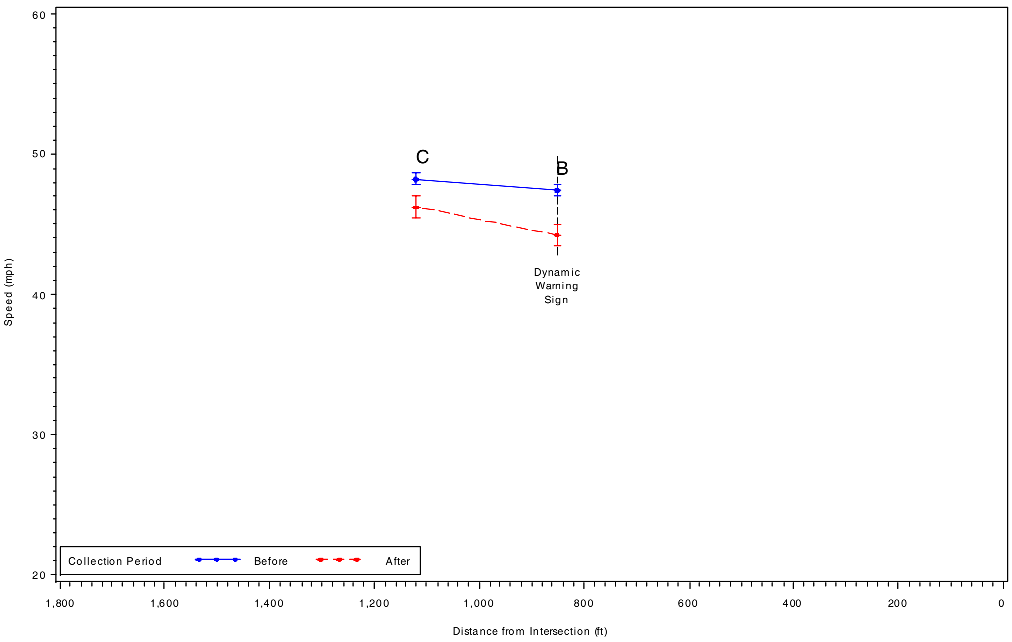


Exhibit 5-41 **Speed Profile for EB Traffic at WA1**

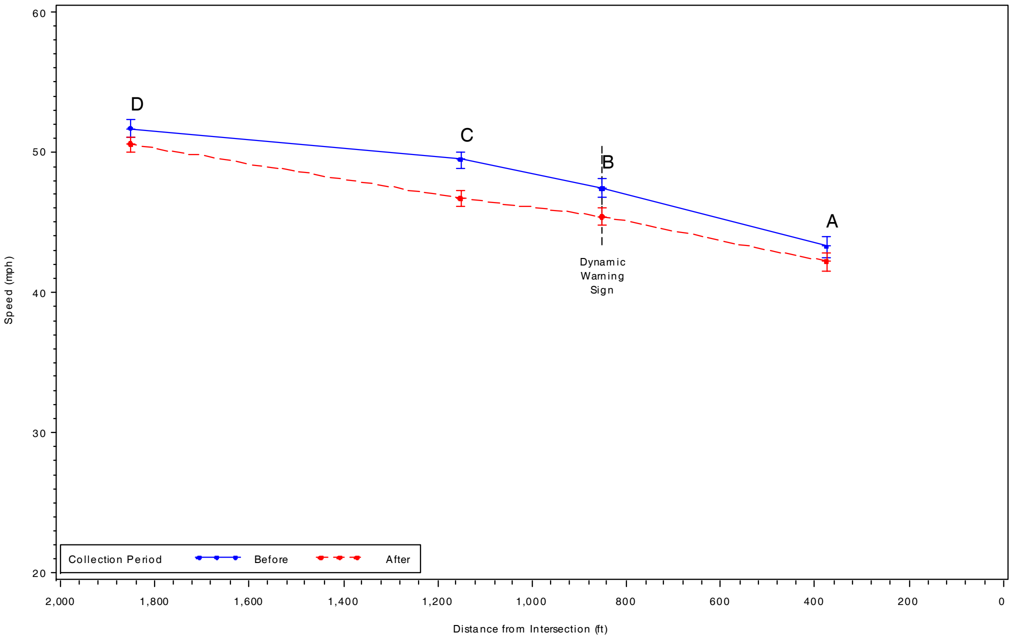


Exhibit 5-42 **Speed Profile for WB Traffic at WA1**

5.5.2.11 Summary of Results from Analysis by Intersection Approach (Step 2 Analysis)

The purpose of the analysis by intersection approach was to determine the overall speed reduction observed along an intersection approach as a result of the treatment installed on that approach. The analysis by intersection approach included 14 intersection approaches, with the three treatment types distributed as follows:

- Peripheral transverse pavement markings – 8 approaches
- Rumble strips – 3 approaches
- Dynamic warning signs activated by speed – 3 approaches

Exhibit 5-43 presents a summary of the results. On all but three of the intersection approaches, the estimated speed difference from before to after treatment installation was negative; that is, the speed decreased after treatment installation. Furthermore, all of the estimated speed reductions were statistically significant. Of the three cases where the estimated speed increased, only one was statistically significant. Another interesting finding is that all three intersection approaches on which dynamic warning signs were installed experienced a statistically significant speed reduction. Also, it appears that speed reductions were greatest on those approaches where dynamic warning signs were installed. The results of the analysis by treatment type are presented in the following section.

Exhibit 5-43 **Summary of Treatment Effect on Speed Profile at Individual Data Collection Sites**

Site No.	Intersection Site	Intersection Approach	Treatment	Estimated Speed Difference (mph)	Standard Error (mph)	Statistically Significant?
OR1	Meridian Rd / Whiskey Hill Rd	NB	Peripheral transverse pavement markings	-1.2	0.3	Yes
		EB	Peripheral transverse pavement markings	-2.1	0.3	Yes
OR2	Canby-Marquam Hwy / Lone Elder Rd	NB	Peripheral transverse pavement markings	0.2	0.2	No
		SB	Peripheral transverse pavement markings	-0.8	0.2	Yes
OR3	Redland Rd / Ferguson Rd	EB	Peripheral transverse pavement markings	-0.4	0.2	Yes
OR4	Redland Rd / Bradley Rd	WB	Peripheral transverse pavement markings	-1.6	0.2	Yes
OR6	SR 6 / Wilson River Loop Rd	EB	Peripheral transverse pavement markings	1.0	0.2	Yes
		WB	Peripheral transverse pavement markings	-0.4	0.2	Yes
TX1	US 271 / FM 726	SB	Rumble strips	-0.3	0.2	Yes
TX2	US 271 / FM 2088	NB	Rumble strips	0.1	0.3	No
		SB	Rumble strips	-1.6	0.7	Yes
TX4	US 82 / SH 98	WB	Dynamic warning sign	-1.9	0.2	Yes
WA1	SR 26 / S 1st Ave	EB	Dynamic warning sign	-2.6	0.3	Yes
		WB	Dynamic warning sign	-1.8	0.2	Yes

5.5.3 Results of Analysis by Treatment Type (Step 3 Analysis)

The previous section discussed potential treatment effects in reducing speeds on an intersection approach. The next logical step is to quantify the effect of a specific speed-reduction treatment across all intersection approaches at which it was installed. Transverse pavement markings were installed at 5 intersection sites for a total of 10 intersection approaches; rumble strips were installed at 2 intersection sites for a total of 3 intersection approaches; and dynamic warning signs were installed at 2 intersection sites for a total of 4 intersection approaches.

The estimated effectiveness of each of the three treatments across all intersection approaches is presented in Exhibit 5-44. The "Main Effect or Interaction" column refers to either the overall treatment effect (Treatment), the interaction effect between treatment and data collection location (abbreviated as "Treatment x Location"), or the treatment effect at the individual locations (A, B, C, or D). The statistical significance of an effect is based on the p-value in the last column. Rows with p-values highlighted in yellow and bold indicate statistical significance based on a p-value cut-off of 0.05 (i.e., 5-percent significance level). The two footnotes pertain to the type of test used to test for significance: an F-test to test for significant treatment or treatment-by-location interaction; a t-test to test for significant treatment effect at a particular data collection location.

The treatment effect is the estimated speed reduction across all intersection approaches. The treatment-by-location interaction tests whether the treatment effect is the same across data collection locations (note that in this analysis, differences between intersection sites are controlled for in the model). The location effects correspond to the estimated speed reduction across sites for each data collection location (i.e., A, B, C, or D).

Exhibit 5-44 Overall Treatment Effect on Speed Profile Across All Intersection Approaches

Treatment Type	Main Effect or Interaction	Estimated Speed Difference (mph)	Standard Error (mph)	Test Statistic	Degrees of Freedom	P-Value
Peripheral transverse Pavement Markings	Treatment[a]	-0.6	0.3	3.68	(1,7)	0.097
	Treatment x Location[a]			6.04	(6,17)	0.002
	Location A[b]	-0.3	0.4	-0.65	17	0.522
	Location B[b]	-0.7	0.4	-1.89	17	0.076
	Location C[b]	-0.9	0.4	-2.33	17	0.032
	Location D[b]	-0.8	0.4	-2.04	17	0.058
Rumble Strips	Treatment[a]	-0.6	0.4	1.83	(1,3)	0.269
	Treatment x Location[a]			23.70	(6,6)	0.001
	Location A[b]	-0.7	0.7	-1.00	6	0.354
	Location B[b]	-0.4	0.5	-0.69	6	0.516
	Location C[b]	-1.3	0.5	-2.45	6	0.050
	Location D[b]	0.2	0.6	0.29	6	0.781
Dynamic Warning Sign	Treatment[a]	-1.7	0.2	81.18	(1,2)	0.012
	Treatment x Location[a]			71.06	(6,3)	0.003
	Location A[a]	-1.1	0.5	-1.98	3	0.141
	Location B[a]	-2.8	0.3	-9.25	3	0.003
	Location C[a]	-2.3	0.3	-7.70	3	0.005
	Location D[a]	-0.9	0.4	-2.44	3	0.093

[a] F-Test
[a] T- Test

Exhibit 5-44 shows the following:

- All treatment installations resulted in speed reductions from before to after installation at given locations, with the exception of rumble strips at Location D (speed increase of 0.2 mph with a standard error of 0.6 mph).
- Only a few speed reductions (either overall or on a location basis) were statistically significant at the 5-percent level.
- Only dynamic warning signs activated by speed have a significant overall effect (at the 5-percent significance level) in reducing speeds from before to after installation, with a mean speed reduction of 1.7 mph (standard error or precision of 0.2 mph).

- Peripheral transverse pavement markings have a significant overall effect (at the 10-percent significance level) in reducing speeds from before to after installation, with a mean speed reduction of 0.6 mph (standard error or precision of 0.3 mph).

- Rumble strips did not have an overall effect in reducing speeds from before to after installation.

- Treatment by location interactions was significant at the 5-percent level for all three treatment types; that is, the effectiveness of each treatment, whether overall statistically significant or not, is not consistent across location along an approach.

- All three treatment types were effective in reducing speeds at Location C (intersection perception/response speed location) with mean speed reduction (standard error) of 0.9 mph (0.4 mph) for peripheral transverse pavement markings; 1.3 mph (0.5 mph) for rumble strips; and 2.3 mph (0.3 mph) for dynamic warning signs activated by speed.

- Dynamic warning signs activated by speed were effective in reducing speeds at Location B (accident avoidance speed location), with a mean speed reduction (standard error) of 2.8 mph (0.3 mph).

- Dynamic warning signs activated by speed showed the largest significant speed reduction as compared to all other reductions, with a mean speed decrease of 2.8 mph (standard error of 0.3 mph) at Location B.

- None of the treatments significantly reduced speeds at Location D (farthest away from intersection), as expected.

5.5.4 Results of Secondary Analysis of 85th-Percentile Speeds

As previously discussed in Section 5.4.4, a secondary analysis of 85th-percentile speeds was conducted for the analysis by intersection approach (Step 2 analysis) and the analysis by treatment type (Step 3 analysis). The results of the analyses, based on a paired t-test of the differences between before and after 85th-percentile speeds, are presented in *Appendix H* and discuss the following:

- Treatment effect on 85th-percentile speed by intersection approach (to match level 2 analysis of mean speeds)

- Overall treatment effect on 85th-percentile speed across all intersection approaches (to match level 3 analysis of mean speeds).

The estimated speed differences in 85th percentiles shown in Exhibit H-1 may be compared to those shown in the treatment effect tables shown in Exhibits 5-4 through 5-40; while the differences are mostly comparable both in magnitude and direction (sign of difference), the significance levels (p-values) are often smaller; this is due to the fact that the variance in the 85th-percentile speed at a given location is ignored in this approach.

Similarly, the estimated speed differences in 85th percentiles shown in Exhibit H-2 may be compared to the estimated speed differences shown in Exhibit 5-44; again, while the differences are mostly comparable both in magnitude and direction (sign of difference), the significance levels (p-values) are often smaller; this is due to the fact that the variance in the 85th-percentile speed at a given location is ignored in this approach.

5.5.5. Testing Results Summary

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

- At approximately 75 percent of the locations, speed reductions of as much as 3.2 mph were observed (with one anomaly speed reduction of 8.7 mph).
- At approximately 25 percent of the locations, speed increases of as much as 1.8 mph were observed.
- Of the 51 before-after speed differences, 34 were statistically significant.

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 – 8 with peripheral transverse pavement markings, 3 with rumble strips, and 3 with dynamic warning signs activated by speed – were included in this analysis. Key findings include:

- At 11 of the 14 intersection approaches, the estimated speed difference from before to after treatment installation was negative; that is, the speed decreased after treatment installation. The estimated speed reductions were statistically significant.
- At 3 of the 14 intersection approaches, the estimated speed difference was positive (the speed 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 speed reduction.
- The speed reductions appeared to be greatest where dynamic warning signs were installed.

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 peripheral transverse pavement markings, 5 with rumble strips, and 4 with dynamic warning signs activated by speed – were included in this analysis. Key findings include:

- Dynamic warning signs activated by speed were the only treatment to have a statistically significant overall effect at the 5-percent significance level in reducing speeds from before to after installation, with a mean speed reduction of 1.7 mph.

- Peripheral transverse pavement markings had a statistically significant overall effect at the 10-percent significance level in reducing 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 speeds from before to after installation

- All three treatment types were effective in reducing speeds at Location C (intersection perception/response speed location), with mean speed reduction of 0.9 mph for peripheral transverse pavement markings; 1.3 mph for rumble strips; and 2.3 mph for dynamic warning signs activated by speed.

- Dynamic warning signs activated by speed were effective in reducing speeds at Location B (accident avoidance speed location), with a mean speed reduction of 2.8 mph.

- Dynamic warning signs activated by speed resulted in the largest speed reduction as compared to all other treatments.

5.6. CONCLUSIONS

Overall conclusions from the testing results include:

- All three treatment types may reduce speeds on high-speed intersection approaches; however, 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 intersection would first become visible to the driver or where the driver might first react to the intersection.

- Of the three treatment types tested, dynamic warning signs activated by speed may be the most effective at reducing speeds. However, this conclusion is based on only three intersection approaches.

- Peripheral transverse pavement marking also appear 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.

6 Guidelines

NCHRP Report 3-74: Guidelines for Selecting Speed Reduction Treatments at High Speed Intersections ("*Guidelines*") assists roadway planners, designers, and operators as they consider and select appropriate speed reduction treatments at intersections located in high-speed environments. While the application of these treatments most often applies to existing intersections that experience undesirably high speeds, the information is also relevant to new intersection designs. The *Guidelines* are not a new standard for implementing treatments. Rather, they are informational, describing good practices for selecting treatments.

Drivers generally choose a reasonable travel speed based on their perception of safety and comfort; however, there are a variety of conditions and circumstances that 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 their behavior, and others are physical. Physical changes to the roadway and surrounding environment may influence driver behavior, which can indirectly reduce speed, improve operations, and/or enhance environmental quality.

The *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 U.S. and abroad, including their effectiveness and implementation considerations. The *Guidelines* also provide insights on 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 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.

6.1 SCOPE OF *GUIDELINES*

The *Guidelines* apply to intersections with approach speeds of 45 miles per hour (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. This document focuses on public roadway intersections; however, many principles also apply to private driveways that include public-roadway–like features.

Intersections are discrete roadway features that occur on roadway or corridor segments. They frequently occur in urban conditions, but 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 influence areas and do not specifically address speed reduction in roadway segments. The influence area of an intersection includes the area within which the typical section of the roadway segment is modified and which is influence by traffic operations (ex. Queuing and deceleration) related to the intersection.

Section 1 introduces the *Guidelines* and presents their purpose, scope and applicability. This section also introduces the importance of differentiating the intersection influence area from adjacent roadway segments.

Section 2 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 and highlights some physical conditions and user characteristics that may make an intersection particularly sensitive to speed. The purpose of this section is to describe many considerations that may be useful in understanding the nature of a speed concern.

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. Excessive speeds generally result when environmental and operational elements are incompatible, sending a mixed message about appropriate behavior to motorists. Speed reduction does not necessarily guarantee safety or environmental benefits.

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 a first consideration in evaluating and selecting an appropriate speed reduction treatment.

Section 3 guides users through the process of selecting speed reduction treatments for intersection approaches. The process includes: intersection pre-screening; treatment screening; and treatment implementation.

This section provides information about the speed-reduction treatments, including their applicability, cost, secondary impacts, implementation considerations, and potential effectiveness in reducing speeds and increasing safety. This information was compiled from a variety of national and international sources. Some of the treatments included in the *Guidelines* have had limited or no documented applications at high-speed intersections; however, based on their function, they are considered potentially applicable at certain high-speed locations. The information provided in this section highlights 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.

Section 3 also provides guidance to help users layout and design selected treatments based on a target speed and the desired driver behavior. Finally, this section gives some direction about evaluating treatments.

Section 4 describes speed reduction treatments in detail. 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. Photos and diagrams are also provided. The information provided in this section should be considered in combination with appropriate local engineering practices and engineering judgment related to the site-specific situation.

The appendices to the *Guidelines* provide a diagnostic flow chart, scenario-based case studies, testing data and results from the testing plan, and references to other relevant studies. *Appendix A*, the diagnostic flow chart schematically depicts the treatment selection process and key considerations. *Appendix B*, the scenario-based case studies, describes several specific applications of the treatment selection process. *Appendix C* provides a list of references that provide additional information about the treatments.

7 Suggested Research

Speed reduction and safety are high priority topics within the transportation profession. The purpose of this NCHRP study was to answer questions specific to speed reduction treatments at high-speed intersections. The research produced guidelines for considering factors at high-speed intersections and a methodology to consider potential treatments. Phase II testing provided valuable data on the specific speed reduction qualities of the following treatments: Peripheral transverse pavement markings, rumble strips, and dynamic warning signs activated by speed. The research team has identified other research topics (in no particular order) for future consideration.

- NCHRP 3-74 provides quantitative data on the speed reduction qualities of the tested treatments. However, measuring the safety effects and conducting safety evaluations can potentially take many years to adequately assess the short-, mid-, and long-term effects of a treatment. Future research should be conducted to evaluate the actual safety performance over a three- to five-year period after the treatments have been in place. Of particular interest would be an effort to understand the role of speed and safety versus driver awareness and safety. Future research may shed light on whether (absolute) speed reduction affects safety or whether treatments influence driver attention to potential workload tasks and therefore, aid drivers in avoiding the conflicts they encounter at an intersection (versus a roadway segment).

- The research team applied a minimum of a three month period between the before and after testing. This period was applied to balance research projects scheduling needs and the potential "novelty effects" of the new treatment. In addition, only one set of after data was collected at each testing location. Future research should consider additional testing to understand driver behavior over time and the long term speed reduction effects over time. The studies might consider understanding and quantifying the novelty effect over time and driver acclimation to treatment types over long periods of time.

- There are many databases (HSIS, FARS, GES, and HPMS) that summarize various safety performance values applications. These databases do not contain sufficient data variables and elements to reveal the true relationships between speeding and safety at intersections. Causal factors for intersection crashes are complex and are significantly affected by intersection and roadway geometry, traffic control, traffic volume, and the location's general environmental context. Human factors, such as driver behavior and interpretation of the intersection context, are equally as important, and are also unknown. Future research should evaluate current databases to assess if they fully serve safety evaluation needs or if current databases could be successfully modified or if a new database would be valuable. The research would evaluate the intended use of the data, recommend data collection needs, identify crash report data recording protocols, define crash data base input needs, and identify a user interface that allows productive queries and manipulation of the data.

- Accurate and precise speed measurement at the various field conditions was challenging. Some of the measuring devices available were precise but not necessarily accurate; with measurement accuracies on each device ranging from plus/minus 2-3 mph. Other devices were accurate and precise but were relatively fragile. These devices might pose challenges to night testing (adjusting devices) and testing during less than desirable conditions. Other measuring devices (LIDAR or RADAR) are proven tools. However, these devices may require data collectors to be visible to drivers and possibly affect the testing results. Accurate, durable devices that provide precision while being inconspicuous and easy to use would be helpful in future testing programs.

- This study focused on understanding the speed reduction qualities of a single speed reduction treatment. Future studies should be conducted that measure the potential and incremental benefit of combining treatment types. Understanding the potential speed reduction effects of combined treatments could provide additional flexibility to professionals in applying a range of treatments to address a unique intersection need. Similarly, future studies could consider the effects of applying supplemental countermeasures such as ITS or Enforcement to enhance the speed reduction qualities of improvements.

- Testing for this project was performed during the best weather possible for before and after measurements. The purpose of this testing approach was to isolate and remove weather conditions from the testing results. Future research could build up on the clear and dry weather testing to understand how night time and other weather conditions affect a treatment's effectiveness.

- This research project collected data a limited number of sites for each type of treatment. Future studies should be conducted at a larger number of sites of the same type of treatment to obtain additional speed reduction data and treatment testing results.

- NCHRP Report 572 (Based on NCHRP 3-65) Roundabouts in the United States, provides a comprehensive summary of roundabout operations and safety performance. NCHRP 3-65 collected spot speed data at existing roundabout locations throughout the nation. The data was collected for locations 200 feet before the entrance of the roundabout, at the entrance, and at the exits of the roundabouts. Future research could evaluate NCHRP 3-65 speed data for opportunities to evaluate speed performance at roundabouts.

- As roundabouts are still relatively new in the United States, there are some reservations to applying them in high speed environments. The FHWA publication *Roundabouts: An Informational Guide* provides insights about approach curvature and other methods to reduce speed. Those methods and applications have been referenced in this report. Future studies could consider speed reduction applications on roundabout approaches. The findings and study methods may provide insights and be transferable to approach treatments for conventional intersection forms.

- Speed tables and other vertical deflection methods are common traffic calming tools. However, there has been no published research or testing results for speed table applications on high-speed facilities or specifically at intersection approaches. Future studies could explore speed table applications on lower speed facilities and consider a broader application to facilities with higher speeds.

- As the speed reduction qualities of treatments are identified, a logical next step would be to understand the optimal location, design, and specifications to obtain optimum configurations. Future studies (conducted using field testing and/or driving simulators) could test a range of possible configurations and make recommendations for design guidelines. For transverse pavement markings this may include the most effective placement of the markings in relationship to roadway segment and intersection influence areas. This could include near or away from existing signing or at alternative stopping sight distances. In addition future research could consider the number of series of treatments, bar design (widths and spacing), or combinations of peripheral and full transverse markings. Dynamic Warning Signs placement and design should also be investigated in future studies. This could include understanding the influence of sign size and orientation and the types of messages provided.

- A number of supplemental lighting and marking devices are now available. The continued creative use of light emitting diodes (LEDs) and fiber optic products creates the opportunity to supplement existing signing and pavement markings. Future studies might consider how these visual aids supplement current devices and traffic control.

- Future research could consider driver or traffic attributes such as commuter traffic versus new or unfamiliar motorists. Research could also consider the treatment effectiveness based on driver age range or experience levels (new versus experienced operators). Future research might consider the affects of various fleet types, including large trucks and buses.

- The testing results showed that speed values and relationships varied by direction or approach at the same intersection. For example, speeds might have been reduced on one approach but not on another. Future research might consider how to assess and quantify the effects of various contextual environments of upstream segments. This research would help understand the roles and relationships between roadway segments and intersection influence areas. The study efforts could help researchers understand what elements influence driver behavior and how those elements effect driving speed.

- This project was able to test stop-sign and uncontrolled intersection approaches. Future research should focus on investigating speed reduction needs and influences of various traffic control types including signalized intersections, four way stops, and yield controlled approaches or movements (such as a dedicated right-turn lane).

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APPENDIX A

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Relationship Between Roundabout Geometry and Accident Rates	Owen Arndt	Apr-98
Geometric Design Practices for European Roads	Jim Brewer, John German, Ray Krammes, Kam Movassaghi, John Okamoto, Sandra Otto, Wendell Ruff, Seppo Sillan, Nikiforos Stamatiadis, Robert Walters	Jun-01
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A Model of Driver Behavior at High Speed Intersections	Sheffi, Yosef	Jan-80
Driver Response to Active Advance Warning Signs at High-Speed Signalized Intersections	Sabra, Ziad	1985
Transverse Pavement Markings For Speed Control and Accident Reduction	Agent, Kenneth R.	1980
An Effective Speed Reduction as a General Traffic Safety Measure in Urban Traffic	Hyden, Christer	1981
Factors Affecting Drivers Choice of Speed on Roadway Curves	Kanellaidis, G.	1995
Speed Perception in Road Curves	Milosevic, S; Milic, J	1990
Accidents on Spiral Transition Curves	Tom, GKJ	Sep-95
Impacts of Traffic Calming	Ewing, R.	Dec-00
Design and Safety of Pedestrian Facilities		Mar-98
Effectiveness of Roadway Safety Improvements	Thomas, GB; Smith, DJ	Mar-01
Curvilinear Alignment: An Important Issue for More Consistent and Safer Road Characteristic	Lamm, R; Smith, BL	1994
Operating Speed and Relation Design Backgrounds: Important Issues to be Regarded in Modern Highway Alignment Design	Lamm, R; Eberhard, O; Heger, R	1997
Crash Reductions Following the Installation of Roundabouts in the US	Persuad, BN; Retting, RA; Garder, PE; Lord, D	Mar-00
Special Signs and Pavement Markings Improve Pedestrian Safety	Retting; RA; Van Houten, R; Malenfant, L; Van Houten, J; Farmer, CM	Dec-96
Designing for Pedestrians	Zegeer, CV; Seiderman, CB	Aug-01
Humps - A Speed Reduction Strategy in Local Street Systems	Datta, S; Datta, TK	1997
Speed Reductions: Strategies that Reduce Traffic Speeds		Jun-04

APPENDIX B

Appendix B Literature Review - Document Screening

The following document summarizes the critical concepts and general information outlined in each task of the Amplified Research Plan. These bullet points will be used as criteria to screen and prioritize the sources that we have gathered thus far. A source that does not provide insight on one of the following criteria may not have specific relevance to our research goals. The concepts have been categorized by task and sub-task in order to refer back to the original Amplified Research Plan for further detail on each topic if needed.

B.1 TASK 1 – ANALYZE POTENTIAL TREATMENTS

- Relationship between frequency and/or severity of crashes based on speed
- Factors that affect intersection safety and speed
- Speed transition areas
- Impacts of treatments on speed and safety
    - Effectiveness of treatments
- Evaluation criteria for treatments, safety and speed reduction (1.2, 1.3)
- Case studies that discuss experience with applying various treatments to different roadway environments (1.2)
- Types of speed reduction techniques (1.4)
    - Beyond the list shown in the research plan
- Effectiveness of speed enforcement on intersection approaches (1.5)
    - With or without particular geometric or traffic control treatments
- Relationship between geometric design speed reduction techniques and non-design treatments (1.5)

B.2 TASK 2 – CHARACTERISTICS FACTORS OF HIGH RISK INTERSECTIONS

- Characteristics of intersections with high crash rates
- Characteristics of high-speed intersections with a history of severe crashes
- Categorization of potential speed reduction treatments
    - Visual, physical, operations
- Factors that contribute to speed (2.1)
    - Conflicts and friction, roadside impedances, roadside environment, etc.
- Speed characteristics and trends (2.2)
    - Based on facility type, roadway environment, climate, traffic control devices, etc.

- Safety characteristics of the factors that influence speed (2.3)
    - A low volume, high-speed road could experience a low frequency of severe crashes, whereas a high volume, low speed facility could experience a high number of low severity crashes
- Relationship between human factors and intersection safety and speed (2.3)
    - How does human behavior influence speed?

B.3 TASK 3– RECOMMEND TREATMENTS

- Performance measures of speed reduction treatments
- Relationship between roadway facility characteristics and speed and safety (3.1)
- Relationship between speed differentials and the risk of crashes (3.2)
- Evolution of speed characteristics on a specific facility or area (3.2)
    - Volume growth
    - Adjacent land uses changing
- Amount of speed reduction (3.2)

B.4 TASK 4 – OUTLINE GUIDELINES

- Guidelines for mitigating high risk intersection with speed reduction treatments
- Case studies that discusses experience with applying a roundabout or roundabout design principles to a conventional intersection
- How to define “target” speeds for treatments and/or roadway environments (4.2)
- Duration and/or distance of speed reduction (4.2)
- Relationship between roadway system and isolated treatments (4.3)
- Impacts of treatment on safety of non-auto road users (4.3)

B.5 TASK 5 – DEVELOP TESTING PLAN

- Ability to implement and test a specific speed reduction treatment
- Effectiveness of using driver simulators to test treatments
- Treatment testing methodology

APPENDIX C

SURVEY ON HIGHWAY AGENCY USE OF SPEED-REDUCTION TREATMENTS ON INTERSECTION APPROACHES

The National Cooperative Highway Research Program (NCHRP) is conducting research in NCHRP Project 3-74 to investigate the effectiveness of treatments to reduce vehicle speeds at intersection approaches, where needed. NCHRP is sponsored by the Federal Highway Administration (FHWA) and the American Association of State Highway and Transportation Officials (AASHTO) and is managed by the Transportation Research Board (TRB). Kittelson & Associates, Inc. and Midwest Research Institute are conducting the research in NCHRP Project 3-74. The following questionnaire is seeking information on your agency's experience and current practices in employing speed-reduction treatments on approaches to at-grade intersections. There will be an opportunity for interested highway agencies to participate in the research. The research results will be available for utilization by all highway agencies. Your assistance in taking a few minutes to respond to this questionnaire would be greatly appreciated.

1. What type of highway agency do you represent (check one)?
___ State highway agency
___ City highway agency
___ County highway agency
___ Other (please describe):

2. Does your agency incorporate geometric treatments specifically intended to reduce speeds on approaches to at-grade intersections? ___ YES ___ NO

If YES, please indicate which of the following geometric treatments have been used by your agency and indicate whether your agency considers the treatment to be effective (i.e., would you use them again?):

		Effective? (YES / NO)	In current use? (YES / NO)
____	Reduced lane widths (lane width narrower than upstream midblock roadway)	________	________
____	Shoulder treatments	________	________
____	Speed tables	________	________
____	Rumble strips in the traveled way on intersection approaches	________	________
____	Roundabouts	________	________
____	Introduction of horizontal curvature on approaches to conventional at-grade intersections	________	________
____	Introduction of reverse horizontal curvature (successive curves in opposing directions) on approaches to conventional at-grade intersections	________	________
____	Introduction of other roundabout-like treatments on approaches to conventional at-grade intersections	________	________
____	Roadside treatments such as cross-sectional changes, "gateways", or landscaping	________	________
____	Other (please describe): ________________________ ____	________	________

3. Does your agency use signing (i.e., STOP signs or other messages), other than posted speed limits or advisory speed signs, specifically intended to reduce speeds on approaches to at-grade intersections?
___ YES ___ NO

If YES, please indicate which of the following signing treatments have been used by your agency and indicate whether your agency considers the treatment to be successful (i.e., would you use them again?):

		Effective? (YES / NO)	In current use? (YES / NO)
____	Dynamic warning signs activated by speed of approaching vehicle	________	________
____	Dynamic warning signs activated by potentially conflicting vehicles on another approach to the same intersection	________	________
____	Other (please describe): ________________________ ____	________	________

4. Does your agency use pavement markings specifically intended to reduce speeds on approaches to at-grade intersections? ___ YES ___ NO

If YES, please indicate which of the following pavement marking treatments have been used by your agency and indicate whether your agency considers the treatment to be successful (i.e., would you use them again?):

		Effective? (YES / NO)	In current use? (YES / NO)
____	Wider edge line markings	________	________
____	Wider centerline markings	________	________
____	Transverse pavement markings on the roadway	________	________
____	Transverse pavement markings on the shoulder	________	________
____	Other (please describe): ________________________ ____	________	________

5. If your agency has design policies, traffic control policies, specifications, or typical drawings for the speed-reduction treatments you identified in your response to Questions 2, 3 and 4, a copy of the policies, specifications, or typical drawings would be appreciated. Material can be emailed or sent to **Ingrid Potts** (contact information listed at end of survey).

6. Has your agency conducted formal research or performed evaluations to determine the effects on vehicle speeds or safety of the treatments you identified in Questions 2, 3, and 4? ___ YES ___NO

If YES, please describe the research or attach a copy of the research or evaluation report:

7. NCHRP Project 3-74 is considering the conduct of evaluations to determine the effectiveness of selected intersection speed-reduction treatments like those mentioned in Questions 2, 3, and 4. For each treatment on the following list, please rate the potential importance to your agency of obtaining the results of a formal effectiveness evaluation. Please rate each treatment on a 1 to 5 scale with 5 meaning "greatest need for evaluation" and 1 meaning "least need for evaluation".

____ Reduced lane widths (lane width narrower than adjacent midblock roadway)
____ Shoulder treatments
____ Speed tables
____ Rumble strips in the traveled way on intersection approaches
____ Roundabouts
____ Introduction of horizontal curvature on approaches to conventional at-grade intersections
____ Introduction of reverse horizontal curvature (curves in opposing directions) on approaches to conventional at-grade intersections
____ Introduction of other roundabout-like treatments on approaches to conventional at-grade intersections
____ Roadside treatments such as cross-sectional changes, "gateways", or landscaping
____ Wider edge line markings
____ Wider centerline markings
____ Transverse pavement markings on the roadway
____ Transverse pavement markings on the shoulder
____ Dynamic warning signs activated by speed of approaching vehicle
____ Dynamic warning signs activated by potentially conflicting vehicles on another approach to the same intersection
____ Other (please describe):

8. In order to determine the effectiveness of selected intersection speed-reduction treatments, the research may consider the following evaluation criteria (listed below). Please rate the importance of including each criterion in the evaluation, based on your agency's potential need for evaluation results incorporating that criterion. Please rate each criterion on a 1 to 5 scale with 5 meaning "very important" and 1 meaning "not important" to your agency's needs.

____ Vehicle speed profile (midblock speed vs. intersection approach speed)
____ Mean or 85th percentile vehicle speed before vs. after treatment
____ Vehicle lateral position
____ Accident frequency or severity (before vs. after treatment)

9. Are there additional evaluation criteria that your agency considers important to include in the evaluation of speed-reduction treatments on intersection approaches? ___ YES ___ NO

If YES, please describe:

10. Has your agency installed speed-reduction treatments on existing intersection approaches in the last three years that you would be willing to have included in an effectiveness evaluation to be conducted by the NCHRP Project 3-74 research team? ___ YES ___ NO

If YES, please indicate the type of treatments installed and the approximate number of projects:

11. Would your agency be interested in participating in an effectiveness evaluation of speed-reduction treatments on intersection approaches to be installed in 2005? Such an evaluation would be conducted by the NCHRP Project 3-74 research team. ___ YES ___NO

If YES, please identify the type of treatments your agency might consider implementing:

____ Reduced lane widths (lane width narrower than adjacent midblock roadway)
____ Shoulder treatments
____ Speed tables
____ Rumble strips in the traveled way on intersection approaches
____ Roundabouts
____ Introduction of horizontal curvature on approaches to conventional at-grade intersections
____ Introduction of reverse horizontal curvature (curves in opposing directions) on approaches to conventional at-grade intersections
____ Introduction of other roundabout-like treatments on approaches to conventional at-grade intersections
____ Roadside treatments such as cross-sectional changes, “gateways”, or landscaping
____ Wider edge line markings
____ Wider centerline markings
____ Transverse pavement markings on the roadway
____ Transverse pavement markings on the shoulder
____ Dynamic warning signs activated by speed of approaching vehicle
____ Dynamic warning signs activated by potentially conflicting vehicles on another approach to the same intersection
____ Other (please describe):

12. Do you have any other comments?

13. May we have the name of an individual in your agency that we may contact for further information?

Name ____
Agency ____
Address ____
____
____
Phone: ____________________ Fax: ______________
E-mail: ____

14. Are there other agencies in your state, including cities and counties, that you think might have an interest in participating in an effectiveness evaluation of speed-reduction treatments on approaches to at-grade intersections. ___ YES ___ NO

If YES, please provide the name of the agency and/or contact information for a key individual:

THANK YOU FOR YOUR ASSISTANCE. Please mail your response by October 29, 2004, to:

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APPENDIX E

Appendix E Prioritizing Treatments

E.1 OVERVIEW

This Appendix describes the research team's approach to considering the range of potential treatments, the published effectiveness of the treatments, and the professional judgment on the expected effectiveness of each treatment, independent of the extent of published information that was available.

The research team reviewed the literature review results to prioritize those treatments that were documented as having the ability to reduce speeds. Based on the team member's professional experience and expectation for treatment effectiveness, each member ranked the treatments. During a work session, team members discussed their reasoning and ranking for each treatment. From these discussions, the team developed a consensus ranking of the expected effectiveness of each treatment. This ranking process is detailed in subsequent subsections of this text.

Ultimately, the team correlated its consensus ranking with results of the highway agency survey responses to recommend specific treatments for testing in Phase II. This discussion is detailed in the subsequent sub section "Testing Program Approach."

E.2 LITERATURE REVIEW FINDINGS

E.2.1 Overall Findings

Through the literature review, the research team found a significant amount of information associated with speed characteristics and factors that affect speed. In reviewing this information, it was clear there is little quantifiable data on those factors. Of that information, there is little quantifiable data about measurable speed reduction performance at intersections in general and specifically at high-speed locations. Similarly, there is an extensive amount of information about roadway intersection safety but little direct correlation between safety and speed, especially at intersections.

There are a variety of potential speed reduction treatments used domestically and internationally. Unfortunately, there is little quantifiable data about their effectiveness. Where safety considerations or performance of a particular treatment has been documented, the role of the speed reduction of the treatment is often not clear. These apparent gaps in quantifiable information may help in prioritizing potential testing applications

It is intuitive that some speed reduction information for segments would have potential applications at intersections. Phase II testing should help identify relationships between segment speeds and intersections and how speed reduction treatments could be applied. The safety affects of speed reduction treatments at high-speed intersections will require a number of years to monitor conditions after the treatments have been implemented. Therefore, Phase II testing results will focus on quantifying speed reduction for specific treatments.

EE.2.22 Potential Speed Reduction Treatments

Considering the variety of potential speed reduction treatments, there are a variety of scenarios that will help guide the research team in developing the guidelines and testing plan. Exhibit E-1 shows a range of potential scenarios and corresponding actions that might guide development of a testing program.

Exhibit E-1 Possible Scenarios

Scenario	Potential Action
A treatment has shown to be effective at reducing speeds	• Quantify predicted speed reduction • Determine potential side effects • Identify conditions for application
A treatment has shown to be ineffective at reducing speeds	• Remove from consideration as potential speed reduction treatment recognizing it may be beneficial in other ways, such as wider longitudinal striping improve visibility
A treatment lacks documentation on its potential effectiveness	• Consider the potential of this treatment to reduce speed • If potential is high, consider for testing
An agency intends on implementing a treatment with unknown effectiveness	• Consider this agency as a possible testing candidate • Document findings

E.2.33 Research Team Treatment Ranking

The research team rated and ranked each prospective treatment as a first step in prioritizing treatments for testing in Phase II. Upon clarifying some base assumptions for some of the treatments, the research team created simple, qualitative ranking criteria that included: expected speed reduction effectiveness, ease of implementation, and low side effect potential.

Expected speed reduction effectiveness considered anticipated speed reduction and not the expected safety benefits associated with treatments. The *ease of implementation* criterion was meant to encompass only construction and design efforts of a particular treatment. *Low side effect* potential included maintenance requirements and negative impacts to safety, multimodal users, or the roadway environment that could result from a particular treatment.

The research team recognized the criteria varied in level of importance for these ranking purposes; therefore, weights were applied to the criteria. Expected speed reduction effectiveness received 60 percent of the weight, low side effects received 30 percent of the weight, and ease of implementation received 10 percent of the weight. The team recognized these values were subjective. However considering the lack of published data on the speed reduction of potential treatments, the team prioritized the treatments to test their actual effectiveness at reducing speeds. The research team understood that ease of implementation is an important consideration; however, easy-to-implement treatments such as wider longitudinal striping have little to no published speed reduction qualities.

Each team member ranked the treatments, based on his or her professional experience and expectation for treatment effectiveness, based on the literature review results. During a work session, team members discussed their reasoning and rankings for each treatment. From these discussions, the team developed a consensus ranking of the expected effectiveness, ease of implementation, and side effects of each treatment. Exhibits E-2, E-3, and E-4 present research team consensus ranking and a summary of team comments.

Exhibit E-2 Research Team Consensus Ranking

	Weight:	**6**	**1**	**3**		
Number	**Treatment**	**Expected Speed Reduction Effectiveness**	**Ease of Implementation**	**Low Side Effect Potential**	**Un-weighted Total**	**Weighted Total**
1	Roundabouts (uncontrolled)	5	1	4	3.3	4.3
2	Speed tables (uncontrolled)	5	3	3	3.7	4.2
3	Approach reverse curvature (uncontrolled)	5	2	3	3.3	4.1
4	Rumble strips (stop)	4	4	4	4.0	4.0
5	Transverse pavement markings (stop)	3	4	4	3.7	3.4
6	Dynamic warning signs-speed (uncon.)	3	4	4	3.7	3.4
7	Splitter islands (stop)	3	3	4	3.3	3.3
8	Dynamic warning signs-conflict (uncon.)	3	3	4	3.3	3.3
9	Gateways (stop)	3	3	3	3.0	3.0
10	Dynamic warning signs-speed (stop)	2	4	4	3.3	2.8
11	Reduced lane width (uncontrolled)	3	3	2	2.7	2.7
12	Visible shoulder treatments (stop)	2	3	4	3.0	2.7
13	Visible shoulder treatments (uncontrolled)	2	3	4	3.0	2.7
14	Landscaping (uncontrolled)	2	3	4	3.0	2.7
15	Dynamic warning signs-conflict (stop)	2	3	4	3.0	2.7
16	Wider longitudinal markings (stop)	1	5	5	3.7	2.6
17	Wider longitudinal markings (uncontrolled)	1	5	5	3.7	2.6
18	Reduced lane width (stop)	2	3	3	2.7	2.4
19	Roadside design features (stop)	2	3	3	2.7	2.4
20	Roadside design features (uncontrolled)	2	3	3	2.7	2.4
21	Landscaping (stop)	1	3	4	2.7	2.1

Rating (5=best, 1=worst)

Exhibit E-3 Research Team Consensus Ranking for Stop-Controlled Approaches

Treatment	Research Team Rank	Category	Research Team Comments
Rumble Strips	1	Physical	• Potential Side Effects o Noise pollution o Maintenance issues in snow areas, such as snow plowing. o Maintenance issues with debris collection
Transverse Pavement Markings	2	Visual	• Potential Side Effects o Similar maintenance issues as conventional pavement marking, such as paint breaking up. o Potentially more maintenance needs than wider longitudinal pavement marking or other markings because these are actually being driven over by vehicles. o Can create a slick surface for motorcycles or bikes
Splitter Islands	3	Visual, Physical	• Purpose is to cause horizontal deflection
Gateways	4	Visual, Physical, Operational	• More effective if used to give the illusion of a physically constrained roadway. o Limiting the sight distance • Does this give a driver a message to slow down (signing) or does it actually scare the driver into reducing their speeds? • Possible assumptions o Physical change o Environmental change o Aesthetics o Applied to other treatments • Potential Side Effects o Narrowing roadway may be seen as a safety hazard by some agencies. o Potential distractions for drivers o Roadside safety concerns • At a stop-controlled approach the driver will already be slowing down to complete a stop, will a gateway really affect the speed profile at which they approach?
Dynamic Warning Signs – Speed	5	Visual, Operational	• If placed at the intersection, it may be too late to be effective. Therefore, advanced placement may be more effective. • Possibly used in conjunction with other treatments • Warning may only appear if certain maximum speed thresholds are exceeded • Signs that appear at specific threshold speeds would be more effective than signs that stay on continuously. • Ease of Implementation o Requires power supply for sign, radar, loop detectors o Increase in maintenance of loop detectors or other detectors.
Visible Shoulder Treatments	6	Visual	• Drivers would be less likely to notice visible shoulder treatments on higher speed facilities. • Shoulder treatments could be used to alert drivers of a change in cross section. • At a stop-controlled approach the driver will already be slowing down to complete a stop, will shoulder treatments really affect the speed profile at which they approach? • Potential Side Effects o Different colors may have different freezing and thawing effects o Potential hazard for bikes o If lane width is reduced, may be tracked by trucks and buses • Ease of Implementation o Can consist of a wide variety of projects, such as colored pavement, texture, vegetation, and rumble strips.
Dynamic Warning Signs – Conflict	7	Visual, Operational	• If a driver is already going to stop at the approach, is this treatment really necessary? • If drivers see that there are no conflicting cars present, this may encourage them to violate the stop control. • Ease of Implementation o Requires power supply for sign, radar, loop detectors o More complicated than speed monitoring signs because of loop detectors or other vehicle detectors. o Increase in maintenance of loop detectors or other detectors.
Wider Longitudinal Pavement Markings	8	Visual	• There may be other reasons that this treatment is used beyond speed reduction, such as increased visibility in general and older drivers specifically. • At a stop-controlled approach the driver will already be slowing down to complete a stop, will pavement markings really affect the speed profile at which they approach? • Potential Side Effects o Similar maintenance issues as conventional pavement marking, such as paint breaking up.
Reduced Lane Width	9	Visual, Physical, Operational	• Does this treatment provide a visual illusion of a constrained roadway or does this physically constrain the roadway? • Difference in effectiveness between major road vs. minor road • The effective width and length of reduced lane width has not been determined. • Potential Side Effects o Narrowing roadway may be seen as a safety hazard by some agencies. o Less severe at stop control approaches because the driver is already slowing down. • Ease of Implementation o Depends on the type of lane narrowing. Re-striping would be easy, but physical reduction in cross section would be more difficult. o What is easy may not be the most effective.
Roadside Design Features	10	Visual	• Assumes drivers are complying with stop control o Not as effective at stop control approach, because the driver is already slowing down to stop. o Would a driver really notice roadside features when they are concentrating on stopping? • If there are problems with control violation, this treatment could encourage compliance. • Roadside features give an overall message to the driver. • Potential Side Effects o Fixed object hazard
Landscaping	11	Visual	• At a stop-controlled approach the driver will already be slowing down to complete a stop, will landscaping really affect the speed profile at which they approach? • Potential Side Effects o Maintenance o Fixed object hazard

Exhibit E-4 Research Team Consensus Ranking for Uncontrolled and Yield Control Approaches

Treatment	Research Team Rank	Category	Research Team Comments
Roundabouts[1]	1	Physical, Operational	• Placing an object in the middle of the intersection would have a greater effect. • Where is the speed reduction taking place? Start of splitter island, R0, or R1? • Potential Side Effects o Requires a lot of right-of-way to implement o Expensive
Speed Tables	2	Visual, Physical	• No speed table applications have been found for high-speed facilities. • European example: Plateau combined with yield control. No information on effectiveness or applications. • Speed tables dictate a maximum speed due to the vertical deflection. What is the appropriate maximum speed to design for? • Potential Side Effects o Lower emergency response o Increase travel time of buses o Maintenance – drainage • Ease of Implementation o May require maintenance of traffic, such as diverting or re-routing traffic during construction.
Approach Reverse Curvature	3	Physical, Operational	• Potential Side Effects o Over tracking into the bike lane or shoulder o General safety concerns of introducing a curve into the roadway
Dynamic Warning Signs – Speed	4	Visual, Operational	• If placed at the intersection, it may be too late to be effective. Therefore, advanced placement may be more effective. • Possibly used in conjunction with other treatments • Warning may only appear if certain maximum speed thresholds are exceeded • Signs that appear at specific thresholds would be more effective than signs that stay on continuously. • Ease of Implementation o Requires power supply for sign, radar, and loop detectors o Increase in maintenance of loop detectors or other detectors.
Dynamic Warning Signs – Conflict	5	Visual, Operational	• More effective at this type of approach because it would actually caution drivers to reduce their speeds if they saw a conflicting car was present. • Ease of Implementation o Requires power supply for sign, radar, loop detectors o More complicated than speed monitoring signs o Increase in maintenance of loop detectors or other detectors.
Reduced Lane Width	6	Visual, Physical, Operational	• More effective if there is a change in roadway width at a particular roadway location, versus a continuous narrowing roadway. • More effective if the reduced lane width includes physical reduction in width, versus re-striping a narrower lane. • The effective width and length of reduced lane width has not been determined. • Potential Side Effects o Narrowing roadway may be seen as a safety hazard by some agencies. o More severe at uncontrolled approaches than stop-controlled intersections. • Ease of Implementation o Depends on the type of lane narrowing. Re-striping would be easy, but physical reduction in cross section would be more difficult. o What is easy may not be the most effective.
Visible Shoulder Treatments	7	Visual	• More effective if there is a change in roadway width at a particular roadway location, versus a continuous narrowing roadway. • Does this give a visual illusion of a constrained roadway or does this physically constrain the roadway? • Visual vs. Physical • Potential Side Effects o Different colors may have different freezing and thawing effects o Potential hazard for bikes o If lane width is reduced, may be tracked by trucks and buses
Landscaping	8	Visual	• More effective if there is a change in roadway width at a particular roadway location, versus continuous landscaping along the entire roadway. • Potential Side Effects o Maintenance o Fixed object hazard
Wider Longitudinal Pavement Markings	9	Visual	• More effective at this type of approach because there would be more time and distance to notice the striping. • There may be other reasons beyond speed reduction that this treatment is used for. Such as, increase visibility, older drivers. • Potential Side Effects o Similar maintenance issues as conventional pavement marking, such as paint breaking up.
Roadside Design Features	10	Visual	• Roadside features give an overall message to the driver. • More effective at this type of approach because the driver would have more time to become effected by the environment. • Does the size of treatment affect the effectiveness? • What are the distinguishing features between roadside features and landscaping? • Urban vs. rural environment • At what distance from the roadway are these treatments placed? o Are roadside design features as effective as shoulder treatments, when they are farther away from the roadway? • Potential Side Effects o Fixed object hazard

[1] Approaches to roundabouts are yield control.

E.2.4 Integrating State Survey Results

Cooperation with state agencies will be a critical means of implementing a successful testing program of speed reduction treatments. States that are considering testing programs can help leverage Phase II testing funding, assuming the agencies implement the treatments. The results of the survey are presented in *Chapter 2*. The survey results indicated a number of states have an expressed interest in participating in studying the effectiveness of potential treatments. Question 7 of the state agency survey allowed state agencies to share their input about what speed reduction treatments they felt were most important to be evaluated to determine a level of effectiveness. Question 11 investigated the number of states that would be interested in participating in an effectiveness evaluation of speed reduction treatments at intersection approaches to be installed in 2005. The research team integrated the information gathered from the state agency survey to determine the relationship between the interest of the states and the research team treatment ranking.

Determining the actual treatments to be tested would require ongoing coordination with the agencies. In some cases, the research team has a high interest in treatments that are of low priority to the states. Similarly, the states are interested in testing treatments that are a lower priority to the research team. The value and logic of testing treatments each group rates of high value and interest is obvious; but there can be value in considering those areas where the priority or interest is different. In situations were states are interested in testing a treatment that is a lower priority than the research team, potential testing may validate the speed reduction effectiveness of a treatment. Similarly, testing treatments that are of interest of the research team (and not the states) could provide insights about countermeasures with which the states had little experience.

Exhibit E- 5 shows the various testing objectives that may help direct the testing of potential treatments.

Exhibit E-5 Testing Objectives

Organization	Priority/interest	Testing Objectives
State Agency	High	Validate effectiveness of current state agency program.
Research Team	Low	
State Agency	High	Determine and quantify effectiveness.
Research Team	High	
State Agency	Low	Validate treatments that states may not have considered.
Research Team	High	

In Phase II, further activities would focus on confirming what types of treatments agencies plan on testing and when they plan to implement these treatments. Further coordination will help determine the number of potential test sites for each type of treatment. Depending on the number of potential test sites, the team can determine the confidence level of the results for each treatment test.

E.2.5 Comparing Treatment Priorities

Selecting potential treatments for testing considers the research team and state agency priorities and interests for implementing a treatment. The research team consensus ranking was categorized as “high” (ranked 1-4), “medium” (ranked 5-8), and “low” (ranked 9-21). These categories were developed looking at natural breaks in the weighted values for each treatment. Similarly, the research team reviewed the number of state responses for interest and priorities for implementing treatments in 2005. The state responses for a particular treatment were categorized as “high” (9-6 states), “medium” (5-4 states), and “low” (3-0 states). These categories were established by considering natural breaks in the state responses.

This exercise was not a direct comparison and served as a means of correlating the differing information to aid in prioritizing treatments. The research team considered and evaluated potential treatment rankings for their expected effectiveness at uncontrolled and stop/signal-controlled intersection approaches. The states did not make this distinction; however, the concept provides helpful guidance in recommending treatments for testing. Because of this difference in considering treatments, the dynamic warning signs fell into more than one “high”, “medium”, or “low” category. The research team ranked dynamic warning signs activated by speed and conflicting vehicles a low ranking at stop/signal-controlled approaches and a medium ranking at uncontrolled approaches

Exhibit E-6 compares the treatment type, its rating category, comments, and recommendations for testing.

Exhibit E-6 Comparing Agency and Research Team Treatment Priorities

Treatment	State Agency Usage	Research Team Estimated Effectiveness for Speed Reduction	Research Team Comments
Rumble Strips	HIGH	HIGH	• Consider testing this treatment because of the high interest by state agencies? • Considerable past research on the effectiveness of this treatment. Is this information sufficient to preclude testing? • Are states implementing this because of policy guidelines or because they want to determine their effectiveness?
Wider Longitudinal Pavement Markings	HIGH	LOW	• This treatment was ranked very low by the research team, but many states are interested in implementing this treatment. • States are using this treatment with little knowledge about its effectiveness. Therefore, testing could determine if it really is effective. • Are states implementing this treatment to reduce speeds or for other reasons, such as increasing the visibility of markings.
Reduced Lane Width	MEDIUM	LOW	• States have shown interest in implementing this treatment, but this treatment was not ranked very high by the research team. • Type of lane reduction • Re-striping • Physical change in cross section
Roundabouts	MEDIUM	HIGH	• Should roundabouts be a central focus of our study? • Roundabout projects are large and long term • Requires coordination with NCHRP 3-65 or other research. • Opportunities to coordinate with state agency contacts • Washington, Maryland, Kansas, Iowa, Arizona?
Roadside Environment	MEDIUM	LOW	• No discussion
Transverse Pavement Markings	MEDIUM	MEDIUM	• Transverse pavement markings could be applied to the shoulder or on the traveled way. • These are good treatments to test because it matches our lack of knowledge with the interest of the states
Dynamic Warning Signs activated by speed of vehicle	MEDIUM	MEDIUM*	• These are good treatments to test because it matches our lack of knowledge with the interest of the states
Visible Shoulder Treatments	MEDIUM	LOW	• No discussion
Dynamic Warning Signs activated by conflicting vehicle	LOW	MEDIUM*	• These are good treatments to test because it matches our lack of knowledge with the interest of the states
Approach Reverse Curvature	LOW	MEDIUM	• This treatment can consist of horizontal curvature on the approach or reverse horizontal curvature on the approach. • This treatment may be appropriate to test the effectiveness of applying roundabout-like treatments to conventional intersections. • This treatment may become the focus for a longer term, larger scale testing
Speed Tables	LOW	HIGH	• No states reported any plans for implementing this treatment in 2005. • This treatment was ranked high by the research team.
Splitter Islands	LOW	MEDIUM	• No states reported any plans for implementing this treatment in 2005. • This may not have been considered by states as a speed reduction treatment. • This treatment may have been categorized by states as a roundabout-like treatment.

*The research team ranked dynamic warning signs activated by speed and conflicting vehicles a LOW ranking at stop-controlled approaches and a MEDIUM ranking at uncontrolled approaches

E.2.6 Selecting Treatments for Testing

The state highway agency interest for treatment implementation in 2005 and agency opinions of treatment evaluation importance was balanced with the research team judgment to develop three testing priority groupings. Table 7 illustrates the primary, secondary, and alternative treatments that were considered for testing. The primary list includes research team and state agency “high” rankings, as depicted previously in Table 6. The secondary list includes those treatments that were ranked “medium” by the research team and state agencies. Alternatives treatments are those receiving a “low” and “medium” by either the research team or state agency.

Exhibit E-7 Priority Groupings of Treatments

	Treatment	State Agency Usage	Research Team Estimated Effectiveness for Speed Reduction	Consider For Testing
Primary	Rumble strips	HIGH	HIGH	X
	Roundabouts	MEDIUM	HIGH	X
	Speed tables	LOW	HIGH	X
	Approach reverse curvature	LOW	HIGH	X
	Wider longitudinal pavement markings	HIGH	LOW	X
Secondary	Transverse pavement markings	MEDIUM	MEDIUM	X
	Dynamic warning signs – speed	MEDIUM	MEDIUM	X
Alternative	Reduced lane width	MEDIUM	LOW	
	Visible shoulder treatments	MEDIUM	LOW	
	Roadside Environment	MEDIUM	LOW	
	Splitter islands	LOW	MEDIUM	
	Dynamic warning signs - conflicting vehicles	LOW	MEDIUM	

Priority grouping is the starting point, but final recommendations are based on additional consideration including state testing programs and state importance rankings. Finally, the research team applied its judgment to consider factors such as coordination with other research activities or prior experience. The following discussion presents considerations for primary and secondary treatments.

E.2.6.1 Rumble Strips

According to state highway agencies, rumble strips are one of the most important treatments to be evaluated for speed reduction effectiveness. The state agency survey also indicated there are nine states that have interest in implementing rumble strips for testing in 2005. The research team has a strong interest in testing this treatment based on the apparent expected performance of this treatment documented in the literature review. Therefore, the research team recommends this treatment for testing in Phase II.

E.2.6.2 Roundabouts

Because of other ongoing research on roundabouts, the research team recommends focusing the proposed research on conventional at-grade intersections. NCHRP 3-65 *Applying Roundabouts in the United States* will provide a comprehensive summary of roundabout operations and safety performance. NCHRP 3-65 has collected spot speed data at existing roundabout locations throughout the nation. The data has been collected for locations 200 feet before the entrance of the roundabout, at the entrance, and at the exits of the roundabouts. Due to the other on-going research activities the research team does not recommend testing roundabouts in Phase II. However, future research could evaluate NCHRP 3-65 speed data for opportunities to evaluate speed performance.

E.2.6.3 Speed Tables

There is extensive information and interest about speed tables and their impact on safety and speed. However, much of the information relates to segment, roadway volumes, or roadways with operating speeds less than 45 mph. There is has been no published research or testing results for speed table applications on high-speed facilities or specifically at intersection approaches. Therefore, the research team recommends future studies to explore speed table applications on lower speed facilities. With and understanding of applications on low speed facilities, future testing could consider a broader application to facilities with higher speeds.

E.2.6.4 Approach Reverse Curvature

Approach reverse curvature was not ranked high by the states as far as interest in implementation or importance for testing. However, the research team observed that many of the speed reduction principles used to design modern roundabouts (deflected paths) could be applicable to conventional intersection approaches. The FHWA publication *Roundabouts: An Informational Guide* highlighted concepts of introducing curvature to reduce approach speeds at roundabouts. These concepts could form the basis for applications at conventional intersections. Therefore, the research team recommends this treatment for testing in Phase II.

E.2.6.5 Wider Longitudinal Pavement Markings

The research team consensus ranking revealed a low interest in testing wider longitudinal pavement markings. However, six state agencies have expressed interest in implementing this type of speed reduction treatment for testing in 2005. Wider longitudinal pavement markings could have benefit in increasing the visibility of the roadway segment and intersection striping. However, there is no indication that wider markings reduce speed. Therefore, the research team does not recommend this treatment for testing in Phase II.

E.2.6.6 Transverse Pavement Markings

Transverse pavement markings were ranked high by the states as far as importance for testing this treatment. In addition, five states have expressed plans for implementing this treatment in 2005. The research team consensus ranking revealed a medium interest in testing. However, because of the high interest by the states, plans for implementing this treatment in 2005, and the results of the literature review, the research team recommends this treatment for testing in Phase II.

E.2.6.7 Dynamic Warning Signs – Speed

Dynamic warning signs activated by vehicle speed received the highest ranking by states in terms of importance and five states have expressed plans for implementing this treatment in 2005. The research team consensus revealed a medium interest in testing. Because of the high state interest and results of the literature review, the research team recommends this treatment for testing in Phase II.

E.2.7 Number of Treatments

Determining the number of treatments relies on balancing the number of potential treatments and the number of test sites per treatment. If too few treatments were tested, there would be limited quantifiable data on a variety of treatments. If too many treatments are selected, there could be insufficient resources to conduct an adequate testing plan. The number of test sites per treatment affects the validity of the testing results and the testing costs. Increasing the number of test sites per treatment increased the confidence of the test results but raises the testing budget. Testing conducted in cooperation with agency treatment implementation plans creates the best opportunity to leverage NCHRP and agency funding.

Exhibit E-8 provides a means of considering the number of treatments that can be tested within the present NCHRP funding for Phase II. The table allows a variety of “what-if” scenarios to be considered depending on the types of treatment being implemented, their relative proximity for efficient data collection, and the number of treatments selected and the number of sites tested. This planning level tool can be modified to consider the need to testing budget reserves should a supplemental testing contingency be desired to review or retest specific treatment types.

After considering the potential budget issues, it appears that three to five treatments might be able to be tested in Phase II. These numbers would be refined upon consultation with the Panel and further coordination with the state agencies implementing projects in the next year.

Exhibit E-8 Sample Testing Budget

TREATMENT TESTING BUDGET

Cost Per Test

Activity	**Time (hours)**	**Cost ($/hr)**	**Total Cost ($)**
Coordination with State Agencies	24	100	$2,400
Testing Set-up	80	100	$8,000
Conduct Testing	80	100	$8,000
Summarize Testing Results	40	100	$4,000
Final Coordination and Final Report	8	100	$800
Additional Miscellaneous Expenses			$3,000
Total Cost Per Test			**$26,200**
Number of Treatments Tested:			4
Number of Test Sites per Treatment:			3
Total Cost for Testing Plan			**$314,400**
Guidelines Preparation			**$50,000**
Finalize Testing Plan			**$15,000**
Total Cost of Phase II			**$379,400**
Estimated Budget for Phase II			***$392,199***

APPENDIX F

Appendix F Histograms of Speed Profile Data at 10 Sites

This appendix provides a series of 14 exhibits, one for each intersection approach discussed in the speed profile analysis. In each exhibit, speed data are summarized in the form of a histogram for each approach location (A through D) and data collection period (before and after) combination. The exhibits generally consist of a set of 2 x 4 panels—2 columns representing before and after data collection periods; 4 rows representing Locations A through D. In some instances, fewer locations are available (e.g., Exhibits F-3 and F-13); in other instances, a histogram may be further subdivided by approach lane (e.g., Exhibit F-9). When an individual panel is empty (e.g., Exhibit F-10), either no speed data were available that match the time window or no data were originally collected at that location in that lane.

The physical layout of each exhibit allows for direct before-after comparison, as well as the comparison of speed profiles along an approach from Location D to Location A (i.e., toward the intersection) for each data collection period. The inset in each histogram provides basic descriptive statistics (number of vehicles; minimum, mean, and maximum speeds; and speed standard deviation). A vertical dashed gray line is drawn at the posted speed limit of each approach. The curve of a normal distribution (blue dashed line) with sample mean speed and sample standard deviation speed is superimposed on each histogram.

The speed histograms illustrate the following features of the data:

- For a given time period, the reduction in mean speeds along the approach
- For a given location, the shape of the speed data distribution: approximately normal; skewed in one direction; long tails in one or both directions; or bimodal
- Changes in the dispersion of the speed measurements across data collection periods

Bimodal data, represented by two distinct peaks on a histogram, is indicative of two driver populations—one driving straight through the intersection and another, perhaps turning. This occurs at Location A for many intersection approaches.

Speed measurements summarized in the histograms for each data collection period separately (before or after) are from approximately the same vehicles passing through the measurement locations.

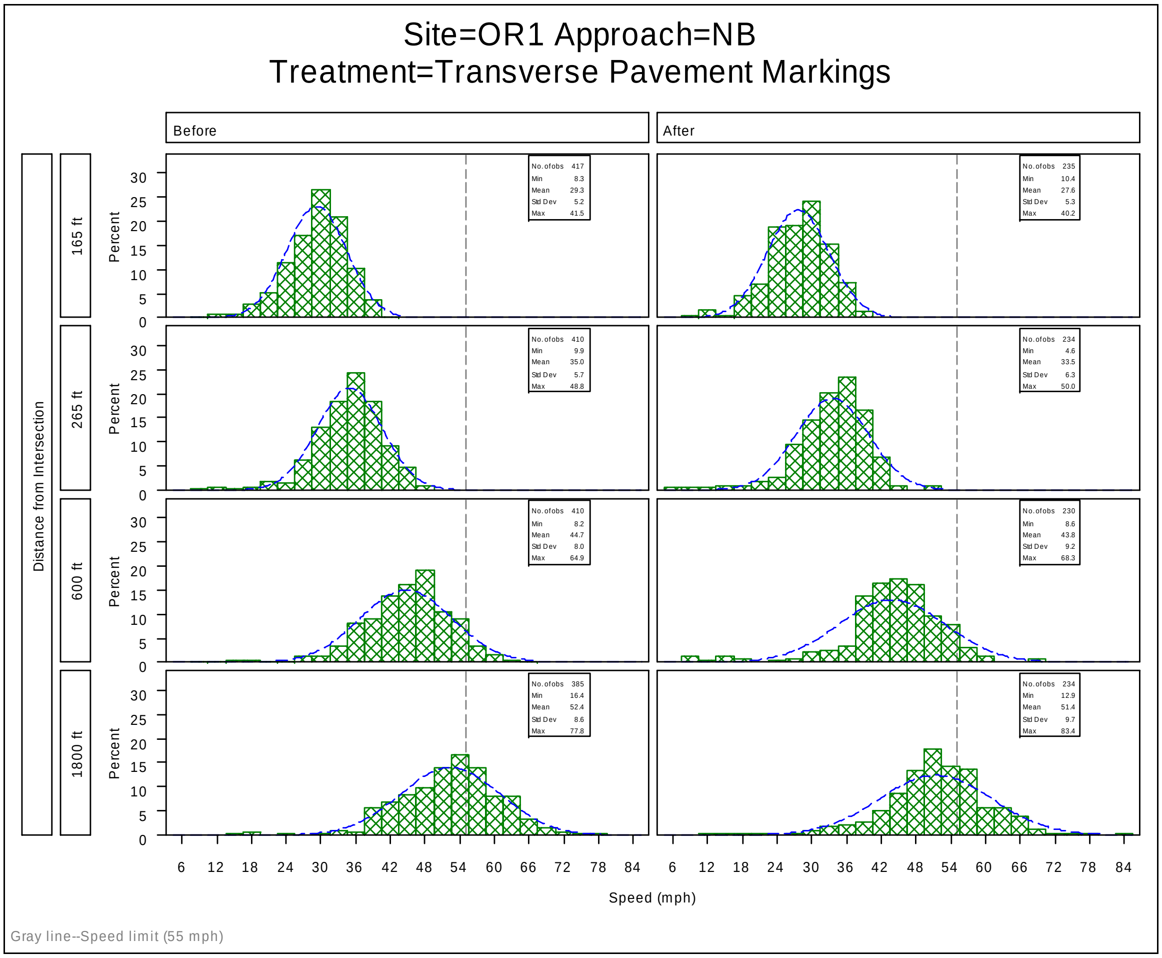

Exhibit F-1 Distribution of Speeds by Data Collection Period and Location for OR1 Northbound

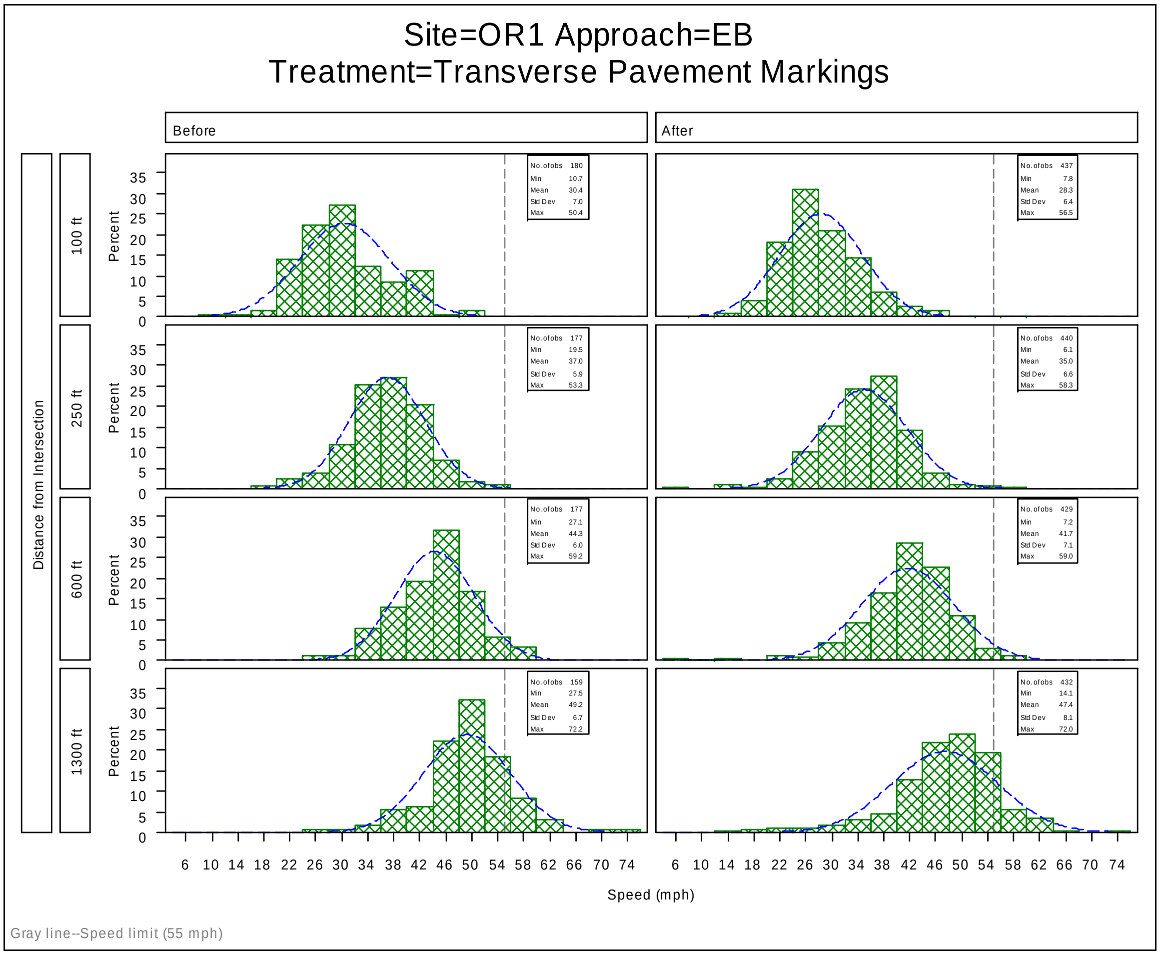

Exhibit F-2 Distribution of Speeds by Data Collection Period and Location for OR1 Eastbound

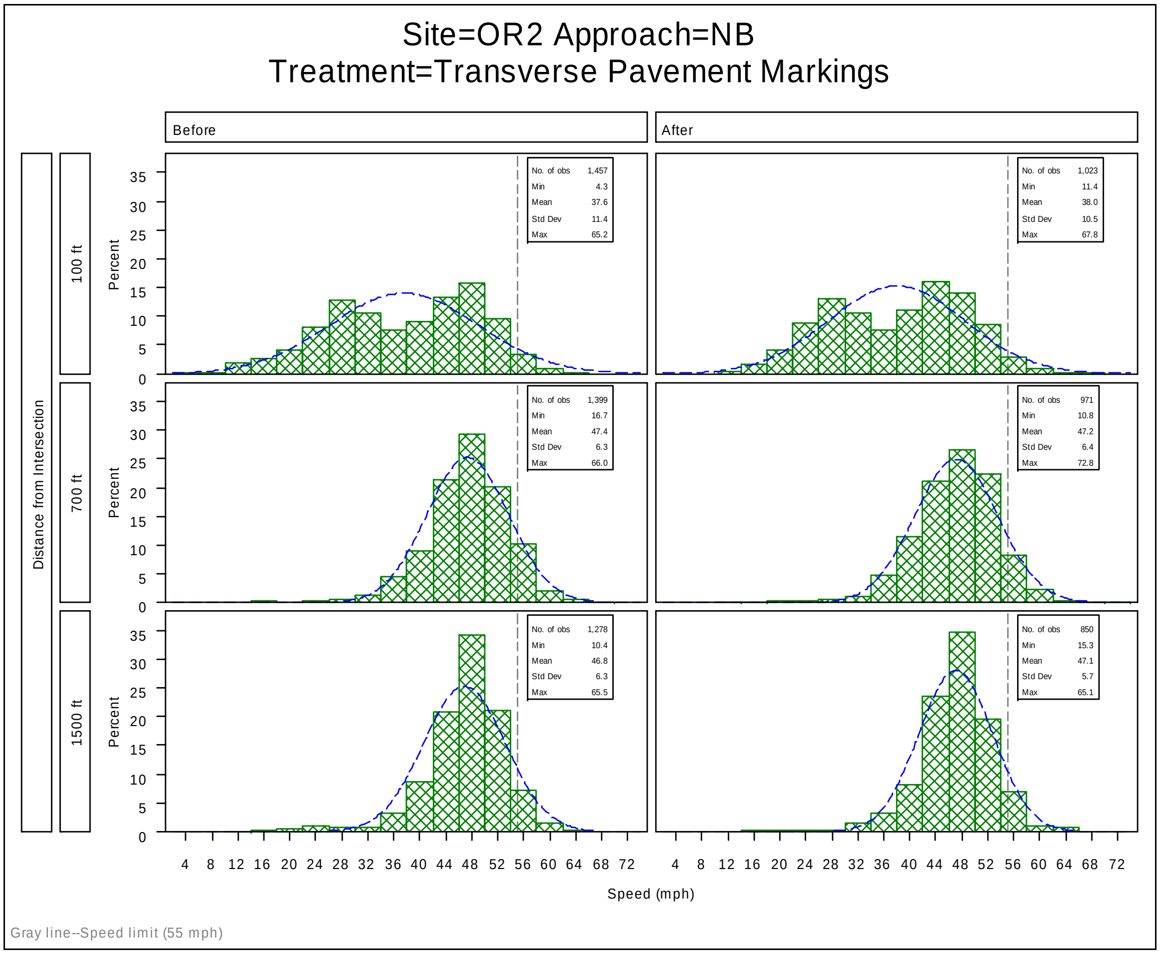

Exhibit F-3 Distribution of Speeds by Data Collection Period and Location for OR2 Northbound

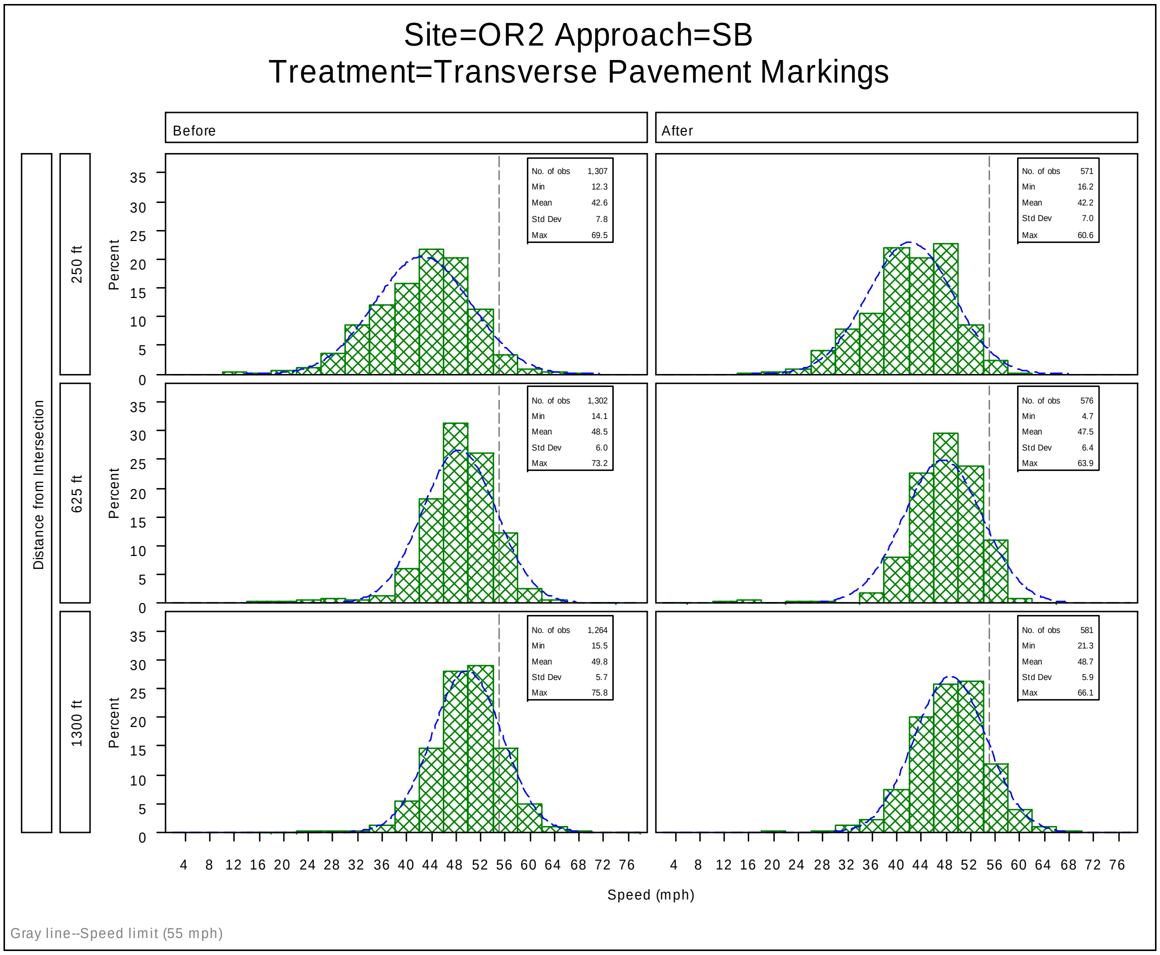

Exhibit F-4 Distribution of Speeds by Data Collection Period and Location for OR2 Southbound

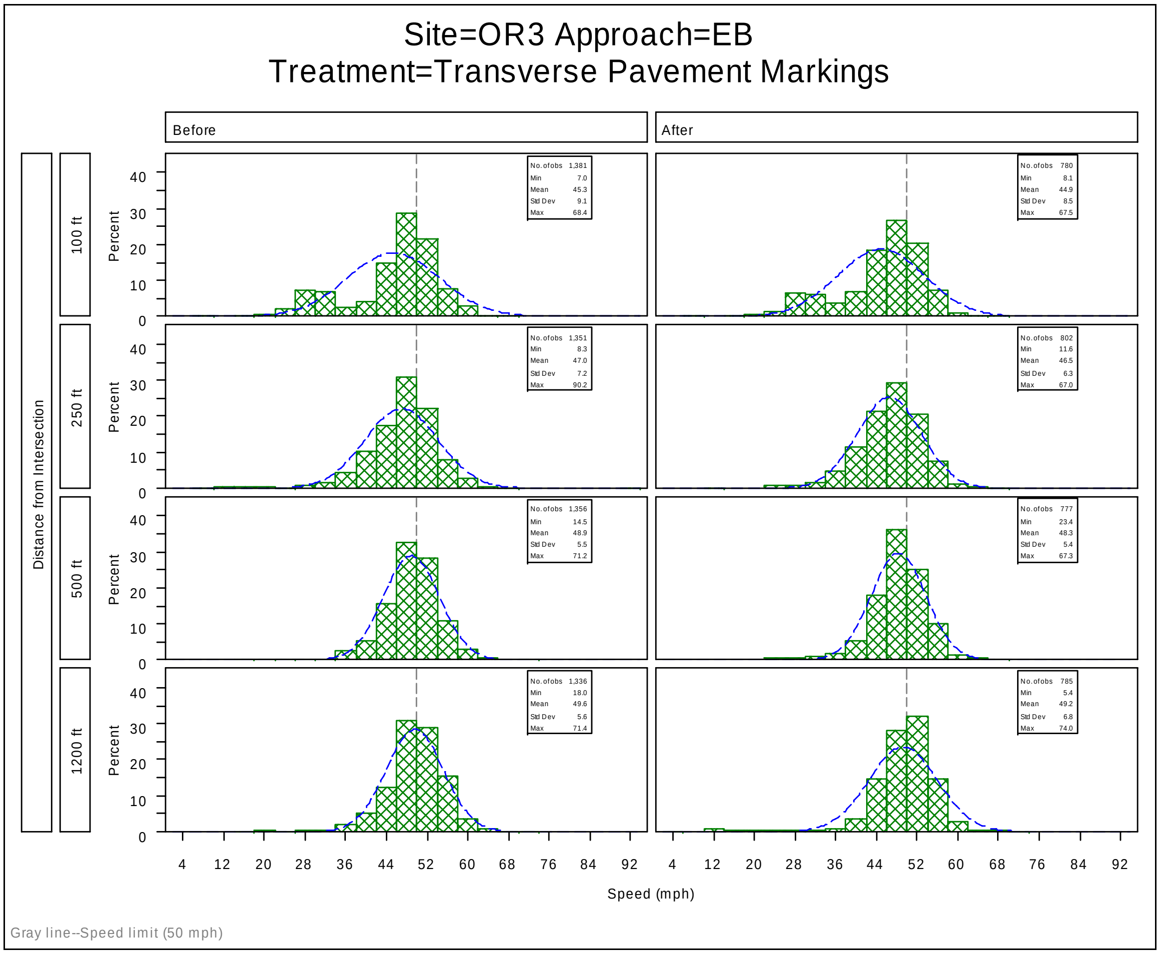

Exhibit F-5 Distribution of Speeds by Data Collection Period and Location for OR3 Eastbound

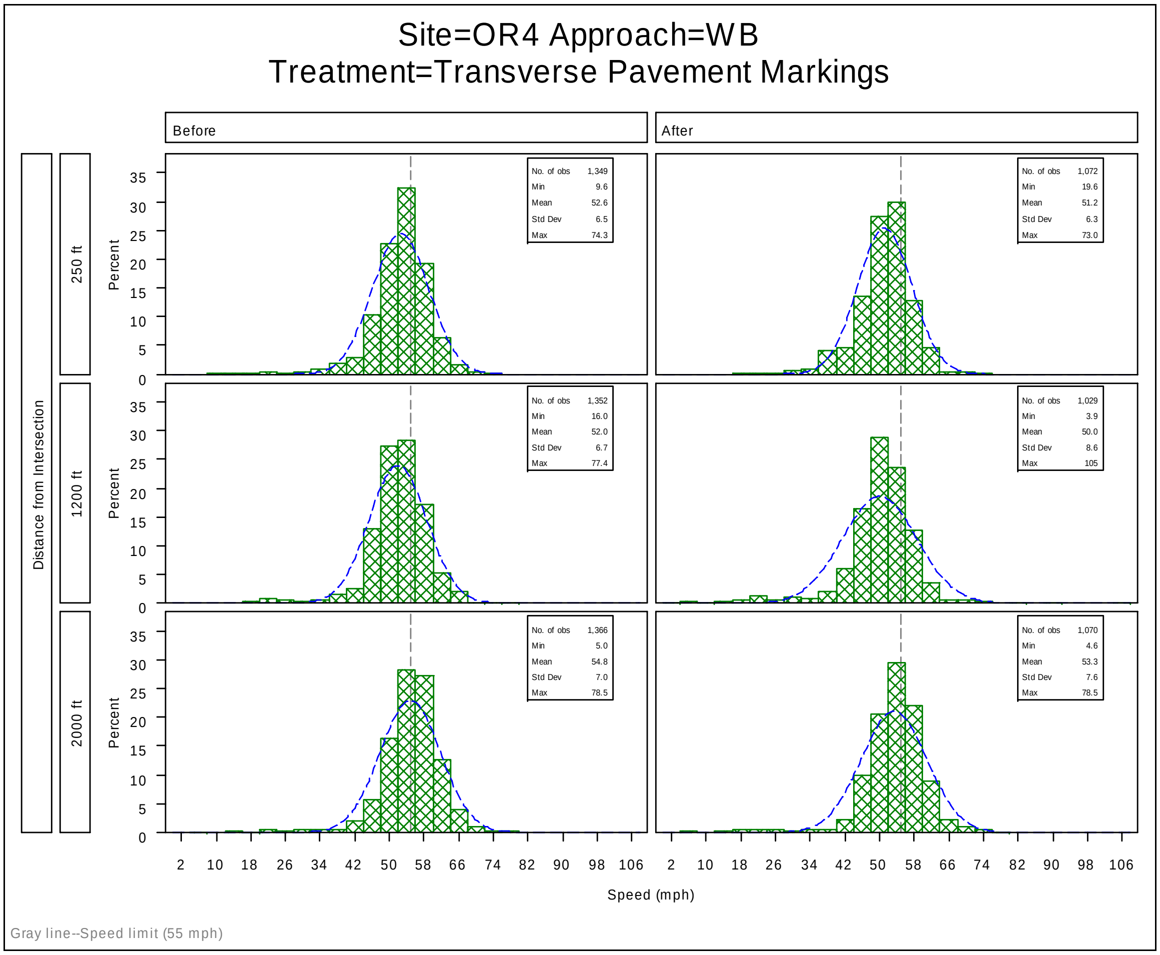

Exhibit F-6 Distribution of Speeds by Data Collection Period and Location for OR4 Westbound

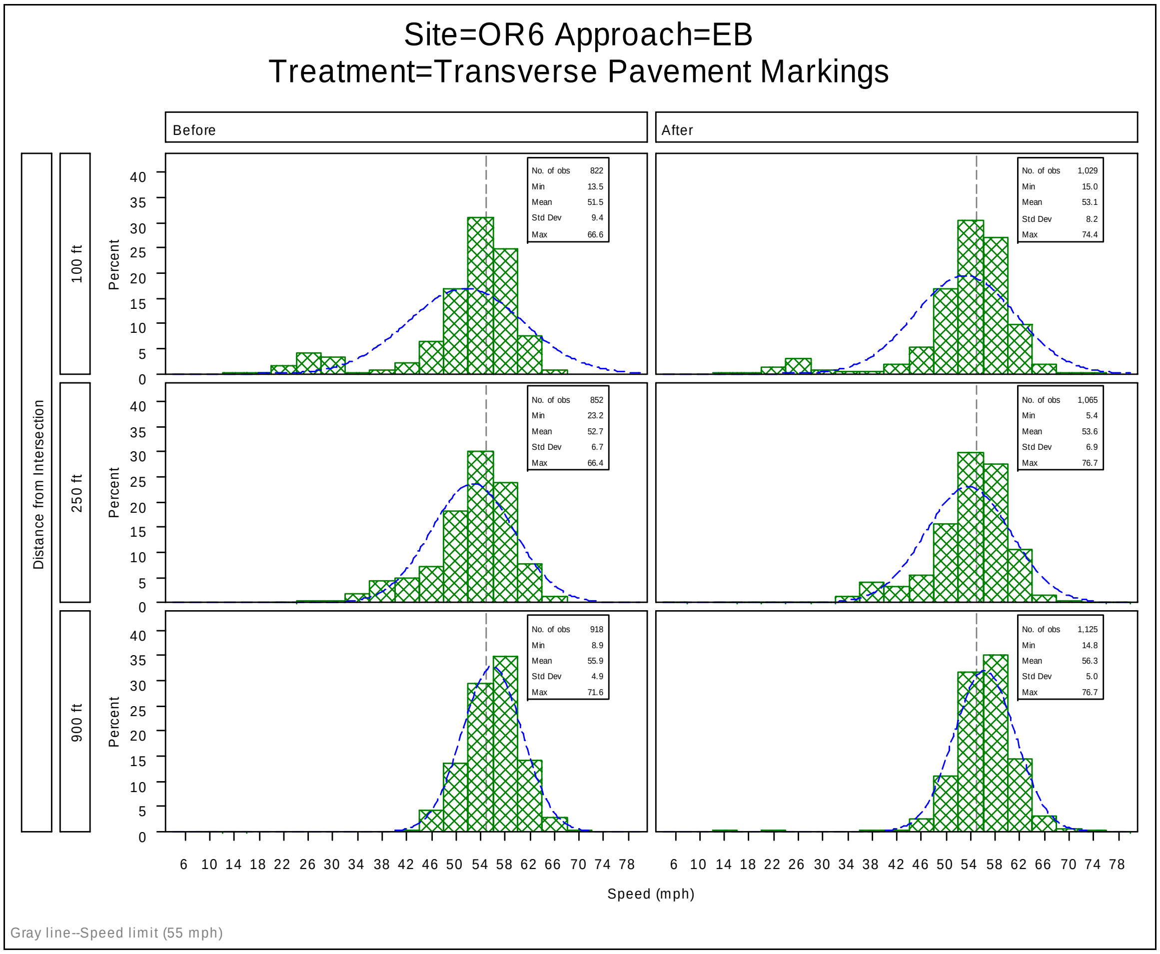

Exhibit F-7 Distribution of Speeds by Data Collection Period and Location for OR6 Eastbound

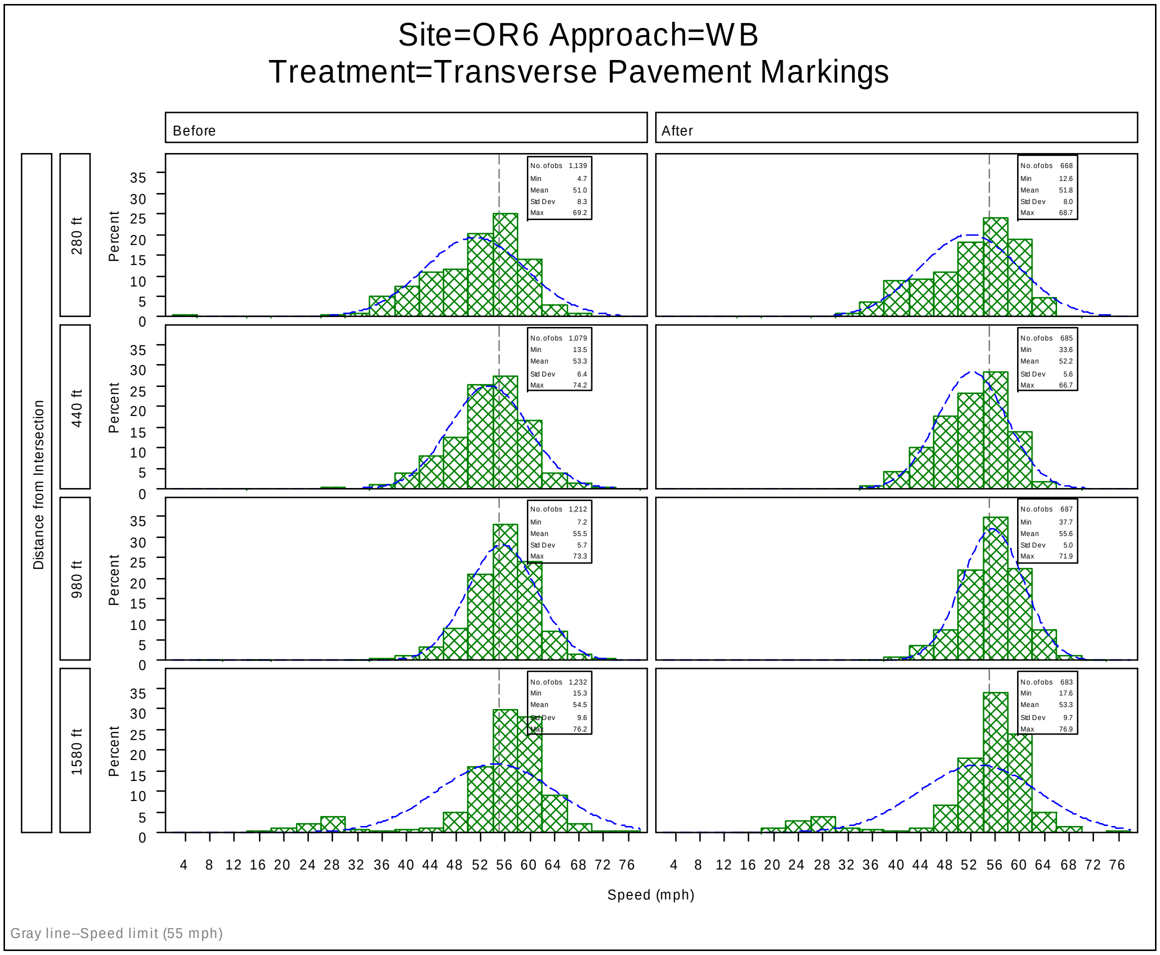

Exhibit F-8 Distribution of Speeds by Data Collection Period and Location for OR6 Westbound

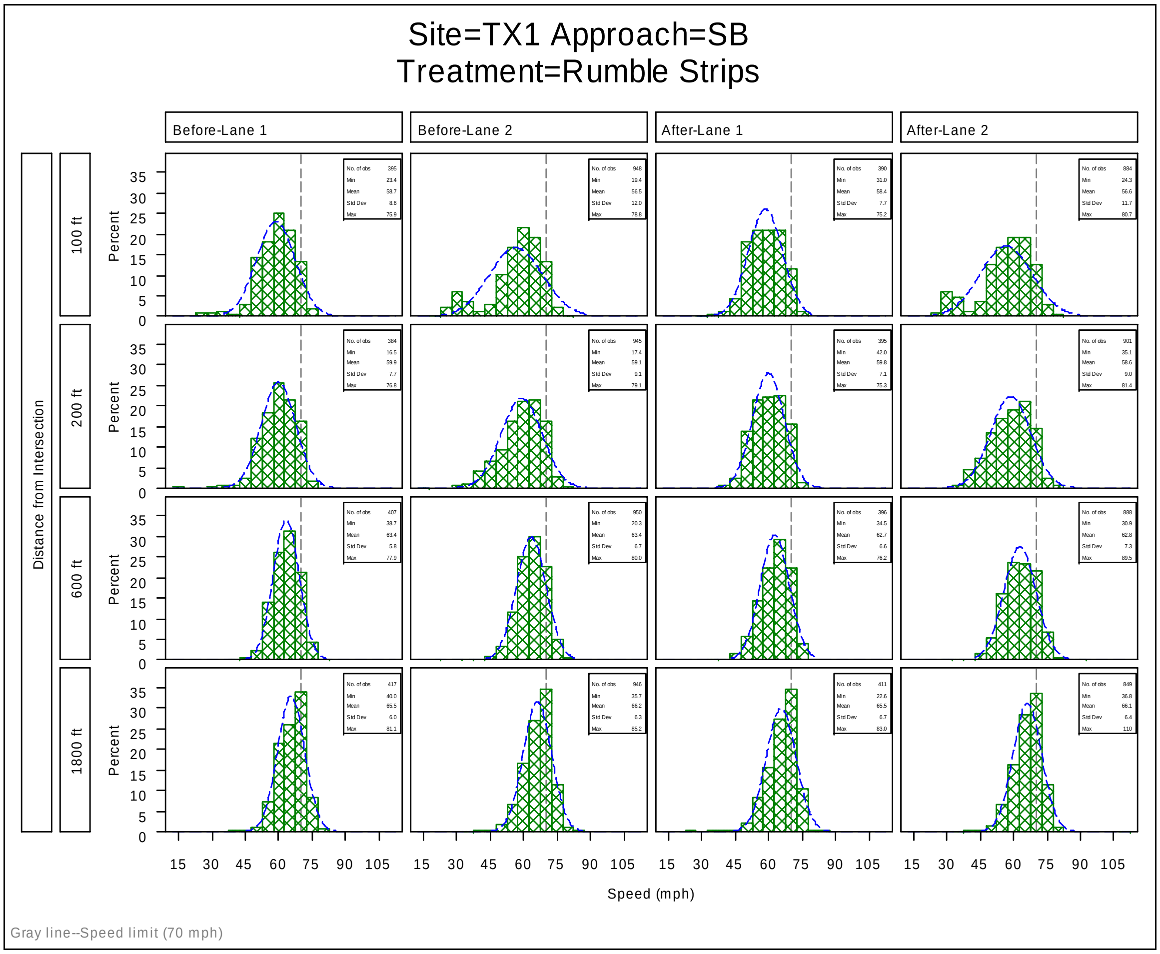

Exhibit F-9 Distribution of Speeds by Data Collection Period and Location for TX1 Southbound

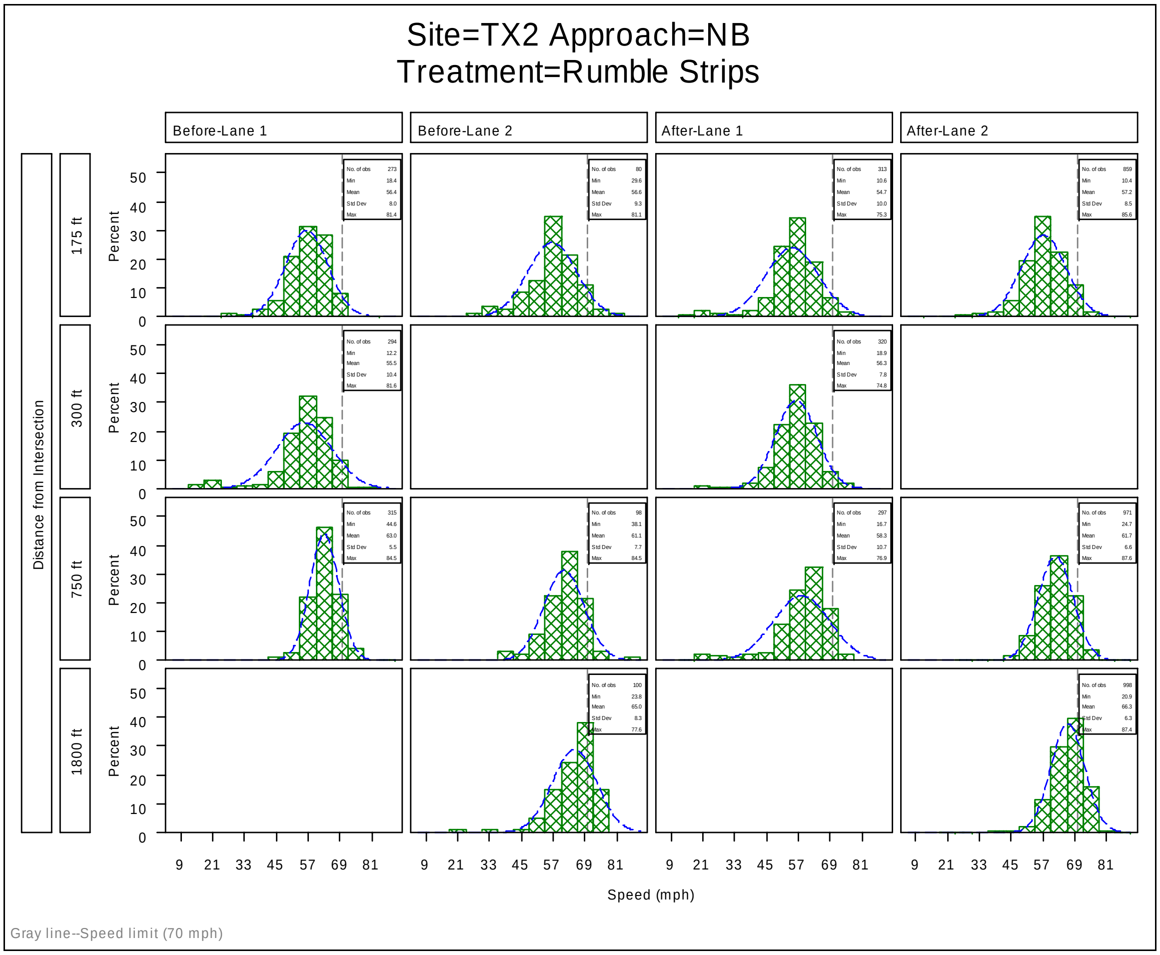

Exhibit F-10 **Distribution of Speeds by Data Collection Period and Location for TX2 Northbound**

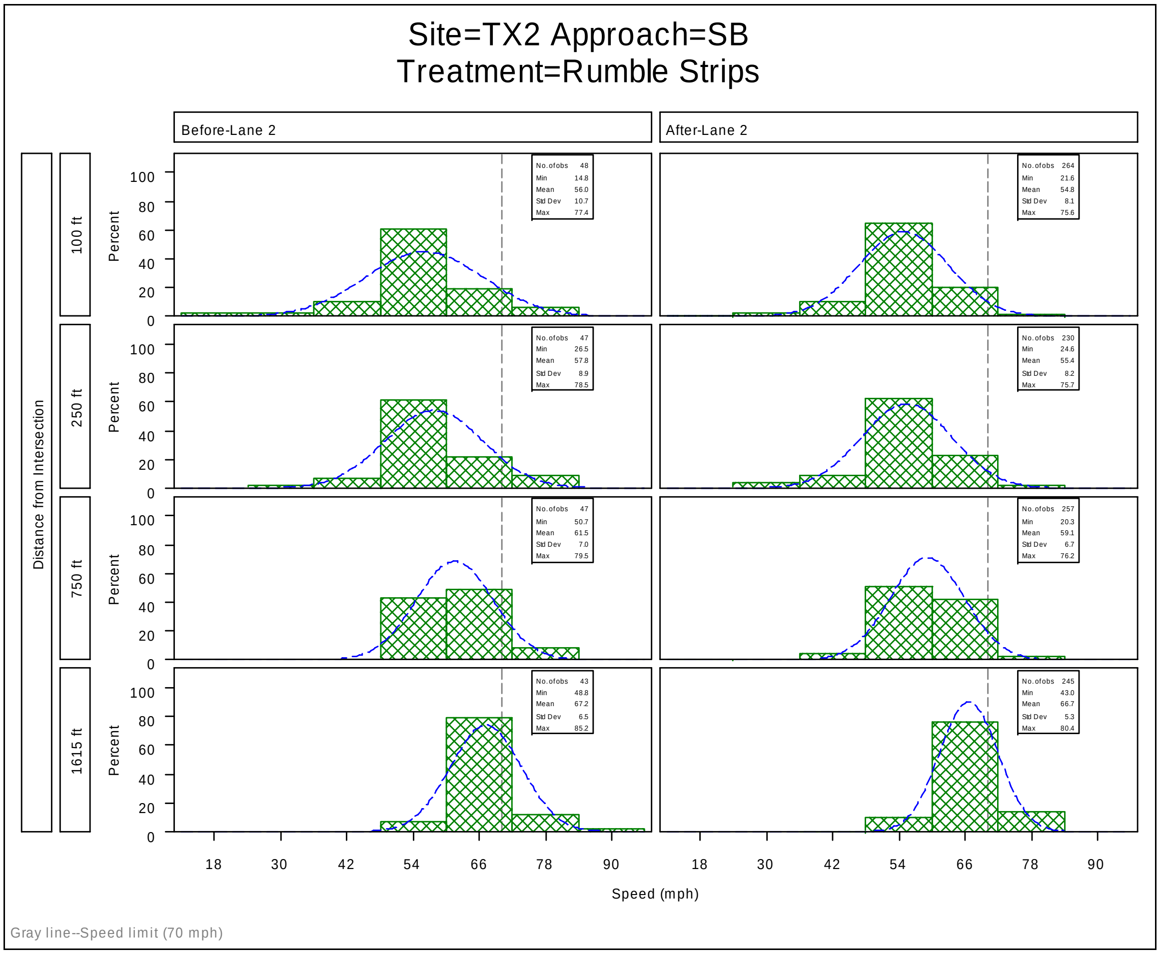

Exhibit F-11 **Distribution of Speeds by Data Collection Period and Location for TX2 Southbound**

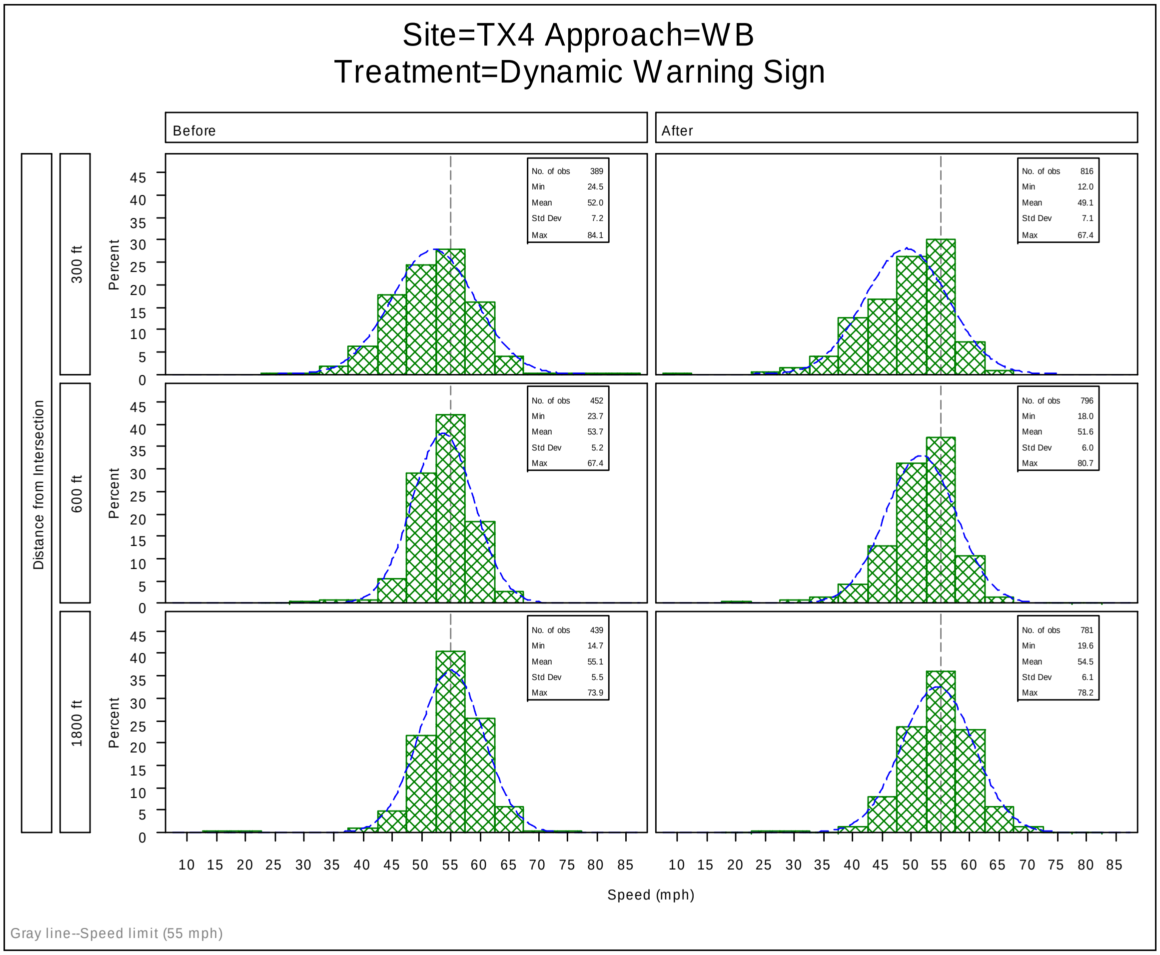

Exhibit F-12 **Distribution of Speeds by Data Collection Period and Location for TX4 Westbound**

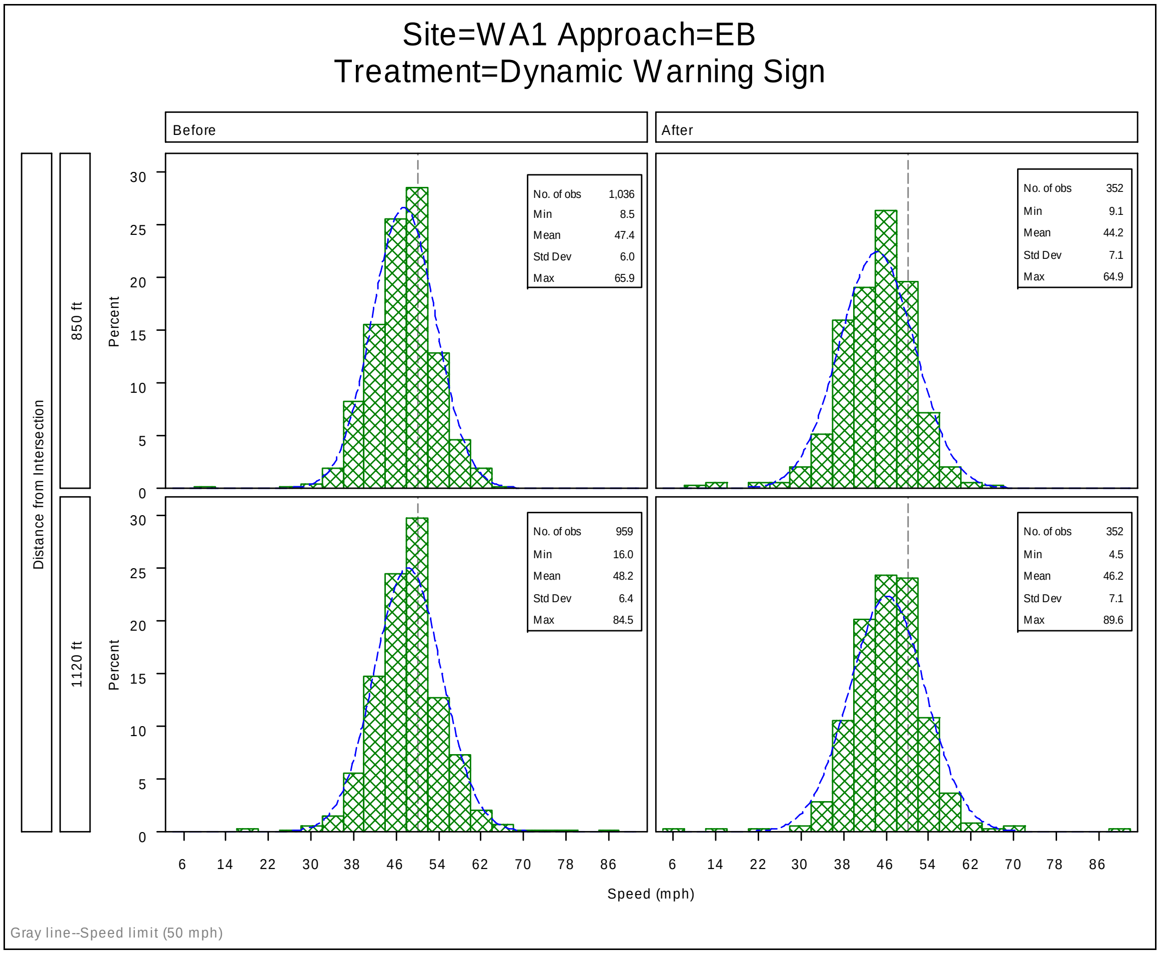

Exhibit F-13 **Distribution of Speeds by Data Collection Period and Location for WA1 Eastbound**

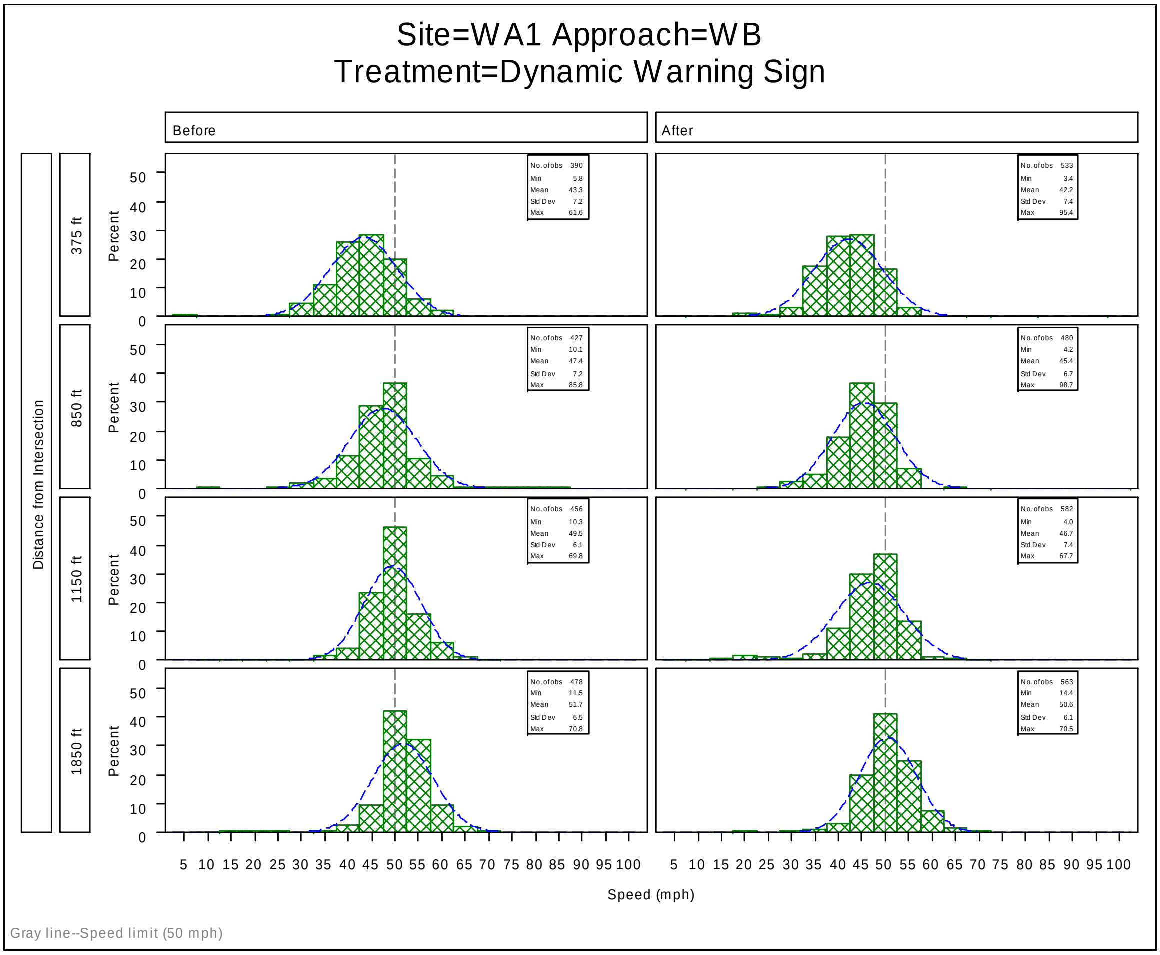

Exhibit F-14 **Distribution of Speeds by Data Collection Period and Location for WA1 Westbound**

APPENDIX G

Appendix G Speed Analysis by Individual Approach LLocation (Step 1 Analysis))

This appendix presents descriptive summaries and before-after speed comparisons for the individual data collection locations (A through D) at each intersection approach. The data analyzed here are all valid data collected at each location. No attempt was made to match vehicles driving through all locations within a given time period at a particular approach. Direct comparisons between locations (i.e., profile studies) are not warranted for this dataset as they would not compare the same driver populations. This is in contrast to the comparisons presented in Chapter 5 of the report where speed profiles across locations along an intersection approach were considered. There, great care was taken to consider only those data collection periods during which all traffic classifiers on an intersection approach (Locations A, B, C, and D) were collecting speed data. This permitted the general assumption that the same vehicles traversed all four data collection locations and that the population of vehicles at Location D were generally the same as the population of vehicles at the other locations.

The speed reduction at an individual location was determined by comparing the speed data at an individual location before and after treatment installation. This comparison approach is perhaps less meaningful than those presented in the report because it estimates the effectiveness of the treatment only at a specific point along the intersection approach. The results do not provide information about speed reduction at any other point along that intersection approach; thus, no information is provided about the treatment's effect on the overall speed profile. However, the examination of individual location speed data and their before-after comparisons presents some insight into all the data as they were collected.

Exhibit G-1 presents basic descriptive summaries of the speed data collected at each location by intersection approach, separately for the before and after treatment periods. Descriptive summaries are:

- number of measurements (clearly different between the two collection periods)
- speed range (i.e., minimum and maximum speeds)
- mean, median, and 85th percentile speeds
- speed standard deviation

Exhibit G-2 summarizes the statistical comparisons of before and after speeds for each location. The normality of the speed data was first assessed visually to assess obvious departures from normality (e.g., severely skewed data, bimodal data). The next step was to compare speed variances using the modified Levene's test of homogeneity of variance. Based on the results of the normality assessment and the equality of variance test, the statistical approach used for comparing the center (e.g., mean, median) of the speed values for the before and after data collection periods is:

- Normally-distributed speed data and equal variances: a two-sample t-test with pooled variance

- Normally-distributed speed data and unequal variances: a two-sample t-test with weighted variance (with Satterthwaite's approximation of degrees of freedom [df])
- Non normally-distributed (skewed or bimodal) speed data (no test of equal variance is needed): a Wilcoxon rank-sum test

Each line in Exhibit G-2 presents the test results pertaining to the before-after speed comparison at a particular approach location. The individual columns are organized as follows:

- Columns 1, 2, and 3: Physical location
- Column 4 notes whether the speed data appear normally distributed
- Columns 5 through 7 address the issue of equal variance:
    - Column 5 shows the ratio of the after to before speed standard deviation
    - Column 6 shows the F-test statistic and its degrees of freedom (the omitted df is always 1)
    - Column 7 shows the p-value associated with the equality of variance test. A p-value of 0.05 or less indicates significance at the 5-percent significance level (row with p-value highlighted in yellow and bold).
- Columns 8 through 12 provide the comparison results of the after speed data to the before speed data; thus, a negative mean or median speed difference indicates a decrease from the before to the after period:
    - Column 8 shows the mean speed difference
    - Column 9 shown the median speed difference
    - Column 10 indicates which comparison test was used in accordance with the steps explained earlier
    - Column 11 shows the test statistic (either t-test or Wilcoxon rank sum test in accordance with Column 10 results) and its degrees of freedom

The last column indicates the statistical significance level of the test statistic. A p-value of 0.05 or less indicates significance at the 5-percent significance level (row highlighted in yellow).

Mean and median differences are provided in all cases; however, the statistical test to assess whether the treatment installation had an effect on speed pertains to comparing either the means or the medians. Therefore, median differences were grayed out when mean differences are the appropriate speed statistics, and vice versa.

Some observations based on Exhibit G-2 follow:

- Of the 51 before-after speed comparisons made at individual intersection-approach locations, 40 were based on mean speed comparisons and 11 were based on median speed comparisons.
- Of the 51 comparisons, 34 were statistically significant at the 5-percent level (including a p-value of 0.051) with the following breakdown by location:
    - 8 at Location A (closest to intersection)
    - 10 at Location B
    - 10 at Location C
    - 6 at Location D
- The center of the speed values (mean or median) shifted from an increase of 1.8 mph to a decrease of 8.7 mph from before to after treatment installation. It should be noted that the decrease of 8.7 mph (Location A at WA1 eastbound) is an anomaly. The next largest decrease is 3.2 mph.

Exhibit G-1 Descriptive Statistics

			Before Speed (mph)						After Speed (mph)					
Site	**Approach**	**Location**	**Number of Measurements**	**Speed Range Minimum-Maximum**	**Mean**	**Median**	**85th Percentile**	**Standard Deviation**	**Number of Measurements**	**Speed Range Minimum-Maximum**	**Mean**	**Median**	**85th Percentile**	**Standard Deviation**
OR1	NB	A	426	8.3 - 41.5	29.3	29.8	34.2	5.2	235	10.4 - 40.2	27.6	28.1	32.9	5.4
		B	419	9.9 - 48.8	35.0	35.2	40.4	5.6	234	4.6 - 50.0	33.5	34.4	39.4	6.3
		C	419	8.2 - 64.9	44.7	45.3	52.3	8.0	230	8.6 - 68.3	43.8	44.5	52.1	9.2
		D	385	16.4 - 77.8	52.4	53.1	61.2	8.6	234	12.9 - 83.4	51.4	51.9	59.5	9.7
	EB	A	679	10.7 - 55.0	30.6	29.9	37.6	6.6	439	7.8 - 56.5	28.3	27.4	34.6	6.4
		B	675	12.7 - 57.6	37.1	37.2	42.3	5.6	443	6.1 - 58.3	35.0	35.5	40.8	6.6
		C	677	12.1 - 63.3	44.7	44.9	50.3	5.9	429	7.2 - 59.0	41.7	42.4	48.1	7.1
		D	159	27.5 - 72.2	49.2	49.4	55.5	6.7	432	14.1 - 72.0	47.4	48.5	54.1	8.1
OR2	NB	A	1,457	4.3 - 65.2	37.6	38.8	49.6	11.4	1,023	11.4 - 67.8	38.0	39.5	49.2	10.5
		C	1,399	16.7 - 66.0	47.4	47.7	53.7	6.3	971	10.8 - 72.8	47.2	47.5	53.0	6.4
		D	1,278	10.4 - 65.5	46.8	47.5	52.4	6.3	850	15.3 - 65.1	47.1	47.5	52.1	5.7
	SB	A	493	17.2 - 70.0	42.0	43.7	51.1	9.3	572	13.4 - 60.5	40.2	41.5	48.7	8.7
		B	1,432	12.3 - 69.5	42.6	43.6	50.1	7.9	770	16.1 - 60.6	42.1	42.7	49.1	7.2
		C	1,322	14.1 - 73.2	48.5	48.8	54.0	6.0	769	4.7 - 66.2	47.7	48.2	53.5	6.2
		D	1,308	15.5 - 75.8	49.8	50.0	55.1	5.7	770	21.3 - 70.0	49.0	49.2	54.9	5.9
OR3	EB	A	1,381	7.0 - 68.4	45.3	47.7	53.1	9.1	780	8.1 - 67.5	44.9	46.9	52.3	8.5
		B	1,352	8.3 - 90.2	46.9	47.9	53.0	7.2	1,183	6.6 - 68.1	46.2	47.0	52.4	6.7
		C	1,356	14.5 - 71.2	48.9	49.1	54.0	5.5	1,131	8.6 - 68.1	48.2	48.5	53.3	5.5
		D	1,336	18.0 - 71.4	49.6	49.8	54.6	5.6	1,097	5.4 - 74.0	49.3	49.9	54.6	6.4

			Before Speed (mph)						**After Speed (mph)**					
Site	**Approach**	**Location**	**Number of Measurements**	**Speed Range Minimum-Maximum**	**Mean**	**Median**	**85th Percentile**	**Standard Deviations**	**Number of Measurements**	**Speed Range Minimum-Maximum**	**Mean**	**Median**	**85th Percentile**	**Speed Range Minimum-Maximum**
OR4	WB	B	1,349	9.6 - 74.3	52.6	53.3	58.2	6.5	1,072	19.6 - 73.0	51.2	51.8	56.7	6.3
		C	1,352	16.0 - 77.4	52.0	52.4	57.5	6.7	1,443	3.9 - 105.0	50.6	51.4	57.0	8.2
		D	1,366	5.0 - 78.5	54.8	55.4	60.5	7.0	1,480	4.6 - 78.5	53.6	54.4	59.7	7.5
OR6	EB	A	822	13.5 - 66.6	51.5	54.0	58.5	9.4	1,029	15.0 - 74.4	53.1	54.7	59.0	8.2
		B	852	23.2 - 66.4	52.7	54.1	58.6	6.8	1,065	5.4 - 76.7	53.6	54.8	59.3	6.9
		C	918	8.9 - 71.6	55.9	56.2	60.4	4.9	1,126	14.8 - 76.7	56.3	56.4	60.6	5.0
	WB	A	1,139	4.7 - 69.2	51.0	52.9	58.6	8.3	668	12.6 - 68.7	51.8	53.6	59.8	8.0
		B	1,079	13.5 - 74.2	53.3	54.0	59.4	6.4	759	33.6 - 66.7	52.2	53.0	58.0	5.7
		C	1,212	7.2 - 73.3	55.5	55.9	60.4	5.7	762	37.7 - 71.9	55.5	55.7	60.1	4.9
		D	1,232	15.3 - 76.2	54.5	56.6	61.4	9.6	821	17.6 - 76.9	53.5	55.6	60.0	9.5
TX1	SB	A	1,684	19.0 - 78.8	57.5	59.2	67.6	10.6	1,670	20.1 - 80.7	57.4	58.7	67.4	10.2
		B	1,329	16.5 - 79.1	59.4	60.4	68.3	8.6	1,842	33.5 - 81.4	58.9	59.6	67.9	8.5
		C	1,692	20.1 - 80.0	63.3	63.7	69.8	6.5	1,828	13.2 - 89.5	62.6	62.9	70.2	7.3
		D	1,721	35.6 - 85.2	65.9	66.7	71.8	6.3	1,404	22.6 - 110.0	65.9	66.9	71.9	6.5
TX2	NB	A	660	10.1 - 81.4	54.8	56.2	63.4	10.3	1,588	10.4 - 104.6	56.3	57.0	63.9	9.2
		B	795	12.2 - 81.8	55.8	56.9	63.4	9.0	356	18.9 - 74.8	56.5	57.0	63.6	7.9
		C	1,112	14.4 - 84.5	60.1	60.7	67.2	7.6	1,806	16.7 - 93.8	60.5	61.6	67.9	8.5
		D	342	22.0 - 82.1	64.9	65.7	71.4	7.3	998	20.9 - 87.4	66.3	67.0	72.1	6.3
	SB	A	575	10.3 - 80.9	54.9	56.0	63.3	10.0	1,077	15.2 - 76.6	54.3	55.6	63.1	10.4
		B	295	13.6 - 78.5	53.8	55.2	62.3	10.3	290	24.6 - 77.9	55.6	56.4	62.1	8.3
		C	741	10.8 - 87.6	58.7	58.8	65.4	7.3	1,450	15.3 - 97.1	58.8	59.0	66.2	8.1

Site	Approach	Location	Before Speed (mph)						After Speed (mph)					
			Number of Measurements	Speed Range Minimum-Maximum	Mean	Median	85th Percentile	Standard Deviation	Number of Measurements	Speed Range Minimum-Maximum	Mean	Median	85th Percentile	Standard Deviation
		D	832	10.6 - 96.4	66.2	67.4	71.9	7.7	1,160	21.6 - 105.3	66.3	67.2	71.6	6.5
TX4	WB	B	432	24.5 - 84.1	52.0	52.4	58.4	7.3	816	12.0 - 67.4	49.1	50.5	55.9	7.1
		C	1,029	23.7 - 71.6	53.6	53.9	58.6	5.4	796	18.0 - 80.7	51.6	52.4	56.9	6.0
		D	439	14.7 - 73.9	55.1	55.3	60.4	5.5	781	19.6 - 78.2	54.5	54.7	60.3	6.1
WA1	EB	A	557	16.5 - 65.3	42.4	43.4	50.6	8.3	99	6.2 - 53.7	34.8	34.7	44.0	9.4
		B	1,036	8.5 - 65.9	47.4	47.8	53.2	6.0	352	9.1 - 64.9	44.2	44.9	51.0	7.1
		C	959	16.0 - 84.5	48.2	48.4	53.7	6.4	614	4.5 - 89.6	45.3	46.0	51.9	7.7
	WB	A	793	4.6 - 62.4	43.1	43.3	50.3	7.3	855	3.4 - 95.4	42.3	42.4	49.0	7.0
		B	836	10.1 - 94.1	47.5	47.5	52.9	7.6	480	4.2 - 98.7	45.4	46.0	50.9	6.7
		C	539	10.3 - 69.8	49.5	49.6	54.6	6.1	879	4.0 - 68.3	47.0	47.8	52.4	7.0
		D	564	11.5 - 70.8	51.8	51.8	56.8	6.2	563	14.4 - 70.5	50.6	50.6	56.0	6.1

Exhibit G-2 Analysis by Location

Site	Approach	Location	Distribution Normal?	After/Before Std Dev	F-statistic (df)	P-Value	Mean Difference (mph)	Median Difference (mph)	Selected test	T-statistic (df)	P-Value
OR1	NB	A	Yes	0.96	0.77 (659)	0.382	-1.7	-1.7	Equal var. t-test	3.90 (659)	<.001
		B	Yes	0.89	1.19 (651)	0.275	-1.4	-0.8	Equal var. t-test	2.98 (651)	0.003
		C	Yes	0.87	0.66 (647)	0.416	-0.9	-0.8	Equal var. t-test	1.30 (647)	0.194
		D	Yes	0.89	0.39 (617)	0.534	-1.0	-1.2	Equal var. t-test	1.29 (617)	0.197
	EB	A	Yes	1.03	1.87 (1,116)	0.172	-2.3	-2.5	Equal var. t-test	5.84 (1,116)	<.001
		B	Yes	0.84	7.44 (1,116)	0.006	-2.1	-1.7	Unequal var. t-test	5.64 (833)	<.001
		C	Yes	0.83	6.29 (1,104)	0.012	-3.0	-2.4	Unequal var. t-test	7.18 (787)	<.001
		D	Yes	0.83	3.20 (589)	0.074	-1.8	-1.0	Equal var. t-test	2.53 (589)	0.012
OR2	NB	A	No	1.09	10.96 (2,478)	<.001	0.4	0.7	Wilcoxon rank sum test	0.66 (2,478)	0.509
		C	Yes	0.99	0.01 (2,368)	0.905	-0.2	-0.2	Equal var. t-test	0.79 (2,368)	0.427
		D	Yes	1.11	1.30 (2,126)	0.254	0.2	0.0	Equal var. t-test	-0.89 (2,126)	0.374
	SB	A	No	1.08	3.90 (1,063)	0.049	-1.8	-2.2	Wilcoxon rank sum test	3.42 (1,063)	<.001
		B	No	1.10	4.02 (2,200)	0.045	-0.5	-0.9	Wilcoxon rank sum test	1.52 (2,200)	0.129
		C	Yes	0.97	0.02 (2,089)	0.876	-0.8	-0.6	Equal var. t-test	2.95 (2,089)	0.003
		D	Yes	0.97	1.77 (2,076)	0.183	-0.8	-0.8	Equal var. t-test	3.01 (2,076)	0.003
OR3	EB	A	No	1.06	1.17 (2,159)	0.280	-0.5	-0.8	Wilcoxon rank sum test	1.46 (2,159)	0.144

Site	Approach	Location	Distribution Normal?	After/Before Std Dev	F-statistic (df)	P-Value	Mean Difference (mph)	Median Difference (mph)	Selected test	T-statistic (df)	P-Value
		B	Yes	1.08	0.02 (2,533)	0.880	-0.8	-0.9	Equal var. t-test	2.80 (2,533)	0.005
		C	Yes	1.00	0.04 (2,485)	0.834	-0.7	-0.6	Equal var. t-test	3.07 (2,485)	0.002
		D	Yes	0.88	0.28 (2,431)	0.595	-0.3	0.1	Equal var. t-test	1.15 (2,431)	0.249
OR4	WB	B	Yes	1.04	0.03 (2,419)	0.866	-1.4	-1.5	Equal var. t-test	5.35 (2,419)	<.001
		C	No	0.82	9.64 (2,793)	0.002	-1.4	-1.0	Wilcoxon rank sum test	5.17 (2,793)	<.001
		D	Yes	0.94	1.04 (2,844)	0.308	-1.2	-1.0	Equal var. t-test	4.33 (2,844)	<.001
OR6	EB	A	No	1.15	6.98 (1,849)	0.008	1.6	0.7	Wilcoxon rank sum test	3.67 (1,849)	<.001
		B	No	0.97	0.41 (1,915)	0.521	0.9	0.7	Wilcoxon rank sum test	3.34 (1,915)	<.001
		C	Yes	0.97	0.00 (2,042)	0.992	0.4	0.2	Equal var. t-test	-1.95 (2,042)	0.051
	WB	A	Yes	1.04	0.15 (1,805)	0.702	0.8	0.7	Equal var. t-test	-1.97 (1,805)	0.050
		B	Yes	1.13	1.96 (1,836)	0.162	-1.1	-1.0	Equal var. t-test	3.94 (1,836)	<.001
		C	Yes	1.15	3.90 (1,972)	0.048	0.0	-0.2	Unequal var. t-test	-0.16 (1,782)	0.875
		D	No	1.02	0.16 (2,051)	0.689	-1.0	-0.9	Wilcoxon rank sum test	3.12 (2,051)	0.002
TX1	SB	A	No	1.03	0.34 (3,352)	0.560	-0.1	-0.5	Wilcoxon rank sum test	0.65 (3,352)	0.518
		B	Yes	1.02	1.14 (3,169)	0.285	-0.5	-0.8	Equal var. t-test	1.67 (3,169)	0.095
		C	Yes	0.90	24.95 (3,518)	<.001	-0.8	-0.8	Unequal var. t-test	3.28 (3,515)	0.001

Site	Approach	Location	Distribution Normal?	After/Before Std Dev	F-statistic (df)	P-Value	Mean Difference (mph)	Median Difference (mph)	Selected test	T-statistic (df)	P-Value
		D	Yes	0.97	0.00 (3,123)	0.953	-0.1	0.2	Equal var. t-test	0.33 (3,123)	0.744
TX2	NB	A	Yes	1.11	6.67 (2,246)	0.010	1.5	0.8	Unequal var. t-test	-3.27 (1,121)	0.001
		B	Yes	1.14	2.22 (1,149)	0.137	0.8	0.1	Equal var. t-test	-1.36 (1,149)	0.175
		C	Yes	0.89	3.38 (2,916)	0.066	0.3	0.9	Equal var. t-test	-1.01 (2,916)	0.310
		D	Yes	1.15	1.35 (1,338)	0.246	1.3	1.3	Equal var. t-test	-3.19 (1,338)	0.001
	SB	A	No	0.97	1.69 (1,650)	0.193	-0.6	-0.4	Wilcoxon rank sum test	1.13 (1,650)	0.257
		B	Yes	1.23	7.66 (583)	0.006	1.8	1.1	Unequal var. t-test	-2.39 (563)	0.017
		C	Yes	0.91	4.75 (2,189)	0.029	0.1	0.2	Unequal var. t-test	-0.28 (1,627)	0.777
		D	Yes	1.19	2.09 (1,990)	0.148	0.1	-0.1	Equal var. t-test	-0.34 (1,990)	0.730
TX4	WB	B	Yes	1.02	0.00 (1,246)	0.945	-2.8	-1.9	Equal var. t-test	6.66 (1,246)	<.001
		C	Yes	0.89	4.73 (1,823)	0.030	-2.0	-1.5	Unequal var. t-test	7.27 (1,599)	<.001
		D	Yes	0.90	6.20 (1,218)	0.013	-0.6	-0.6	Unequal var. t-test	1.69 (989)	0.091
WA1	EB	A	No	0.88	0.05 (654)	0.822	-7.6	-8.7	Wilcoxon rank sum test	7.71 (654)	<.001
		B	Yes	0.84	7.71 (1,386)	0.006	-3.2	-2.9	Unequal var. t-test	7.57 (530)	<.001
		C	Yes	0.83	8.27 (1,571)	0.004	-2.9	-2.4	Unequal var. t-test	7.85 (1,128)	<.001
	WB	A	Yes	1.04	0.30 (1,646)	0.584	-0.9	-0.9	Equal var. t-test	2.42 (1,646)	0.016
		B	Yes	1.14	4.89 (1,314)	0.027	-2.1	-1.5	Unequal var. t-test	5.16 (1,106)	<.001
		C	Yes	0.87	1.47 (1,416)	0.225	-2.5	-1.8	Equal var. t-test	6.79 (1,416)	<.001
		D	Yes	1.03	0.31 (1,125)	0.577	-1.2	-1.2	Equal var. t-test	3.40 (1,125)	<.001

APPENDIX H

Appendix H Secondary Analysis of 85th-Percentile Speeds

This appendix presents the results of the 85th-percentile speeds analysis:

- By intersection approach (to match level 2 analysis of means).
- Across all intersection approaches with the same treatment (to match level 3 analysis of means), summarized in Exhibit H-2.

In each case, the dependent variable of interest was the paired difference between the after minus the before 85th-percentile speeds at each location at each site.

ANALYSIS BY INTERSECTION APPROACH

Exhibit H-1 presents the results of the treatment effect on 85th-percentile speeds, separately for each intersection approach (across Locations A, B, C, and D). Here, the results are based on a paired t-test at each site where each location contributes a single paired difference. Columns 5 and 6 show the estimated speed difference in 85th-percentile speeds and its standard error. The last two columns show the results of the paired t-test with the last column indicating statistical significance of the treatment: a p-value of 0.05 or less (highlighted in yellow and bold) will indicate a significant effect at that intersection approach at the 5-percent significance level.

Exhibit H-1. Treatment Effect on 85th-Percentile Speed by Intersection Approach

Treatment Type	Site No.	Intersection Approach	Number of Locations	Estimated Speed Difference in 85th Percentiles (mph)	Standard Error (mph)	T-Statistic	P-Value
Transverse Pavement Markings	OR1	EB	4	-2.5	0.6	-3.95	0.029
		NB	4	-1.0	0.3	-3.26	0.047
	OR2	NB	3	-0.5	0.1	-4.13	0.054
		SB	3	-0.7	0.1	-5.36	0.033
	OR3	EB	4	-0.6	0.2	-3.81	0.032
	OR4	WB	3	-1.2	0.2	-5.75	0.029
	OR6	EB	3	0.4	0.1	3.30	0.081
		WB	4	-0.5	0.6	-0.72	0.526
Rumble Strips	TX1	SB	4	0.0	0.2	0.13	0.905
	TX2	NB	4	0.1	0.2	0.28	0.796
		SB	4	-2.0	0.8	-2.43	0.093
Dynamic Warning Sign	TX4	WB	3	-1.4	0.7	-1.94	0.191
	WA1	EB	2	-1.8	0.4	-4.50	0.139
		WB	4	-1.5	0.3	-4.97	0.016

ANALYSIS BY TREATMENT TYPEE

The estimated effectiveness of each of the three treatments across all intersection approaches on 85th-pwercentile speeds is presented in Exhibit H-2. The results are based on an ANOVA where the dependent variable is, as before, the paired difference between the before and after 85th-percentile speeds at each site and location.

The "Main Effect or Interaction" column refers to either the overall treatment effect (Treatment), the interaction effect between treatment and data collection location (abbreviated as "Treatment x Location"), or the treatment effect at the individual locations (A, B, C, or D). The statistical significance of an effect is based on the p-value in the last column. Rows with p-values highlighted in yellow and bold indicate statistical significance based on a p-value cut-off of 0.05 (i.e., 5-percent significance level). The two footnotes pertain to the type of test used to test for significance: an F-test to test for significant treatment or treatment-by-location interaction; a t-test to test for significant treatment effect at a particular data collection location.

The treatment effect is the estimated 85th-percentile speed reduction across all intersection approaches. The treatment-by-location interaction tests whether the treatment effect is the same across data collection locations (note that in this analysis, differences between intersection sites are controlled for in the model). The location effects correspond to the estimated 85th-percentile speed reduction across sites for each data collection location (i.e., A, B, C, or D).

Exhibit H-2. Overall Treatment Effect on 85th-Percentile Speed Across All Intersection Approaches

Treatment Type	Main Effect or Interaction	Estimated Speed Difference in 85th Percentiles (mph)	Standard Error (mph)	Test Statistic	Degrees of Freedom	P-Value
Transverse Pavement Markings	Treatment[a]	-0.9	0.2	17.23	(1,24)	0.0004
	Treatment x Location[a]			0.17	(3,24)	0.9130
	Location A[b]	-0.9	0.5	-1.91	24	0.0675
	Location B[b]	-1.0	0.4	-2.32	24	0.0289
	Location C[b]	-0.6	0.4	-1.64	24	0.1150
	Location D[b]	-1.0	0.4	-2.42	24	0.0234
Rumble Strips	Treatment[a]	-0.7	0.4	2.42	(1,8)	0.1584
	Treatment x Location[a]			0.54	(3,8)	0.6697
	Location A[b]	-1.1	0.8	-1.26	8	0.2445
	Location B[b]	-1.2	0.8	-1.44	8	0.1886
	Location C[b]	-0.5	0.8	-0.60	8	0.5673
	Location D[b]	0.2	0.8	0.18	8	0.8623
Dynamic Warning Sign	Treatment[a]	-1.4	0.1	167.05	(1,5)	<.0001
	Treatment x Location[a]			15.95	(3,5)	0.0054
	Location A[b]	-1.4	0.3	-4.70	5	0.0053
	Location B[b]	-2.3	0.2	-13.13	5	<.0001
	Location C[b]	-1.6	0.2	-9.42	5	0.0002
	Location D[b]	-0.4	0.2	-1.84	5	0.1254

[a] F-test
[b] T-test