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16. Abstract

This report documents the first year activities of a two-year project in which various work zone traffic control devices, treatments, and practices were implemented and evaluated. The focus has been on rural high-speed work zones.

Nine work zones have been studied. Four work zones have been on two-lane highways with flagger operations and the remaining five were on a multilane highway with a single lane closure. The devices evaluated in the flagger-controlled work zones include fluorescent orange signing, radar drone, fluorescent yellow-green vests and hard hat covers, handheld strobe light attached to flagger vest, visibility improvement attachments for cones, and high-visibility retroreflective magnetic strips on flagger vehicles. The devices evaluated in the lane closure work zones include fluorescent orange signing, radar drone, fluorescent yellow-green vests and hard hat covers, visibility improvement attachments for cones, speed display trailer, advisory speed signing, and high-visibility retroreflective magnetic strips on work vehicles.

Speeds, conflicts, driver surveys, maintenance crew surveys, and recorded CB conversations were used to evaluate the different devices. Preliminary analyses show that the most promising devices include the fluorescent orange signing, fluorescent yellow-green worker vests, radar drone, and speed display trailer. Recommended research activities for year two include further evaluation of these promising devices along with other innovative devices such as portable rumble strips and portable stop bars.

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EVALUATION OF TRAFFIC CONTROL DEVICES FOR RURAL HIGH-SPEED MAINTENANCE WORK ZONES

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DISCLAIMER

The contents of this report reflect the views of the authors, who are responsible for the opinions, findings, and conclusions presented herein. The contents do not necessarily reflect the official views or policies of the Federal Highway Administration (FHWA) or the Texas Department of Transportation. This report does not constitute a standard, specification, or regulation, nor is it intended for construction, bidding, or permit purposes. The engineer in charge of the project was H. Gene Hawkins, Jr., P.E. #61509.

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Project Director

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Project Advisory Panel

- Danny Brown, Childress District, Texas Department of Transportation;
- Greg Brinkmeyer, Traffic Operations Division, Texas Department of Transportation; and
- Terry Keener, Childress District, Texas Department of Transportation.

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CHAPTER 1
INTRODUCTION AND SUMMARY

As the roadway transportation system of the U.S. and Texas has matured, roadway construction under traffic conditions has become the rule, rather than the exception. There is little construction taking place on new alignment. Instead, transportation agencies must maintain, repair, and reconstruct existing roadway facilities while allowing traffic to continue using the roadway. Sharing of right-of-way between construction and traffic creates the potential for many conflicts and can have a negative impact on safety.

A recent study by the Texas Transportation Institute (TTI) demonstrates the magnitude of this problem (*1*). In 1994, there were 706 fatal crashes and 4942 injury crashes unrelated to alcohol in work zones, with 20,885 property-damage-only crashes (*2*). There is a strong possibility that without intervention and education, these numbers could increase as more road work is concentrated on maintenance, rehabilitation, and expansion. The TTI study estimates the cost of these incidents to be $1.9 billion in fatalities, $122 million in injuries, and $44 million in property damage (*1*).

One of the means of minimizing the hazards associated with work zones is the use of traffic control devices. The standard practices for traffic control in work zones are identified in the Manual on Uniform Traffic Control Devices, also known as the MUTCD. However, despite significant experience with work zone traffic control, work zone crashes have continued to increase. As a result, transportation agencies at all levels have been actively searching for new traffic control devices, treatments, and practices that can improve safety in work zones for workers and road users.

BACKGROUND

Despite all conventional efforts, work zones remain hazardous places. Research has shown that crash frequency increases in work zones. It has been long theorized and shown that many drivers fail to recognize that they are in a work zone environment until there is a crash. For many reasons, conventional signing does not adequately alert many drivers to the changed conditions of a work zone. During the past few years, through the Strategic Highway Research Program (SHRP) and other initiatives, several innovative devices have been developed that assist drivers in recognizing the presence of a work zone environment. These new devices range from fairly simple devices, such as portable rumble strips, to ITS-related in-vehicle warning technology. The Texas Department of Transportation (TxDOT) has not taken full advantage of this research to date. Additionally, it is felt that evaluation of these new and innovative technologies will trigger and foster conceptualization of refinements to these recent technologies or conceptualization of additional systems, yet to be developed. Possible areas for consideration include: physical warning devices (such as portable rumble strips), auditory warning devices for rural areas (possibly such devices could warn workers of errant or erratically driven approaching vehicles), very conspicuous, dynamic visual devices that alert drivers when they are operating at unsafe speeds for the work zone condition (such as a strobe effect device linked to a speed detecting system), visibility enhancements to existing signs (e.g., a dynamic flagging mechanism), or other developments yet to be determined.

This two-year research effort is intended to identify existing and new technologies that will assist drivers in recognizing work zones. The research will evaluate the appropriate use of the most promising of these technologies in field studies in construction and maintenance work zones and make appropriate recommendations.

The focus of this research will be TxDOT maintenance activities on rural high-speed highways. The type of activities under consideration are for work taking place in daytime only, indicating short-term stationary (1 to 12 hours) or short-duration (up to 1 hour) work zones. The applications will be on two-lane roads and multilane divided/undivided highways.

This report describes the first-year activities, research findings, and evaluation recommendations. Potential activities for the second year of the project are also included.

RESEARCH APPROACH

The research efforts of this project were specifically oriented to provide results that will lead directly to implementation activities. The evaluation of new or innovative traffic control devices, treatments, and practices will provide TxDOT with the information needed to implement, in the most cost-effective manner possible, the devices, treatments, and practices, thereby improving safety for workers and/or road users. This research, conducted by the Texas Transportation Institute, was focused on satisfying the following goal.

- Identify and evaluate new or innovative traffic control devices, traffic control treatments, or traffic control practices that have the potential to improve worker and/or road user safety in temporary traffic control zones (work zones).

Progress toward meeting this goal is measured through quantifiable objectives, which are used to determine the necessary research activities. Based upon the research goal, the following specific and quantifiable objectives were established for this research project:

- Identify new or innovative traffic control devices, treatments, or practices for temporary traffic control zones (work zones) that are not currently used by TxDOT workers or contractors on TxDOT projects.
- Determine the potential for these new or innovative devices, treatments, or practices to improve worker and/or road user safety.
- Conduct field evaluations of selected devices, treatments, or practices.
- For devices, treatments, or practices that appear to have positive safety attributes, assess the ability to implement the devices, treatments, or practices.
- Document the activities and findings of the research project in annual reports.

The objectives of this research project are to be met through an iterative process where the objectives will be satisfied twice – once in the first year and then again in the second year. This iterative process was chosen so that the most promising findings from year one activities can be emphasized in year two. A carefully formulated work plan was developed to outline the iterative process. Table 1 summarizes the tasks involved in this plan. This work plan was structured to provide TxDOT with useful, practical, and reliable information that can be used to improve the safety of road users and TxDOT/contractor workers in temporary traffic control zones.

Table 1. Work Plan Tasks.

Task	Description
1	Conduct Kick-off Meeting with TxDOT Project Advisors
2	Determine the State-of-the-Art
3	Conduct Survey of State Transportation Agencies
4	Identify and Classify Innovative Devices, Treatments, and/or Practices
5	Select Potential Devices, Treatments, or Practices for Preliminary Field Evaluations
6	Develop Plan for Preliminary Field Evaluations
7	Conduct Preliminary Field Evaluations
8	Analyze Preliminary Field Evaluation Data
9	Prepare First Research Report
10	Meet with Project Advisors
11	Select Potential Devices/Treatments/Practices for Final Field Evaluations
12	Develop Plan for Final Field Evaluations
13	Conduct Final Field Evaluations
14	Analyze Field Data and Develop Recommendations
15	Prepare Second Research Report and Project Summary Report
16	Meet with Project Advisors
17	Assist in Research Implementation

The research activities and findings from the first eight tasks are described within this report. This report represents task nine. The remaining tasks will be addressed in year two.

RESEARCH SUMMARY

During the first year of the study, researchers completed eight major research tasks toward meeting the project objectives. A kick-off meeting was held with the TxDOT Advisory Panel to identify needs and concerns of TxDOT. An extensive information gathering effort was conducted to discover and provide information about the pertinent devices, treatments, and practices that have been documented. A survey of state transportation agencies was administered to determine other state experience with new or innovative devices, treatments, and practices. In addition to the state DOT survey, the members of the Advisory Panel and the research team met at the Annual ATSSA Traffic Expo in San Antonio. At this meeting, the group perused work zone traffic control vendor displays and discussed potential products for evaluation. Using the findings from these initial tasks, the researchers developed a preliminary list of new and innovative devices, treatments, and practices for consideration. In a subsequent TxDOT Advisory Panel meeting, the preliminary list of new and innovative devices, treatments, and practices was evaluated and reprioritized to include a list of the most promising devices for evaluation. Field evaluation plans were developed for the selected devices, treatments, and practices. The field evaluation plans were presented to the Advisory Panel and included applicable measures of effectiveness, previous evaluations, and an indication of whether FHWA permission to experiment would be required. Field evaluations were conducted and the data were analyzed to determine the effectiveness of the selected devices, treatments, and practices. This report documents these efforts in greater detail. The report concludes with the findings and recommendations for year two activities. The following paragraphs summarize each chapter.

Identification and Selection of Devices, Treatments, and Practices

The research efforts associated with satisfaction of the first five tasks of the work plan are described in chapter 2. The information gathering tasks and product identification and selection efforts are the primary focus. The chapter concludes with a list of prioritized traffic control devices, treatments, and practices. The Advisory Panel and research team agreed to structure the first-year efforts on the device, treatments, and practices ranked ‘high’ in terms of showing the most promise for meeting the project’s overall objective. Consequently, the following devices were evaluated during the first year: fluorescent orange signing, high-visibility clothing, radar drones, radar speed displays, traffic control device attachments, and vehicle visibility improvements.

More specifically, the two-lane two-way highways with flagger operations were supplemented with the following devices:

- fluorescent orange signs,
- radar drone,
- fluorescent yellow-green vests,
- fluorescent yellow-green hard hat covers,
- handheld strobe light attached to flagger vest,
- Safe-T Spins (visibility improvement attachments for cones), and
- high-visibility retroreflective magnetic strips on the flagger vehicle.

The work zones on the multilane divided highways consisted of lane closure operations. The following devices were tested in these work zones:

- fluorescent orange signs,
- radar drone,
- fluorescent yellow-green vests,
- fluorescent yellow-green hard hat covers,

- Safe-T-Spins (visibility improvement attachments for cones),
- speed display trailer,
- advisory speed signing, and
- high-visibility retroreflective magnetic strips on work vehicles.

Research Methodology

Tasks 6 and 7 include the experimental plan, site selection process, data collection equipment, data collection procedures and activities, and data reduction efforts. These items are explained in detail in chapter 3. Essentially, three data collection trips were made to the Childress District during the first year. The resulting data from these trips are organized and presented in this chapter. Innovative traffic control devices, treatments, and practices were evaluated in nine different work zones. Four of these work zones were on two-lane two-way highways with flagger operations. The remaining five were on four-lane divided highways with lane closure operations. A reference point system was established to make comparisons between work zones. Details of the development of this referencing system are explained in chapter 3.

Data Analysis

Task 8 consists of the data analysis. The analysis techniques and results are presented in chapter 4 and appendices B and C. The analysis techniques consisted of a series of analysis of variance testing for the speed data. The other data were mostly evaluated using a subjective technique because of the difficulty in finding or using quantifiable measures of effectiveness. These types of data included responses from driver surveys, input from maintenance crews, and recorded citizen's band (CB) conversations.

The analysis results are presented by the measure of effectiveness used to evaluate the different devices. The speed data is presented first and is split into two categories: flagger operations and lane closure operations. The driver survey results, maintenance crew comments, and conflict analysis are then discussed.

Summary of First-Year Findings and Recommended Second-Year Activities

The findings from year one activities have been divided into two categories: flagger operations and lane closure operations. The subsequent findings should be considered preliminary due to the lack of statistically valid sample sizes. The findings from the flagger operations (i.e., the two-lane two-way highway work zones) include:

- The speed data show that after implementation of the innovative devices, treatments, and practices, vehicle speeds were reduced by about 2 mph on all but one work zone.
- No significant conflicts were found at any of the four flagger-controlled sites.
- The driver survey showed that of all the innovative devices, treatments, and practices implemented, drivers notice the fluorescent signing the most. Drivers said the presence of the radar drone influenced their driving the most. They also commented on the visibility of the fluorescent yellow-green vests worn by the maintenance crews.

- The TxDOT maintenance crew workers felt that the fluorescent yellow-green vests provided the best safety-related improvement.
- The recorded CB conversations demonstrated the effectiveness of the unofficial advance warning system the truck drivers use through their communication with the CB radios. Truckers were well aware of the radar drone before entering the work zone.

The findings from the work zones with lane closure operations (i.e., the four-lane divided highway work zones) include:

- The speed data showed again that the radar drone was effective in reducing speeds. However, the speed display trailer proved to create the largest speed reductions, ranging from 3 to 6 mph.
- Radar drones decreased the conflict rate and the speed trailer increased the conflict rate when compared to when no innovative devices were being tested. The conflict rate is a measure of how many erratic maneuvers occur at the site.
- No driver surveys were conducted on the multilane highways for safety reasons.
- The TxDOT maintenance crew workers felt that the fluorescent yellow-green vests and speed display trailer provided the best safety-related improvement.
- Once again, the recorded CB conversations demonstrated the effectiveness of the unofficial advance warning system the truck drivers use through their communication with the CB radios. Truckers were well aware of the radar drone and speed display trailer before entering the work zone.

In particular, the specific devices and their effectiveness are summarized below. Some of the findings are based on subjective evaluations by the research team, drivers, or maintenance crew personnel, while others are based on the statistical analyses described and presented in chapter 4.

- Fluorescent orange signing (Figure 1)
    - Motorists noticed the fluorescent orange signing more than any other innovative device, treatment, or practice implemented in the flagger-controlled work zones. They commented that the fluorescent orange signing helped them be better prepared for the upcoming work zone.
    - Maintenance crew opinions were also positive concerning use of fluorescent orange signing.
    - The main advantage of fluorescent signing occurs during periods of low light. The advantages of fluorescence are especially noticeable on cloudy days, in the morning, in the evening, or in shady areas. A secondary advantage to fluorescent orange signing is that most signs are made of prismatic retroreflective sheeting. Consequently, if the signs were used during nighttime conditions, they would appear brighter than the beaded retroreflective material normally used.
- Fluorescent yellow-green worker vests (Figure 2)
    - Both the drivers surveyed and the maintenance crews responded favorably to the fluorescent yellow-green vests.

- The vests were more conspicuous than the standard orange vests that TxDOT personnel normally wear. The fluorescent yellow-green vests provide a distinct contrast between the highway workers and the orange traffic control devices, which can sometimes act as camouflage for highway workers.

Figure 1. Fluorescent Orange Signing.

Figure 2. Example of High-Visibility Clothing.

- Fluorescent yellow-green hard hat covers (Figure 2)
  - No opinions, favorable or unfavorable, were received regarding the hard hat covers. It is the opinion of the research team that the hard hat covers provided as much of an increase in worker conspicuity as the fluorescent yellow-green vests.
- Handheld strobe light attached to flagger vest
  - The strobe used was not very visible during daylight conditions. The size and weight of the unit was also a concern. This device would be better suited for nighttime conditions.
- High-visibility retroreflective magnetic strips on work vehicles (Figure 3)
  - While these devices added some obvious conspicuity to the vehicles, there were no direct measures of their benefit. However, the fluorescence of the strips would provide a significant increase in conspicuity during low-light conditions.
  - Because the strips are retroreflective, the strips' main benefit would occur at night.
- Safe-T-Spins (Figure 4)
  - These visibility-enhancing devices attached to the top of normal traffic control cones proved to be effective attention getting devices for flagging operations.

They were implemented on the cones on the taper and then intermittently through the work zone. Several truck drivers mentioned the increased visibility.
    - Highway maintenance personnel were impressed with these devices when used on flagger-controlled sites where the speeds of the vehicles passing the devices were not at the normal highway operating speed.
    - When used on the multilane highways where lane closures were used, the devices appeared to have a negative effect. With vehicles, especially trucks, passing so close to the devices and at speeds near highway operating speeds, the devices caused the cones to blow over. They required constant attention from the maintenance personnel in order to keep them in an upright position.

Figure 3. Vehicle Visibility Improvements.

Figure 4. Safe-T-Spins.

- Radar drone
    - The use of the radar drone generally reduced speeds. Speeds in the work zones were about 2 mph less with the radar drone compared to when the radar drone was not present.
- Speed display trailer (Figure 5)
    - The speed trailer resulted in the largest reductions at the beginning of the work zone and within the work zone. Speed reductions at the speed trailer were between 2 and 7.5 mph, and reductions within the work zone ranged from 3 to 6 mph.

Figure 5. Speed Trailer.

CHAPTER 2
IDENTIFICATION AND SELECTION OF DEVICES, TREATMENTS, AND PRACTICES

This chapter is divided into two main sections. The first explains how information on newly developed and innovative temporary traffic control devices, treatments, and/or practices was gathered. This section concludes with a preliminary list of traffic control devices, treatments, and/or practices feasible for further study. The second section summarizes the findings related to the devices, treatments, and/or practices that have been evaluated and documented elsewhere. This section concludes with a reprioritized list of the most promising devices.

INFORMATION GATHERING EFFORTS

The initial information gathering task of this project was conducted very methodically to ensure that a complete state-of-the-art review of newly developed and innovative temporary traffic control devices, treatments, and/or practices was performed. This task of the research was critical in that it established the foundation for the remainder of the project. Several steps were involved in this information gathering task such as querying the National Work Zone Safety Information Clearinghouse, reviewing findings from the Strategic Highway Research Program, visiting the American Traffic Safety Services Association Traffic Expo, and surveying the state DOTs. Research studies that documented the effectiveness of various devices were also examined. These steps are summarized herein. A preliminary list of discovered traffic control devices, treatments, and/or practices feasible for further study is discussed at the end of the first section of this chapter.

National Work Zone Safety Information Clearinghouse

Culminating more than a decade of leadership in the highway construction safety arena, American Road and Builders Association (ARTBA) in September 1997 signed a cooperative agreement with the FHWA to establish and operate a National Work Zone Safety Information Clearinghouse. The Clearinghouse can be located at http://wzsafety.tamu.edu. The Clearinghouse has, for the first time, provided a centralized, comprehensive information resource that assists those interested in reducing incidents associated with temporary highway work zones.

The Clearinghouse provides transportation agencies, law enforcement departments, highway designers and contractors, labor unions, insurance companies, motor clubs, and other interested parties with a wealth of information on how to make road construction zones safer for motorists, pedestrians, and highway workers. The Clearinghouse contains more than 250 suggested "best practices." These best practices cover a variety of topics, including guidelines for better work zone design, innovative contracting techniques, research reports, information on mounting public awareness and law enforcement campaigns, work zone policies in place around the country, and data on innovative work zone safety measures. The Clearinghouse is a cooperative venture between the Federal Highway Administration and the American Road & Transportation Builders

Association. ARTBA is partnering on the project with TTI, which is housing the facility and handling its day-to-day operations.

The "best practices" were reviewed in order to identify newly developed and innovative temporary traffic control devices, treatments, and/or practices. The "best practices" provided many potentially feasible options. Specifically, they identified several innovative treatments that were currently being used around the country that may have an application on Texas roads. These treatments may not be applicable to all work zones. Some of the measures identified from the Clearinghouse included:

- *CB Radio Warning Systems* - Pennsylvania currently utilizes a system that broadcasts work zone alerts over CB radios.
- *High-Visibility Worker Apparel* - Iowa, Minnesota, and Pennsylvania all currently utilize fluorescent yellow-green retroreflectorized vests.
- *Queue Length Detectors* - Missouri uses queue length detectors to relay warning information to variable message signs upstream of the work zone in order to alert motorists to upcoming delays.
- *Radar Activated Speed Displays* - Virginia tested a changeable message sign that displayed a warning message when speeding vehicles entered a work zone.
- *Radar Drones* - Massachusetts, Ohio, and Virginia have all tested radar drones at work zones in order to slow vehicles down.
- *Rumble Strips* - Ohio sometimes places rumble strips prior to a work zone in order to help increase driver awareness.

Strategic Highway Research Program (SHRP)

SHRP was established by Congress in 1987 as a five-year, $150 million research program to improve the performance and durability of our nation's roads and to make those roads safer for both motorists and highway workers. One of the emphasis areas of SHRP was the development of new work zone safety devices. However, there have been some implementation difficulties associated with some of these devices. Some of these difficulties can be attributed to the fact that the individuals/organizations who developed the devices in the research phase had little or no experience in developing traffic control devices. As a result, they were not aware of many requirements that affect the use of traffic control and other safety devices. In some cases, the devices developed as part of SHRP had to be significantly changed prior to implementation, or existing standards had to be modified to incorporate the features of a device. In any case, the products were evaluated and their potential as it related to increasing the safety of workers and drivers in rural high-speed work zones was subjectively determined. Because of the inconclusiveness of the feasibility of implementation, the only device selected for possible evaluation as part of this project (portable rumble strips) was scheduled for year-two activities. A portable stop bar device for flagger operations on two-lane roadways, a spin-off of the portable rumble strips, was also selected to be evaluated in year two. Some of the innovative devices developed by SHRP are:

1. *Flashing Stop/Slow Paddle* - This device required a special action by the National Committee on Uniform Traffic Control Devices (NCUTCD) and FHWA because the

design of the device (with the flashing lights contained in the face of the Stop sign) conflicted with existing MUTCD standards for Stop signs. The design should have placed the flashing lights outside of the sign face. However, the device is one of the most popular products to emerge from the SHRP research, and it is already being used in many states *(3)*.

2. *Opposing Traffic Lane Divider* - This device has been used successfully in actual implementation. This device was also recommended for implementation by a TTI research study *(4)*.
3. *Direction Indicator Barricade* - This product requires FHWA permission to experiment in order to be used. Permission requires the agency to submit a report on the effectiveness of the device.
4. *Queue Detector* - A recent TTI study found that this device requires improvements in technology to increase the reliability of the device *(4)*.
5. *Intrusion Alarm* - These types of devices are market ready, but have demonstrated some difficulties, due to many different factors that affect their effectiveness. One of the most significant of these factors is the false alarm rate. A TTI study found that these alarms require improved technology as well as increased reliability and reduced setup effects before widespread implementation *(4)*.
6. *Portable Rumble Strip* - A recent TTI study found that this type of devices does not always stay down on the pavement *(4)*.
7. *Remotely Driven Vehicle* - This device is not yet market ready *(5)*.

American Traffic Safety Services Association (ATSSA)

ATSSA is an industry organization for manufacturers, vendors, suppliers, and contractors in the field of traffic control devices. As such, members stay current with new technologies and provide a valuable resource for information. The annual meeting (Traffic Expo) of this organization was held in February 1999 in San Antonio. The Traffic Expo exhibit area represents the largest traffic control related exhibit in the U.S. The research team and members of the Advisory Panel met at the Traffic Expo and spent an entire afternoon perusing the exhibits and discussing products that appeared to have potential in meeting the project objectives. Promising devices, treatments, and/or practices were added to the overall list for evaluation.

Survey of State DOTs

In December 1998, TTI researchers distributed a survey to the state traffic engineer in each state. The survey contained seven parts and addressed issues of significance on numerous research projects. One of these parts addressed work zone traffic control. One question in this part was specifically related to the issues of significance on this project. The question and substantive responses are provided in Figure 6 and Table 2, respectively.

TTI will be conducting field evaluations of new or innovative traffic control devices and practices that may improve worker safety in short-term stationary work zones on rural highways. Please list any devices, practices, or treatments that you think should be included in the field evaluations. For each item, please indicate whether your agency has any experience with it. If available, names of vendors or suppliers would be appreciated. Use the other side of this sheet if necessary.

Figure 6. State DOT Survey Question.

Table 2. State DOT Survey Responses.

State	Response
California	Trailer mounted temporary traffic signals in lieu of a flagger. No real experience. Caltrans is trying to implement it.
Idaho	Audible alarms, const. zone radar activated speed signing, hydro barriers.
Iowa	See attached evaluation plan.
Maryland	Intrusion alarms; flashing stop/slow paddles; flexible traffic control products (directional indicator barricade, opposing traffic land dividers, tubular markers); Queue detectors to activate portable changeable msg. signs; displays motorist speed thru work zone
Massachusetts	Radar Detector Activators (RDA) - yes, we have used them.
Michigan	Opposing traffic lane divider by Impact recovery systems 246 Josefine St. San Antonio TX
Missouri	Participating in small work zone initiative sponsored by FHWA and CETRE.
Pennsylvania	Wizard CB alert radio; Trafcon Industries, Inc. 81 Texaco Road Mechanicsburg, PA 17055 (717) 697-8007; We use this on long-term const. project to alert truck drivers.
Rhode Island	Pavement delineators for lane shifts in work zones in lieu of painted pavement markings or tape.
South Carolina	1) Intrusion alarms 2) Temp use of Quick Kurb (info attached) 3) Safety assist lights (info attached). We have seen these systems, but have no experience with them.
Tennessee	Some form of detection device that would detect errant vehicles in work zones that warn workers of imminent danger.
Virginia	Intrusion alarms - some experience; drone radar - some experience.

Transport from Silver Platter & Texas A&M Evans Library

The Transport database was thoroughly searched for work zone traffic control and other related terminology. This is the most traditional and common way to conduct a literature search. The documents found through this search were obtained and reviewed for relevancy to this project. The findings were combined with the previously described efforts to develop an ubiquitous list of traffic control devices, treatments, and/or practices that have been evaluated or at least documented in some form.

List of Traffic Control Devices, Treatments, and Practices

Once the information gathering task was complete, the research team developed a preliminary list of the traffic control device, treatments, and practices that were considered feasible for further study. The devices selected for further study had to either be currently in use in a state or have had research studies document their effectiveness. This list is provided below.

- *Direction Indicator Barricades* - This device is described in the Strategic highway Research Program (SHRP) section.
- *Flashing Stop/Slow Paddle* - This device is described in the SHRP section.
- *Fluorescent Signing* - Fluorescent signs provide greater visibility of conventional signs.
- *High-Visibility Clothing* - This is described in the national Work Zone Safety Information Clearinghouse (Work Zone Clearinghouse) section.
- *Intrusion Alarm* - This device is described in the SHRP section.
- *Lane Narrowing* - Lane narrowing through the work zone can be used to accomplish speed reductions.
- *Opposing Traffic Lane Dividers* - This device is described in the SHRP section.
- *Portable Rumble Strips* - This device is described in the SHRP and Work Zone Clearinghouse sections.
- *Portable Changeable Message Signs* - Portable changeable message signs can be used to provide real-time information that alerts motorists of upcoming conditions in the work zone.
- *Portable Traffic Signal* - Portable traffic signals can be used as an alternative to flaggers.
- *Queue Length Detector* - This device is described in the SHRP and Work Zone Clearinghouse section.
- *Radar Drone* - This device is described in the Work Zone Clearinghouse section.
- *Radar Speed Trailer* - This device is described in the Work Zone Clearinghouse section.
- *Remote Driven Vehicle* - This device is described in the SHRP section.
- *Temporary Stop Bar* - Temporary stop bars may be useful to designate stopping points at flagger-controlled work zones.
- *Vehicle Visibility Improvements* - Retroreflective material can be added to worker vehicles in order to improve their conspicuity in the work zone.
- *Water-Filled Barriers* - Water-filled barriers provide a more portable option to concrete barriers.

To determine which of the above provided the most promise, the research team reviewed the documented results from past studies associated with the preliminary list of devices, treatments, and practices. The following section summarizes the findings from this effort.

TREATMENT EFFECTIVENESS AND STATE EXPERIENCES

Based on the results of the panel meeting, a detailed literature search was conducted on those devices, treatments, and/or practices that were chosen by the Advisory Panel and research team as the most promising in terms of the project's overall objectives. The studies identified provided insights into the effectiveness of the various devices, treatments, and/or practices, as well as information about the experiences of various state DOTs with innovative devices or techniques. The devices, treatments, and/or practices identified and selected as most promising were classified into one of four categories. The categories were: worker safety measures, speed control measures, motorist guidance devices, and flagger safety devices.

Worker Safety Measures

The information gathering task yielded several devices that promised to improve worker safety. This was typically accomplished either by increasing the conspicuity of a worker or object or by actually improving work zone barriers. The items included in this section are high-visibility clothing, vehicle treatments, remotely driven vehicles, water-filled barriers, intrusion alarms, and queue length detectors.

High-Visibility Vests and Clothing

The 1993 revision to the MUTCD was the first time that the MUTCD made reference to safety clothing on personnel other than flaggers. The 1993 revision states that "Workers exposed to traffic should be attired in bright, highly visible clothing similar to that of flaggers." The MUTCD further states that "the flaggers vest, shirt, or jacket shall be orange, yellow, strong yellow-green, or fluorescent versions of these colors" (*6*).

A study by the University of Illinois in 1997 indicated that motorists do not see flaggers very well in construction zones (*7*). It stated that flaggers tended to blend in with the orange traffic control devices and equipment present in a typical work zone. A special provision was written into Illinois' Standard Specifications article that stated that the use of yellow-green vests will be used to distinguish the flagger from all of the prevalent orange in the area. The vest was to contain fluorescent orange stripes. The use of fluorescent orange vests will be limited to emergencies only (*7*).

Turner et al. examined a variety of vest colors in order to determine which colors had the highest conspicuity (*8*). They tested the following vest colors: fluorescent green, fluorescent yellow-green, fluorescent yellow, semi-fluorescent yellow, ordinary yellow, fluorescent yellow-orange, fluorescent red-orange, fluorescent red-orange combined with fluorescent yellow-green, fluorescent red mesh, ordinary orange, and fluorescent pink. Vests were placed on mannequins dressed in typical worker attire (white t-shirt with denim pants). The mannequins were setup in a mock work zone with typical orange traffic control devices. Test subjects were driven through the mock work zones at a rate of 20 mph. Every 100 ft. a shutter would open for 300 milliseconds, after which the subject would be asked if they saw any safety clothing. This study found that fluorescent red-orange had the best mean detection distance at 984 ft., followed by fluorescent red mesh at 892 ft., and fluorescent yellow-green at 853 ft. These results seem to validate the requirements of the MUTCD (*8*).

In 1997, the Iowa Department of Transportation started using vests that were yellow-green with orange markings and reflective stripes. If a hard hat was not worn, a yellow-green cap with a reflective stripe was substituted. Pants of similar color were also added for nighttime use. In

1995, the Iowa DOT had experimented with yellow-green open mesh vests due to concerns that plain orange vests were hard to see because they tended to blend in with equipment. They ran into problems with the new yellow-green vests also since the yellow-green blended in with the cornfields *(9)*.

The idea of safety clothing with orange and yellow-green was first formulated by the Minnesota Department of Transportation (MnDOT). Due to the increase in nighttime operations, MnDOT started experimenting with various colors and designs in the summer of 1991, trying to find the combination with the highest visibility. Experimental improved garments were allowed in Minnesota if they met a series of specifications. First, the color had to meet or exceed luminance minimums of 80 cd/m^2 for yellow vests and 35 cd/m^2 for orange-red vests. The garment must also contain two strips of retroreflective material, at least 0.75 in. in width and be at least 0.25 in. away from each outside edge of the article of clothing (either pants or vest). The reflective brilliance must meet minimum retroreflectivity values of 330 cd/lux/m^2 at an entrance angle of -4 degrees and an observation angle of 0.2 degrees, and of 165 cd/lux/m^2 at an entrance angle of +40 degrees and an observation angle of 0.2 degrees. The material must appear silver in daylight and reflect silver at night. The comfort level of the clothing was also analyzed, since this would increase worker compliance. Mesh was allowed under the arms for cooling purposes, while solid weave was used as the base material. Specific placements of the reflective markings were also stated *(10)*.

A MnDOT survey taken in 1995 issued samples of retroreflective vests and shirts to workers in MnDOT District 7, which were of a yellow-green combination *(11)*. Workers responded positively to the garments' visibility, but expressed concerns with it being too large and warm. They also said that the clothes were too bulky and may get caught on machinery. The workers were enthusiastic about the idea of high-visibility clothing and were eager to see improvements made so they could be worn *(11)*.

Vehicle Treatments

A recent survey of innovative traffic control techniques in Europe found that many European countries utilize various retroreflective treatments to improve the visibility of maintenance and incident response vehicles *(12)*. These vehicles have retroreflective material applied to the rear of the vehicle in order to improve the conspicuity within the work zone. The material was typically two-color alternating diagonal stripes that were placed along the perimeter of the rear of a truck or van. Color combinations observed included yellow and orange, red and white, fluorescent yellow-green and blue, and fluorescent yellow-green and black.

Remotely Driven Vehicle

Crash rates for slow-moving maintenance operations are about three times as high as those for other types of maintenance activity. A shadow vehicle, sometimes equipped with a truck-mounted attenuator, is frequently used to protect maintenance vehicles from being struck in the rear. While this protects the maintenance caravan, it puts the driver of the shadow vehicle at risk.

SHRP contracted with ENSCO, Inc. to develop a remotely driven shadow vehicle in order to reduce the risk to the operator of the vehicle. The prototype was a 1991 Ford L8000 dump truck, which was loaned to SHRP by the MnDOT (*5*). It is estimated that a truck can be converted to a remotely driven vehicle (RDV) for between $50,000 and $70,000. The prototype vehicle still retained its ability to perform normal maintenance functions, such as snowplowing (*5*).

The remote control unit can command all of the important vehicle functions. It allows the operator to start the vehicle, adjust the throttle, brake, steer, shift gears, use turn signals, and turn on the headlights. The remote control has a dead-man switch that turns off the remote vehicle if the operator removes his hand from a bar. The remote control weighs 4 lb. and has a range of 1200 ft. It is powered by an internal battery, which has a one week life (*5*).

The RDV has several built-in safety features. Panic buttons are positioned on either side of the truck, allowing workers to immediately shut down the vehicle if necessary. The RDV also has collision sensors that detect obstacles on all sides of the vehicle and stop the truck automatically if anything is detected (*5*).

The RDV has not gained wide acceptance, primarily due to the cost associated with converting an existing vehicle into an RDV. Indiana hosted a test of the device but elected to wait until the cost came down before pursuing it further. Maryland also postponed pursuing the device due to its high cost (*3*).

Water-Filled Barriers

Figure 7. Water-Filled Barrier.

Water-filled barriers have been marketed by manufacturers as a device to improve work zone safety. Figure 7 shows an example of a water-filled barrier. The manufacturer states that the barrier will not be penetrated by an 1800 lb. vehicle striking the barrier at a 20 degree angle at 45 mph. The barrier will also not be penetrated by a 4500 lb. vehicle impacting at a 25 degree angle at 45 mph. However, the barriers are not rigid, and deflections of up to 22.6 feet have been observed during testing. The manufacturer says that the water-filled barrier will bring vehicles to a controlled stop without allowing penetration. This is in contrast to concrete barriers, which deflect vehicles back into the traffic stream, and delineating devices, which do not effectively restrict vehicles from the work area.

The size of a water-filled barrier is similar to that of a concrete barrier. Three heights are available: 28 in., 42 in. (standard), and 54 in. All barriers are 24 in. wide at base and taper to a 10 in. width at the mid-height. It has a length of 78 in., of which 6 in. are used in the interlocking extension that is used to attach several barriers into a row. It comes in white and orange, and weighs 170 lb. empty. When filled with 185 gallons of water, the weight increases to 1700 lb. Water is drained by a small outlet near the bottom of one of the sides. In addition to work zone protection, they can also be used in traffic channeling and control, lane delineation, and building security.

The barriers can be installed by two workers with no special tools (*13*). Contractors have been timed installing the barriers at a rate of 600 ft. per hour (*14*). Forklift holes are provided in case the barrier must be moved once it has been filled with water. The cost for the barriers is approximately $550 per 72 in.

Water-filled barriers have been used in several other states with some amount of success. Other agencies have noted that the barriers are easy to install and remove, but caution that they should not be used as a replacement for concrete barriers due to the large lateral displacements that occur when the water-filled barriers are struck. Other states have noted that the water-filled barriers are used in situations where they would have previously used only plastic barrels (*4*).

The Alabama DOT has used the water-filled barriers in 45 mph work zones and highly recommends them. The barriers performed well during actual incidents. However, some states have noted that the barriers have not always been repairable after collisions (*4*).

There are still a number of questions about the use of these barriers that need to be resolved. New Hampshire expressed some concerns about the potential hazards that could be created by releasing water onto the roadway after a crash. Also, no crash tests were performed when the water in the barriers was frozen. The manufacturer recommends adding antifreeze during cold months, but this creates a disposal issue since water cannot be released using the built-in valves (*4*).

Intrusion Alarms

Intrusion alarms are devices that sound an alarm when a vehicle enters the work area. Three types of alarms are available. Microwave and infrared models are mounted on drums or cones and use microwave signals or beams of infrared light to connect units. When a vehicle crosses into the work zone and interrupts the signal or beams, a high-pitched alarm is sounded near the workers. The pneumatic tube model is placed on the ground, with the tubes being laid perpendicular to traffic. When a vehicle drives into the area and over the tubes, the alarm sounds.

Microwave Intrusion Alarms. A typical microwave intrusion alarm features a transmitter mounted on one drum and a receiver and siren mounted on another drum up to 1000 ft away. Strobe lights can also be included in the system to alert workers under noisy conditions. Some units also feature a drone radar unit that activates radar detectors within 2296 ft. The drone radar can be used to detect vehicle speeds and activate the siren when a vehicle is found to be traveling over a preset threshold speed. Batteries for the microwave intrusion alarms can be recharged using solar cells. The approximate cost of these units is $4000.

Other states have had difficulty in using the microwave intrusion alarms. Reports have indicated that setup time is lengthy, strobe lights were not bright enough, sirens were not loud enough, and initial alignment of the unit was very difficult. A number of states also noted that false alarms were created by rain, dust, or drum movement *(4)*.

The Iowa DOT rejected use of microwave intrusion alarms due to their lengthy setup time. Iowa tries to minimize the amount of time that crews are exposed to traffic, and the setup of the intrusion alarms would serve to extend the amount of time that a crew would need to do their job. The Colorado DOT did not approve the use of the intrusion alarms because it felt that the sirens were not loud enough, the lights were not bright enough, and alignment of the units was too difficult. Alabama DOT also had difficulty keeping test units aligned. Its test devices then failed mechanically and had to be shipped backed to the manufacturer. Pennsylvania DOT noted that false alarms were so frequent that workers ignored the alarms *(4)*. Washington DOT could not get its test unit to operate and noted that there was no troubleshooting guide to help workers determine what was malfunctioning *(3)*.

Infrared Intrusion Alarms. Infrared intrusion alarms are mounted on two cones. A transmitter cone is placed on the shoulder at the beginning of the taper, and a receiver/siren cone is placed diagonally at the opposite end of the detection zone. The alarm's 120 decibel siren is supposed to provide 4-7 seconds of warning to workers. The infrared intrusion alarms met NCHRP crash-worthiness standards regarding fragmentation, vehicle damage, and work zone hazards. Strobe lights and solar rechargers are also available. The approximate cost of the infrared intrusion alarm is $3600 *(4)*.

States testing the infrared intrusion alarm experienced a number of problems. Several states indicated that this unit was too sensitive, creating numerous false alarms. Due to the difficulty in aligning the beams, the infrared intrusion alarms can be used only for stationary operations. Also, it was noted that on hot days traffic cones become more flexible, causing the infrared beam to misalign, thereby triggering false alarms *(4)*.

The Colorado DOT tested an infrared intrusion alarm but found that the CB frequency used by the alarm had too much interference, creating many false alarms. New York DOT recommended that the use of the infrared alarms be limited to sites where workers do not enter and exit the zone while the alarm is operational in order to reduce the number of false alarms. Missouri rejected the system because it was too sensitive, and Iowa did not approve it due to alignment problems. Pennsylvania DOT tested the system, but chose not to use it since the agency could not get consistent results from the system *(4)*. Washington DOT could not align its test units and noted the device did not perform as designed *(3)*.

The Vermont DOT began testing two models of infrared intrusion alarms shortly after two state highway agency employees were injured by an inattentive driver in a work zone. The alarm's first application was in early 1995 on a survey of a bridge deck. The workers reported that when vehicles tripped the alarm, the siren was "more than loud enough" to be heard over the noise of the generator and other equipment in the work zone. The intrusion alarm has since been used at nearly a half-dozen work zones. The research team concluded that the alarm might be best suited for projects that are a day long or shorter. However, even regular users reported having trouble installing it at job sites that lack shoulders wide enough for the placement of the alarm's components *(15)*.

Pneumatic Tube Alarms. The pneumatic road tube intrusion alarm system involves placing road tubes on the roadway perpendicular to the flow of traffic at the beginning of the work zone. The tubes are connected to a transmitter that activates a siren and a strobe light when a vehicle drives over them. They can protect a distance of anywhere from 98 ft to 590 ft. The cost of a pneumatic road tube alarm is between $880 and $4000 depending on the options desired.

States that have tested the pneumatic tube system have also encountered problems. Several states reported that the system does not give enough warning time for workers to respond, and that the setup time is long. There were also questions about the durability of the system and its dependability. Pneumatic tubes are also easily punctured by heavy equipment and may require boosters after several hundred feet to ensure that air pressure is sufficient to activate a switch (*3*).

Queue Length Detector

The queue length detector was developed as part of the SHRP project to develop innovative work zone safety devices. SHRP claims that this device will reduce crashes and injuries near work zones by alerting drivers that downstream traffic has stopped or is moving slowly. This feature will allow motorists to take alternate routes or be prepared to stop. SHRP notes that there is the potential to combine the queue detector with an intrusion alarm since the technologies are very similar. The approximate cost for the queue detector is $3400.

The queue length detector consists of an infrared beam that is transmitted across the road. The beam detects how fast the traffic is moving and sends a signal when traffic slows down below a preset threshold or stops entirely. This signal can be used to activate a changeable message sign, sound a work zone alarm, or alert authorities. The queue detector can transmit this signal via cellular phone, hardwired communication, or other communication device. If a changeable message sign is used, it can be programmed to display the message for a preset amount of time, even if vehicles start exceeding the speed threshold.

Pennsylvania DOT has used a queue detector with limited success. At a work zone along Route 22, eight queue length detectors were placed upstream of the site. Within 1 minute of a detected decrease in speed, informative messages were posted along the series of 15 variable message signs (*16*). The actual detector worked well, but the cellular communication between the detector and the changeable message sign was disrupted during high demand periods. The Virginia DOT examined the queue detector several years ago but had problems with false alarms (*4*).

Speed Control Measures

In 1998, the Fatal Accident Reporting System (FARS) recorded that 41.6 percent of all fatal work zone crashes in Texas listed vehicles exceeding the posted speed limit or safe speed as a contributing factor in the crash. Nationally, 30.7 percent of work zone fatalities had excessive speed as a contributing factor. Given the high percentage of work zone crashes that are at least partially caused by speeding, measures that reduce vehicle speeds through work zones could prove to be very beneficial. The information gathering task found several devices that have the potential to reduce work zone speeds, thereby possibly improving work zone safety. These devices are described in this section. The devices include radar drones, radar speed displays, and narrow lane widths.

Radar Drones

Radar drones are small, lightweight, weatherproof devices that are equipped with sensors that activate radar detectors in vehicles. These devices are used to make drivers with radar detectors think there is a police presence in the area, potentially causing drivers to slow down. They can be mounted on guardrails, signs, or maintenance vehicles. Batteries can last several days without recharging, and vehicle-mounted units can be plugged into cigarette lighters. Radar signals are sent on the K band, which is the band most often used by police.

Studies have shown that vehicles with radar detectors tend to travel faster than those without detectors (*17*). Since excessive speed is a contributing factor in many work zone crashes, radar drones have been used to influence drivers to slow down by making them think that there is a police officer nearby. Radar drone manufacturers claim that their products result in significant decreases in mean speeds and the number of high-speed vehicles. Manufacturers also report a decrease in crashes and speed variance when drone radar is used. Drone radar units typically cost about $400.

Previous studies have shown that while radar drones do not create large reductions in the mean speed of the traffic stream, they can be effective in reducing the number of vehicles traveling 10 mph or more over the speed limit. Benekohal et al. tested radar drones at two sites in Illinois (*18*). They found that mean speeds were reduced 8 mph at their first site, but speeds were not reduced significantly at the second site.

Freedman et al. examined radar drones at a long-term construction site, a short-term work zone, a rural high-crash location, and an urban high-crash location. They found that the maximum reductions in passenger car mean speeds were 3.4 mph in work zones and 1.8 mph at high-crash locations. The maximum reductions in tractor trailer mean speeds were 3.6 mph at work zones and 2 mph at high-crash locations (*19*). A study by Ullman found that radar drones reduced work zone speeds 2 to 3 mph, but had the greatest impact on trucks and vehicles traveling over 65 mph, possibly due to the higher incidence of radar detectors in these vehicles (*20*).

All of these studies noted that commuters and truck drivers who drove the road repeatedly became suspicious if there was no obvious enforcement presence. Occasional police enforcement would seem to be important to maintain the effectiveness of radar drone.

Speed Measurement Laboratories (SML) performed a study from 1995 to 1998 on rural interstates in New Mexico and Texas. In recent years, radar detectors can translate signals into specific warnings. The radar drones SML studied had the ability to send out three programmable messages: Road Hazard Ahead, Emergency Vehicle, and Train Approaching, and the detectors received these messages. The study on I-40 in New Mexico and I-10/I-40 in Texas showed a consistent decrease in traffic speeds. The drones were placed on arrow boards, construction barrels, and department of transportation vehicles. Trucks slowed down an average of 3 to 4 mph while cars reduced their speeds an average of 2.5 mph. Monitoring of CB transmissions revealed that truck drivers communicated the radar detections to each other *(21)*.

The South Dakota Highway Safety Department has used radar drones for over three years, and they have 500 units operating on moving maintenance vehicles. South Dakota found that the number of cars traveling more than 75 mph and the number of crashes involving maintenance vehicles has decreased *(4)*. An increase in the number of severe braking incidents and amount of erratic vehicle behavior near the maintenance vehicles was observed when the drone radar was in use. Since most of this behavior occurred as vehicles passed a maintenance caravan, South Dakota now instructs its maintenance personnel to turn off the radar unit as vehicles pass. The Kentucky Department of Highways also uses drone radar with their moving maintenance operations and has been impressed with its effectiveness *(4)*.

The Massachusetts DOT has used radar drones in work zones for almost two years. Their operation involves the attachment of the radar drone to arrow panels or sign posts. The general observation is that the work areas have become safer with the reduction in vehicle speeds *(22)*.

The 12th district of the Ohio DOT, in the Cleveland area, has used radar drones for approximately three years. The units have been placed on portable changeable message signs for freeway construction projects. These signs are placed in advance of the work zone to serve as a warning device. The main motivation for this project was to alert long haul commercial motor vehicles not familiar with the area. The results of this project are that vehicle speeds have been reduced, especially at night *(22)*.

In 1996, the Virginia DOT purchased 36 radar drone units to use in construction work zones on their interstate system. A study in 1997 found that the devices were reducing the overall speeds in the work zones by 3 to 4 mph. In addition, the variance of the speeds was also reduced. These three transportation departmental applications concluded that the devices could be used in all urban and rural freeways within their states *(22)*.

The Connecticut DOT has used radar drones for over three years but does not feel that it has been particularly effective. They stated that truck drivers quickly became aware of the widespread use of drone radar in the state and began to ignore it. The Missouri DOT does not use radar drones due to concerns about limited effectiveness *(4)*.

Speed Display Devices

Speed display devices combine radar units with a dynamic message interface. The speed display device typically shows either the vehicle's current speed or some other type of warning message to alert drivers of their speed. Speed displays should be more effective than radar drones since vehicles without radar detectors will also be impacted, and a visual component is added to the system. Figure 8 shows an example of a speed display.

McCoy et al. tested a speed display at a work zone in South Dakota *(23)*. The unit tested was manufactured by the South Dakota DOT and utilized a 28 in. by 20 in. display with 9 in. tall digits. The speed display was solar powered and was mounted on a portable trailer. A "Work Zone" advisory sign as well as an advisory "45 mph" were mounted on the radar trailer *(23)*. The unit was tested at a bridge replacement project on I-90 near Sioux Falls, South Dakota. A 55 mph speed limit was in place, and the road carried 9000 vpd. The right lane was closed prior to a median crossover. Two speed monitors were installed 310 ft. in advance of the lane closure taper *(23)*.

Speed data were collected before the units were set up and after they had been in place for one week. This study found an average speed reduction of 4 mph for vehicles with two axles, and a 5 mph average reduction for vehicles with more than two axles. The speed display also significantly lowered the percentage of vehicles traveling more than 10 mph over the speed limit. The number of two-axle vehicles traveling more than 10 mph over the speed limit was reduced between 20 and 25 percent, while the number of vehicles with more than two axles traveling more than 10 mph over the speed limit was reduced by 40 percent *(23)*.

Figure 8. Radar Speed Display.

The Minnesota DOT tested a radar-controlled speed display that constantly displayed the speeds of passing traffic. The sign was tested in a work zone posted at 40 mph. Before the radar speed display was installed, the 85^{th} percentile speed was 58 mph, and 14 percent of all traffic was exceeding 60 mph. After the speed sign was put in place, the 85^{th} percentile speed was 53 mph, and only 1 percent of all traffic was exceeding 60 mph *(24)*.

Garber and Patel tested a radar-activated changeable message sign (CMS) to determine its impact on speeding vehicles driving through interstate work zones. The CMS displayed one of five warning messages when a vehicle was detected traveling more than 3 mph over the posted speed limit. The sign face remained blank if a vehicle had not triggered the message *(25)*.

After testing the messages at seven different interstate sites in Virginia, they determined that the message "YOU ARE SPEEDING -- SLOW DOWN" was the most effective in reducing speeds at the beginning, middle, and end of the work zone. Vehicles that triggered this warning message reduced their speeds by an average of 15.3 mph. The mean speed of the entire traffic stream was reduced by about 4 mph, and the 85^{th} percentile speed of the overall traffic stream was reduced by 6 mph. The percent of vehicles speeding by any amount was reduced from 41.5 percent to 12.2 percent once the CMS with radar was set up, and the percent of vehicles speeding by 5 mph or more was reduced from 14.5 percent to 3.1 percent after the CMS was installed. The percent of vehicles traveling more than 10 mph over the speed limit dropped from 3.8 percent to 1.2 percent. The researchers found all of these reductions to be statistically significant at α=0.05, except for the percent reduction in vehicles speeding by 10 mph or more *(25)*.

Garber and Srinivasan conducted a follow-up study to determine whether the impact of the CMS with radar decreases as the duration of exposure and length of work zone increases. Speed reductions for vehicles that triggered the warning message averaged about 9 mph, which is about 6 mph less than the results from the first phase of the study. Speed reductions were still found to be statistically significant after the sign had been in place for seven weeks, although no specific relationship was found between the duration of exposure and the amount of speed reduction generated. Analysis also revealed that as the length of the work zone increases, the speeds at the end of the work zone tend to increase *(26)*.

Narrow Lane Widths

Vehicle speeds can also be reduced by narrowing the lane widths through a work zone. This can be accomplished using a variety of channelizing devices, including traffic cones, drums, and concrete barriers. By narrowing the lane width, it is possible to create moderate speed reductions throughout the entire length of the narrowed section. Lane narrowing also presents a relatively inexpensive form of speed control for long-term projects since there is usually very little ongoing cost to maintain the narrowing.

There are several disadvantages to using lane narrowings for speed control, however. The capacity of the road may be reduced as a result of reducing the lane widths. Also, certain types of crashes such as sideswipes may increase as a result of the narrower lane widths. Lane narrowings may not be very effective on multilane highways since the middle lanes will not be reduced in width *(27)*.

Richards et al. tested the impact of lane width narrowing on speeds through a work zone. They used traffic cones to reduce lane widths to 11.5 ft. and 12.5 ft. When the lane width was reduced to 12.5 ft., there was an average speed reduction of 2.8 mph. Speeds dropped an average of 3.8 mph when the lane widths were reduced to 11.5 ft. The researchers determined that the difference in speed reduction between the 12.5 ft. lanes and the 11.5 ft. lanes was not statistically significant *(28)*.

The researchers did note some problems with using lane width reduction. While the 11.5 ft. width lanes resulted in lower speeds than the 12.5 ft. width lanes, the standard deviation of the speeds also increased. This may create more vehicular conflicts since vehicles' speeds were more variable. The researchers also noted that trucks tend to cross over the lane line with the 11.5 ft. lanes when there were no vehicles beside them, creating a potential safety problem. The cones were sometimes blown over or struck more frequently with the narrower lane width, making the maintenance of the lane width reduction significant *(28)*.

Motorist Guidance

The work zone environment is very complex, requiring motorists to process a variety of stimuli as they traverse the work zone. The information gathering task revealed several devices that have been put into use in order to more clearly delineate vehicle paths through work zones. The devices described herein include opposing traffic lane dividers, direction indicator barricades, and portable changeable message signs.

Opposing Traffic Lane Dividers

The opposing lane traffic divider (OTLD) is composed of two 12 in. by 18 in. panels, which are mounted back-to-back on a fiberglass post. The post is connected to ballast plate as a base, and the bracket that holds the panel is opened and closed by a foot pedal. The sign contains an upward and a downward arrow, signifying that the lane is used for two-way traffic. The unit weighs 23 lb. and experiences minimal creeping in winds up to 50 mph. The base can be secured to pavement with adhesive for long-term use. Figure 9 shows an example of an OTLD.

The opposing traffic lane divider has been approved by the FHWA, the national MUTCD, and the Texas MUTCD. These documents state that "opposing traffic lane dividers are delineation devices used as center lane dividers to separate opposing traffic on a two-lane, two-way operation." Three companies manufacture OTLDs, and there are no significant differences in the products. The background of the signs is orange, with a minimum of engineer grade sheeting. The supports must also restore to the upright position after a minimum of 50 hits.

The states that have used OTLDs have generally had success with them. The consensus is that they are easy to install and remove, and that they appear to be widely understood by the public. OTLDs can be implemented with very little training, and they appear to be cost-effective *(4)*.

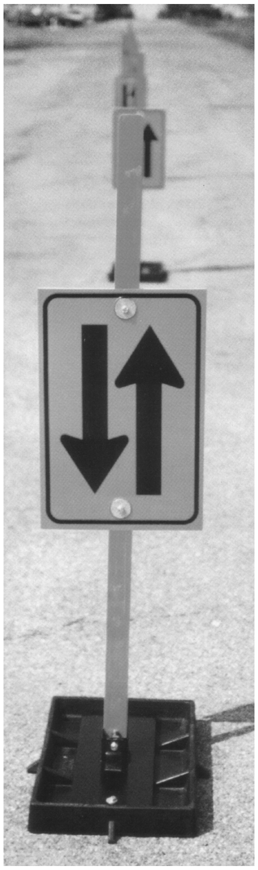

Figure 9. OTLD.

In 1994, after flooding made bridges impassible, Georgia DOT used opposing lane dividers to mark detour routes. The dividers were installed on Route 247 near Macon when rising water forced the southbound portion of the six-lane freeway to be converted to two-way operation *(29)*. The traffic engineer on the job reported that the OTLDs were easy to see and were a very effective means of signing the road. The device offered clearer instructions to drivers traveling on roads with reconfigured paths. The department continues to use the dividers when they need a way to display the changed traffic patterns to motorists *(15)*.

The Indiana DOT modified the traffic on I-70 outside of Indianapolis during a construction project over a summer. Traffic was made to travel in both directions on the westbound lanes. In addition to OTLDs, the department also used temporary curbs and installed delineator tubes. Engineers stated that the OTLDs clearly marked the travel lanes, improving the safety of motorists. The use of OTLDs has grown since a departmental test in 1993. The results of this test were similar to later studies, and drivers were encouraged to stay clear of the temporary centerline *(15)*.

New Hampshire DOT has used commercial OTLDs for over a year. They have had success using them for urban bridge work, but usage on interstates has caused problems since gusts of wind from passing trucks can knock the signs over *(4)*.

Mississippi DOT previously used flexible delineator tubes along the median when converting one-way lanes to two-way lanes on roadways *(15)*. The tubes were not effective in conveying information, and the risks of head-on collisions were high. The department first tested the devices in July 1992, using the OTLDs in the middle third of a project with the delineator tubes on the first and last third. Vehicles were observed to stay further away from the centerline when passing the OTLDs than the tubes.

In addition to the field test, the Mississippi DOT also surveyed motorists as to what message the two devices conveyed. Approximately 95 percent correctly identified the message of the OTLDs, while 51 percent correctly interpreted the delineator tubes. Almost 85 percent of the respondents said that the OTLDs provide more information than the tubes. Based on the favorable results of the field tests and surveys, the department has continued the use of OTLDs. Their added visibility also allowed the department to space the OTLDs 197 ft. apart, as compared to the 98 ft. spacings between delineator tubes. This increase aids in reducing the amount of time it takes to set up the system *(15)*.

Maryland has found that the OTLDs were well respected by motorists and generally received favorable reactions. Maryland also noted that they were easy to install and required almost no maintenance *(3)*.

Several states have experienced problems with the OTLDs. Nebraska has had problems with the durability of OTLDs and noted that they did not stay in place well. Nevada found that they tended to shatter when struck during cold temperatures *(3)*.

The Texas DOT traditionally used concrete barriers to separate traffic flows, but this practice has eventually proved to be too costly for temporary work zones. Also, the time needed to set up these devices was too great. The concrete barriers had to be installed using cranes, and transported to and from the site with tractor trailers. The department reported that OTLDs can be set up by one person and are much easier to remove and transport. According to Thomas Bohuslav, director of the construction division, the low cost of installing the OTLDs has saved the highway department a considerable amount of money. The ease of installation has also reduced the risk of injury to workers *(15)*.

Two TxDOT districts now regularly use OTLDs. The Childress District has estimated that it has saved $1.6 million from direct and passive costs as a result of using OTLDs. TxDOT experienced some initial problems with keeping the panels upright, but this has been corrected by reducing the panel size from 11.8 in. by 23.6 in. to 11.8 in. by 17.7 in. The district engineer in Uvalde said that they had used the OTLDs as an alternative to temporary striping *(4)*. OTLDs have also been used by the private sector in Texas. A Fort Worth contractor had used the devices for over four years. He felt that the OTLDs were superior to any other device available to delineate split traffic operations other than concrete barriers *(4)*.

Direction Indicator Barricades

The direction indicator barricade (DIB) provides positive directional guidance to motorists at the taper to a work zone. The DIB consists of a single plastic panel hinged to a pair of horizontal feet. An arrow sign is at the top of the DIB, and an orange and white diagonal stripe panel is at the bottom of the DIB. If desired, a steady-burn or flashing light can be mounted to the top of the DIB. Figure 10 shows an example of the DIB. The manufacturer claims that the unit is designed to fall flat if hit. The cost is $60-100 depending on the grade of sheeting used and whether a light is attached or not *(4)*.

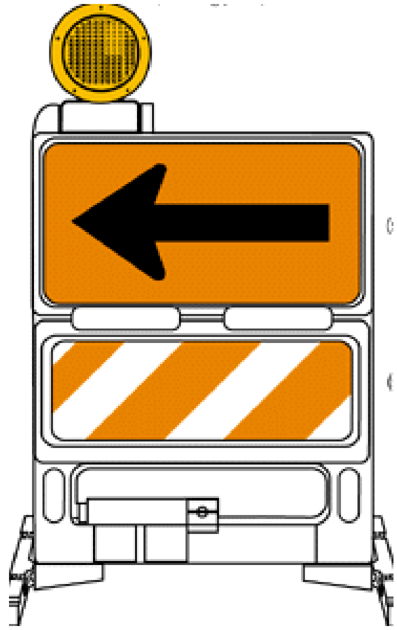

Figure 10. Direction Indicator Barricade.

DIBs have been used by Arkansas, Georgia, Alabama, and Illinois. All four of these states have been pleased with the DIBs. After one year of using the DIB, the Russellville District of the Arkansas DOT reported that the device was very useful. The maintenance crew particularly liked the ease in handling and setting up the device when compared to that of the traditional sawhorse barricade. They also stated that they felt safer with the device in place, and the observed traffic flow in the work zones had improved *(15)*.

Georgia DOT (GDOT) began evaluating the DIBs in the spring of 1994 in the Atlanta metropolitan area, with a majority of the projects on the Interstate system. The maintenance work crews reported that the DIBs performed well in all applications and seemed to be respected by drivers. GDOT also noted that the barriers were quick to install and easy to store, and far superior to barrels. The compact size of the DIBs enabled workers to set them up very quickly, minimizing the amount of time the workers are exposed to traffic *(15)*.

Alabama DOT (ALDOT) tested the DIBs for nearly two months on two-lane and undivided four-lane rural highways that carried a range of speeds and between 150 and 15,000 vehicles per day. The ALDOT reported that the devices were reliable, easy to install and move, and accepted by maintenance workers. Motorists encountering the device appeared to recognize and interpret the device faster than with standard traffic cones. Based on the limited effects by the weather and other factors on the devices, the DIBs proved to be sturdy and durable. ALDOT has approved of the immediate use of the DIBs, but suggests further testing on the device's effectiveness at night and its long-term safety record *(15)*.

Illinois DOT decided to use the DIB in the summer of 1994 on a bridge reconstruction project on I-55 near Springfield. DOT personnel believed that the device was more effective in telling motorists what was expected of them. The arrows provided more positive guidance, and the DOT stated that the devices were perfect for use in the taper end of a closed lane. Illinois received requests from field crews to use more DIBs and has started replacing drums with DIBs *(15)*.

Portable Changeable Message Signs

Changeable message signs (CMSs) are used primarily to provide real time, dynamic information about current road conditions. Specifically, changeable message signs have been used to supply detour information, warn of lane drops, provide additional reinforcement of speed limits, and warn of the periodic use of flaggers. Changeable message signs generally cause little or no disruption to traffic flow, and are effective at night or during inclement weather.

Changeable message signs should only be used for short periods. If they are used for long-term applications, they tend to lose some effectiveness. Users should always make sure that messages are up-to-date and reliable, otherwise drivers will lose confidence in the messages on the CMS. Messages must also be designed so that they are short enough to be read by drivers as they pass by the sign (*30*).

Several studies have been conducted to determine the impact of changeable message signs on work zone traffic conditions. Richards et al. found that a CMS showing a speed limit message reduced vehicle speeds by an average of 3 mph (*31*). Another study by Hanscom found that a CMS that provided warning of an upcoming lane closure increased preparatory lane change activity and reduced speeds by up to 7 mph (*32*). This resulted in significantly fewer late exits from the closed lane.

Benekohal and Shu found that a CMS displaying a speed advisory message ("SPEED LIMIT 45 MPH - WORKERS AHEAD") resulted in speed reductions near the CMS (*33*). This message reduced passenger car speeds by 2.8 mph and truck speeds by 1.4 mph. This study also found that the number of cars exceeding the speed limit was reduced by 20 percent. Vehicles were also observed to increase their speed as they traveled further away from the sign.

The FHWA published a report in 1992 that covered general guidelines for the use and operation of changeable message signs (*34*). This report included the following guidelines:

- It is better to display little or no information if the operator is unsure of current traffic conditions.
- Telling drivers information that they deem trivial or already know results in a loss of sign credibility.
- Run-on messages are not suitable when traffic is moving at freeway speeds.
- Messages must be legible from a distance that allows drivers to read and comprehend the message. The minimum exposure time is one second per short work or two second per unit of information, whichever is larger.
- Character height should be at least 18 in. for freeway applications.

Flagger Safety Devices

Flaggers occupy a very exposed position in the work zone, making their safety very important. Drivers approaching flaggers need to be aware of their presence as well as the message that they are conveying. The information gathering task revealed several devices that either increase the visibility of the flagger, warn approaching vehicles of a flagger's presence, or make the message conveyed by the flagger more visible. These devices include flashing stop/slow paddles, portable traffic signals, portable rumble strips, and temporary stop bars. Other devices described earlier, such as high-visibility vests and clothing, may also have applications to flagger operations.

Flashing Stop/Slow Paddle (Original Design)

The flashing stop/slow paddle is available in 18 in. and 24 in. faces, with "STOP" on one side and "SLOW" on the other. One type (T-series) has two flashing lights that can be seen from either side. Another (J-series) has two lights that can only be seen from the STOP side of the paddle. The signs are attached to an 8 in. long PVC handle, where the batteries are kept. The handle comes with two PVC attachments that can keep the sign 72 in. above grade. Two standard "D" size batteries provide over 24 hours of continuous steady flashing. The paddle face is made with reflective sheeting.

During the spring of 1995, the Pennsylvania DOT distributed flashing stop/slow paddles to its district work crews. The paddles were used at more than 300 work zones on two-lane, two-way highways where speeds at the work zone sites ranged from 35 mph to 55 mph. Flaggers reported that the flashing paddles caused drivers to slow down, although no speed data was collected to substantiate this. Based on these results, Pennsylvania DOT has approved the continued use of the paddles (*29*). Alabama DOT distributed the flashing stop/slow paddles to their eight divisions. The flaggers that utilize the paddles found that they were easy to handle and drivers responded well to them.

Iowa DOT purchased 75 flashing stop/slow paddles and conducted a survey in 1994 and 1995 inquiring the workers of their opinions of the paddles. The overall consensus was that the workers felt very positive and supportive of the extra protection that was provided. The workers felt the signs were effective in poor visibility conditions, such as at dawn, dusk, and during foggy conditions (*15*).

The Kentucky Transportation Center distributed 28 paddles to be tested by workers that underwent a training session provided by the center. The paddles were used in a variety of work zones, ranging from Interstate highways to city streets. When questioned, workers favored the continued use of the devices because the paddles made attracting the attention of drivers easier (*15*).

The New Mexico DOT distributed 12 paddles to its six districts. All workers using the devices said that the paddles did accomplish their intended objectives very effectively. In addition, the flaggers liked the fact that the batteries were placed in the pole of the sign. The paddle's center of gravity was kept low, reducing the top-heaviness of the device. This made the paddle easier to handle and place. Two potential problems were identified by the New Mexico DOT. The battery life of the device was deemed too short, and the lights of the paddle could be broken if the paddle was not treated carefully (*15*).

The South Dakota DOT used flashing stop/slow paddles on two maintenance projects in 1995. The devices equally impressed flaggers and motorists, and the maintenance crews reported that drivers actually pulled over to share positive comments concerning the higher visibility of the paddles. Workers appreciated the low weight of the paddles, which greatly increased the ease of using them. Although they were deemed effective during the daytime hours, the paddles were expected to be used mainly for nighttime applications (*15*).

The Colorado, North Dakota, Maine, Virginia, Oklahoma, and New Jersey DOTs also reported favorable experiences with the flashing paddles. These states indicated that the workers generally felt safer when these paddles were used, and that drivers seemed to respond favorably to the paddles (*3*).

Some deficiencies of the flashing paddles have been noted. The Alabama and Nevada DOTs found that the paddles sometimes create radio interference. Arkansas and Alabama DOTs also had difficulty keeping the batteries charged for the duration of the project. Arkansas also felt that the less expensive flashing paddles were not durable enough. Tennessee and West Virginia DOTs both thought that the flashing paddles improved visibility of the flagger greatly at night, but did not improve visibility very much during the day. They recommended against using the flashing mode during the day in order to conserve battery power (*3*).

Portable Traffic Signals

In 1987 TTI researchers studied the use of portable traffic signals to replace flaggers (*35*). Although portable traffic responsive systems are currently available, this study only examined a fixed time portable signal system. This signal was studied at three work zones with annual average daily traffic (AADTs) between 600 and 10,000 vpd and lengths between 600 and 2600 ft. The cost for the fixed time signals was $8000 per pair. At the time of the study, TxDOT had limited the use of portable signals to lane closures on restricted width bridges where construction would take more than three months (*35*).

The study found that overall delay increased by using the fixed time portable signals instead of flaggers. This was primarily attributable to the fact that flaggers can allow isolated arrivals to drive through the work zone without stopping, and fixed time signals cannot. This had the greatest impact on delay when hourly volumes were low. When the hourly volume was 50 vph, the fixed time signal increased the average delay by 24 s./vehicle over flagging. When the hourly volume was 750 vph, use of the fixed time signal only resulted in a delay increase of 2 s./vehicle over flagging (*35*).

A rough economic analysis was performed to determine if any cost savings was achieved by using the fixed time portable signals instead of flaggers. The initial capital cost of buying the portable signal was not included in the analysis. The calculations assumed a value for travel time of $10.40/vehicle-hour and an hourly rate for flaggers of either $6.00/hr or $9.00/hr. The results of these computations showed that the additional delay incurred by using the signals was more than offset by eliminating the labor costs of the flaggers, creating an hourly savings of between $8.88 and $13.84 (*35*).

The researchers also looked at driver compliance with the portable signals. The rate of noncompliance with the red indication was as high as five vehicles running the red light per 1000 entering vehicles. Some drivers drove straight through the red light without stopping, while others came to a halt and then proceeded through the signal. Red light noncompliance could create a severe hazard in actual construction zones. Additional reinforcement at the signal such as a temporary stop bar or a "STOP HERE ON RED" sign (R10-6) may be necessary to ensure compliance with portable signals *(35)*.

Portable Rumble Strip

A typical portable rumble strip is made of durable neoprene rubber, with dimensions of 20 in. by 120 in. by 0.75 in. It weighs 75 lb. and is laid across the approaching lane, usually about 328 ft. ahead of the flagger. It can be deployed from a pickup by two workers. When driven over, a moderate jolt is delivered to the vehicle to get the driver's attention, and the low rumble is also audible. It is best suited for low-speed roads that carry few heavy trucks. Portable rumble strips meet the specifications in section 6F-8D of the Texas MUTCD. The cost is approximately $100 per rumble strip.

The consensus among the states that have tested the portable rumble strip has been unfavorable. It has been noted that the rumble strips do not work well when high speeds or large truck volumes are present since these cause the strip to shift out of position *(29)*.

In 1995 SHRP reported that most states that had tried the portable rumble strip had difficulty in keeping it in place. Some also had problems handling and deploying the strips, indicating that it took a considerable amount of time to install and remove the strips *(4)*.

The Indiana DOT tested the rumble strips at several locations and found that the strip cracked easily and moved when trucks passed over it. It also noted that some drivers swerved around the strip to avoid it since it looked like a flat tire in the roadway. The Maryland, Utah, and Arkansas DOTs also noted this phenomenon. New Mexico DOT found that the strip wore out quickly, which created a hazard since this exposed the devices used to hold the rumble strip in place. None of the DOTs that studied the portable rumble strip recommended its use *(4)*.

Temporary Stop Bars

Temporary stop bars have been painted on the road in the past in order to designate a stopping point for vehicles when flaggers are present. These temporary stop bars are typically only used when there is going to be long-term construction work since it is not feasible to install temporary markings and then remove them if the project lasts only a short time. Booker et al. tested a removable stop bar that would be appropriate for these short-duration projects *(36)*.

The stop bar tested consisted of six 40 in. long, 6 in. wide, and 0.4 in. thick white rubber interlocking strips. These strips were placed three long by two wide to create a 10 ft. long by 12 in. wide stop bar. This stop bar was evaluated on a two-lane rural highway near Port Arthur, Texas, with an AADT of 7000 vehicles per day. The eastbound lane of this road was closed in order to install a shoulder.

The data collection included collecting approach speeds, speeds through the work zone, and stopping distances relative to the flagger. The temporary stop bar reduced the average stopping distance between the vehicle and the flagger from 57 ft. to 47 ft. in the closed lane, and from 67 ft. to 43 ft. in the open lane. It also reduced the standard deviation of the distance from 32 to 21 ft. in the closed lane and from 99 to 38 ft. in the open lane. The stop bar was observed to have had a very positive impact on designating a stopping point for vehicles. Only 5.5 percent of the vehicles encroached on the bar, and none were observed stopping beyond the bar. The stop bar did not have an impact on speeds *(36)*.

PRIORITIZATION OF MEASURES

The researchers developed an initial list of alternatives during the first six months of the project. Shortly after meeting members of the Advisory Panel at ATSSA's Traffic Expo in San Antonio, the researchers and Advisory Panel reconvened. At this meeting, the preliminary list was refined and subsequently used to develop the experimental approach for the first year data collection. The various techniques and findings summarized in the literature review were used by the Advisory Panel and research team to identify the most promising traffic control devices, treatments, and/or practices. Table 3 shows the measures that were determined to be of high priority to TxDOT, and Table 4 shows the techniques that were considered to be of low or medium priority. The activities in year one of this project focused on examining the most applicable of the high-priority items listed in Table 3.

Table 3. High Priority Measures.

Item	Advantages	Disadvantages
Larger/Fluorescent Signs	• Improved visibility • Easy for workers to set up and remove	• Hard to quantify impact
High-Visibility Clothing	• Improved nighttime visibility • Orange clothing may blend in with work zone background	• Solid fabric vests are more visible, but less likely to be worn during warm weather
Opposing Traffic Lane Dividers	• Can be used as a temporary centerline • Proven effective in other states	• Some states have experienced problems with OTLDs staying upright • Limited application
Portable Changeable Message Signs	• Flexible device with multiple application • Can increase preparatory merging and decrease speeds	• Lengthy setup • Expensive
Portable Rumble Strips	• Combination of tactile and auditory stimulus commands attention	• Problems with deploying and handling strip • Problems with having strips stay in place • Some drivers avoid strip, thinking that it is debris in road
Radar Drone	• Tends to impact vehicles traveling at highest speeds • Vehicles with detectors may slow down surrounding vehicles • Trucks with CB radios relay information to other trucks in area	• Repeated use may lose effectiveness if no enforcement is present • Sudden braking can lead to vehicle conflicts
Radar Speed Display	• Radar signal and visual display help reinforce speed limit • Possibility of implied photo-enforcement	• Expensive • Some drivers may accelerate past display to see speed increase
Sign Attachments	• Helps draw attention to sign	• May lose effectiveness over time
Temporary Stop Bar	• Designates stopping point for vehicles at flagging station	• Anchoring of stop bar may be problematic
Vehicle Visibility Improvements	• Improved vehicle visibility at night	• Additional cost for vehicles

Table 4. Low and Medium Priority Measures.

Item	Advantages	Disadvantages
Direction Indicator Barricades	• Provides more guidance than barrels or cones	• Greater potential for misapplication
Flashing Stop/Slow Paddle	• Lights improve paddle visibility • Approved by national MUTCD	• Battery replacement may be frequent
Intrusion Alarm	• Alerts workers to vehicles entering work area	• Only appropriate for stationary work zones • Susceptible to false alarms • Very long setup times • Expensive
Lane Narrowing	• Speed reductions are possible	• Potential increase in sideswipe crashes
Portable Traffic Signal	• Drivers are familiar with device	• Battery replacement costly • May disrupt downstream intersection operations • Drivers may brake severely or run light if it is not expected
Queue Length Detector	• Provides information on stopped traffic, allowing drivers to slow down or choose alternate route	• Problems with false alarms • Cellular communications can cause problems during peak hours
Remote Driven Vehicle	• Improved safety during moving maintenance operations	• Expensive • Technology requires extensive training
Water-Filled Barriers	• Water absorbs majority of crash impact • NCHRP 350 approved for up to 62 mph	• Standard size water truck can only fill three barriers • Antifreeze must be added in winter months • Mixture must be pumped out when the barrier is moved for environmental reasons • Durability is still a question • Spilled water after impact can create potentially dangerous conditions

CHAPTER 3
RESEARCH METHODOLOGY

This chapter describes three main areas of the first year activities; site selection, data collection, and data reduction. The site selection process was essentially mandated by the type of devices, practices, and/or treatments being evaluated and the need for a type of work zone that would allow for adequate evaluation. The measures of effectiveness are not constant from one device, practice, or treatment to another. Consequently, different types of data were collected. The data collection section describes the equipment used to collect these data and explains how these data were collected. Finally, the procedures used to reduce the data and prepare it for analyses are described.

SITE SELECTION

The main focus of this project is on rural high-speed temporary work zones. The problem statement originated in the Childress District, a rural district with a significant amount of high-speed roadway on the state system. Since this project emphasized safety in rural maintenance work zones, the first year data collection activities all took place in the Childress District.

Sites were chosen based on the need of the maintenance crews, the schedule availability of the research team, and the type of work zone activity needed to evaluate the different traffic control devices, practices, and/or treatments. Once the different traffic control devices, practices, and/or treatments were identified for evaluation, the research team forwarded a schedule of availability to the maintenance crews along with a description of the type of work zones that were needed for product evaluation. The maintenance crews would then set certain activities to the side and expedite others in order to coordinate their needs with the needs of the research team. After a week was identified where the appropriate type of work was planned, the maintenance supervisor and area engineer called the research team and the trip was scheduled.

Therefore, the sites were based on where the work was to be conducted. However, certain qualifications had to be met. The sites had to be rural high-speed roadways on the state system. The sites were either two-lane highways or four-lane divided highways, depending on the devices, practices, and treatments that were being evaluated. Appendix A contains sketches of each work zone layout along with detailed descriptions of the sites.

DATA COLLECTION

Data were collected using the equipment and procedure described below. Speed data, conflict data, and driver surveys were all collected in order to provide insight into the performance of the various treatments.

Data Collection Equipment

The data collection effort used the following equipment:

- Two light detection and ranging (LIDAR) guns (see Figure 11);
- Two pairs of piezoelectric sensors with appropriate traffic counter classifiers; and
- One mobile recording video system with a high-mast camera support. The mobile recording video system includes:
    - outdoor Cohu surveillance camera with a 10 by 105 mm auto-focus lens;
    - 380 mm color monitor;
    - 24 hour time lapse video cassette recorder; and
    - gas-powered generator.

LIDAR guns were used to track speed profiles of vehicles as they approached the work zones (LIDAR guns are more commonly referred to as laser guns). The use of laser guns in speed data collection has two major advantages over the use of radar guns. First, the laser guns can measure distance to a vehicle as well as the speed of that vehicle, while the radar guns only measure speed. To measure speed and distance, hundreds of invisible infrared light pulses are released from the gun every second. As each pulse is transmitted, a time is started. When the energy of the light pulse is received by the device, the time is stopped. Based on elapsed time, the distance is calculated using the known speed of light through the atmosphere. An algorithm is used to derive the speed of the target from a successive number of range calculations.

Figure 11. LIDAR Gun.

The second advantage of laser over radar is that the signal transmitted travels in a straight line, whereas the radar transmission is conically shaped. The narrower beam has at least two distinct advantages associated with it; it is harder to detect with conventional radar and laser detectors, and it allows for more precise measurements of individual speeds. An off-the-shelf device frequently employed by law enforcement personnel for speed enforcement was used in this data collection effort (see Figure 11). It has the capability of continuously tracking a vehicle's speed through a section of the roadway.

The laser guns used in this study are specially adapted for continuous speed and distance measurements. They are supplemented with laptop computers that are linked to the guns. A software program was developed within TTI to transmit the speed, time, and distance from the laser gun to a laptop computer. The transfer of data occurs at a rate of approximately three times per second. A sample of the data retrieved using this method is shown in Table 5.

Table 5. Sample of Laser Data.

Comment	Time	Speed (mph)	Distance (ft.)
DAT	15:57.3	26	107
DAT	15:57.6	26	96
DAT	15:57.9	26	85
DAT	15:58.2	26	73
DAT	15:58.5	26	62
DAT	15:58.8	26	52
REM	grn car 1		

Each time a vehicle's speed was recorded by each researcher, the software prompted for a remark concerning the latest data string. The field technicians input the color of the vehicle, the type, and which lane the vehicle was in. If, at any time during the collection of data for a single vehicle, the vehicle turned, was impeded by another vehicle or pedestrian, or impeded in any other way, the technicians entered "no good" in the remark field.

To collect the speed, headway, and classification data, class II piezoelectric sensors were used in conjunction with traffic counters/classifiers (TCC). Piezoelectric sensors are accurate devices for measuring vehicle speeds and headways. Furthermore, one can classify vehicle type using the FHWA 13 classification scheme. The sensors afford the greatest control of measurement location, can collect data over long periods of time, and can measure speeds, headways, and classifications for practically every vehicle that passes over them.

The mobile video recording system allows for continuous video recording without requiring access to the camera. The system consists of an enclosed trailer (providing protection and storage for the recording equipment) and a 30 ft. telescoping pole with a camera in an environmental housing unit. An internal view of the trailer is shown in Figure 12. Figure 13 shows how the trailer can be hidden when roadside development is present.

Figure 12. Internal View of Video System Trailer.

Figure 13. Video System.

Data Collection Procedure

Data were collected at each site under daytime conditions during weekdays and under normal weather conditions. Piezoelectric sensors and LIDAR guns were used to obtain speed profiles of free-flowing vehicles as they traversed the study sites. The piezoelectric sensors were used to capture spot speeds prior to the work zone (free of any influence from work zone traffic control) and spot speeds approximately two-thirds through the work zone (to capture halo effects). Two LIDAR guns were used to capture speed profiles of free-flowing vehicles between the piezoelectric sensor stations. Operators of the LIDAR guns were as inconspicuous as possible (using state vehicles parked on the sideslope as blinds) and exercised caution ensuring not to be observed collecting speeds.

In addition to speed profiles, CB radio conversations were also recorded during the after periods. Many truck drivers possess both radar detectors and CB radios, and relay information about the presence of law enforcement officials to other drivers approaching their location. Since both the speed trailer and radar drone emitted a signal that triggers radar detectors, CB conversations allowed researchers to identify the extent to which drivers warned others of radar transmissions.

At several of the flagger-controlled sites, a downstream driver survey was conducted in order to learn which devices were most frequently noticed by drivers. The survey station was located approximately 500 ft. downstream of the work zone. A roll-up sign with the legend "TRAFFIC SURVEY" was placed 500 ft. in advance of the survey station, and an additional roll-up sign with an identical legend was placed at the survey station itself. Two members of the data collection team performed the survey activities. One person would flag vehicles to stop, and the other person would administer the survey.

The survey was kept short in order to minimize driver inconvenience and reduce delays. The survey consisted of the following two questions:

- Did you notice anything different or unusual about the work zone you just drove through?
- If so, what did you notice and did it make you drive any differently?

Responses to these two questions were recorded and summarized in order to ascertain which devices made the largest impression on drivers. This provided a qualitative measure of effectiveness for the devices tested.

A data collection summary for each site is provided in Table 6. When discussing individual sites, the site number, as designated in this table, will be used throughout the remainder of this report. In general, however, the discussions from this point forward will focus on flagger operations and lane closure work zones. For additional details regarding each site, see Appendix A.

Table 6. Data Collection Summary.

Site Number	Date	Highway	Speed Data		Driver Survey	Video	CB Radio	Work Zone Operation
			LIDAR	Piezo				
F1	5/11/99	US 83	✔			✔	✔	Flagger
F2	5/12/99	US 83	✔			✔	✔	Flagger
LC1	5/13/99	US 287	✔	✔		✔	✔	Lane Closure
LC2	6/16/99	US 287	✔	✔			✔	Lane Closure
LC3	6/17/99	US 287	✔	✔		✔	✔	Lane Closure
LC4	6/18/99	US 287	✔	✔		✔	✔	Lane Closure
LC5	8/24/99	US 287	✔	✔		✔		Lane Closure
F3	8/25/99	SH 86	✔	✔	✔	✔		Flagger
F4	8/26/99	SH 86	✔	✔	✔	✔		Flagger

DATA REDUCTION

The speed data collection efforts for each site produced two separate files (one from each researcher). After the data were collected, a student worker would join the files, matching each string of speeds using the times (the times on the laptops were synchronized before data collection commenced) and the descriptions of the vehicles. Strings of data marked “no good” were discarded as well as other data that appeared suspect. This effort resulted in one concatenated file from the two previous files for each study site.

Another key element in the data reduction effort was knowing the precise location of each LIDAR gun with respect to traffic control devices in the advance warning areas of the work zones. Before leaving each site, the researchers measured distances to at least two traffic control devices or other referenced features within the right-of-way. This was done in order to locate the exact placement of the LIDAR guns with respect to the roadway. Knowledge of the exact positioning is crucial in matching the speed measurements to the roadway positioning.

Profiles of the work zone, including the approach to the work zone, through the work zone, and the downstream area, were sketched while at the sites. Distances between features were precisely measured with a laser range finder. Using these profiles, the speeds and distances obtained with the LIDAR guns were matched with the exact location of the LIDAR guns with respect to the roadway. This synchronization effort allows the construction of speed profiles along the segment of roadway of interest.

Table 7 summarizes the data reduction efforts. Data were collected but later discarded during the transition period between the before-and-after periods. This transition period was used to set up the various treatments.

Table 7. Summary of Study Sites.

Site	Analysis Period	Time Period	Elapsed Time	Spot Speed Vehicles ①	Speed Profile Vehicles②
F1	Before	12:15 - 1:10 PM	0:55	③	33//9
	After	1:20 - 2:00 PM	0:40	③	19//⑤
F2	Before	9:00 - 9:52 AM	0:52	③	⑤//17
	After	10:07 AM - 12:15 PM	2:08	③	29//29
LC1	Before	11:10 AM - 12:45 PM	1:35	330//625	62//111
	After	1:36 - 3:00 PM	1:34	181//614	95//⑤
LC2	Before	11:00 - 11:38 AM	0:38	260 // 357	27//26
	After	12:18 - 3:15 PM	2:57	673 // 834	103//220
LC3	Before	10:00 - 11:30 AM	1:30	④//533	99//49
	After	12:05 - 3:00 PM	2:55	④//884	208//52
LC4	Before	10:20 AM - 12:00 PM	1:40	④//530	107//63
	After	1:15 - 3:10 PM	2:55	④//852	180//60
LC5	Before	10:30 - 11:30 AM	1:00	167//190	41//40
	After	12:20 - 1:37 PM	1:17	250//274	48//50
F3	Before	11:30 AM - 12:10 PM	0:40	2//8	6//6
	After	1:00 - 3:00 PM	2:00	23//24	8//9
F4	Before	10:25 AM - 12:00 PM	1:35	13//17	8//7
	After	12:30 - 2:10 PM	1:40	13//21	5//5

① Upstream//Downstream. Upstream spot speed counts are reduced because both lanes were open to traffic and the sensors were installed on the shoulder lane. Downstream counts include all vehicles because only one lane was open to traffic.
② Observer 1//Observer 2. The amount of vehicle speed profiles captured with the LIDAR guns varied among the operators.
③ No sensor data was collected at this site.
④ One set of piezo sensors were damaged following the first day of data collection. They were unusable throughout the remainder of the data collection activities.
⑤ The LIDAR gun malfunctioned and did not collect any data.

Reference Points

There are points along the approach to a work zone and through a work zone that may potentially reduce speeds. Using the approach Benekohal et al. (*18*) describe, these points are termed influence points. Influence points are defined as locations within the approach to and throughout the work zone that may have a traffic control device or roadway feature that influences speed.

The use of influence points exclusively, however, can create substantially long gaps in approach speed profiles where one may be interested in comparing speeds. Consequently, additional reference points were used in conjunction with the influence points. The combination of these points are used to assess differences in speeds. All points of interest have been labeled and termed reference points. Tables 8 and 9 list the reference points for the sites that utilized flagger control and those that involved a lane closure on a multilane facility, respectively.

Table 8. Reference Points for Flagger Control Operations.

Label	F1		F2		F3		F4	
	Dist	Description	Dist	Description	Dist	Description	Dist	Description
A	0	1st Ref Pt	0	1st Ref Pt	0	1st Piezo	0	1st Piezo
B	250	2nd Ref Pt	250	2nd Ref Pt	500	1st Ref Point	6366	1st Ref Pt
C	500	3rd Ref Pt	500	3rd Ref Pt	750	2nd Ref Pt	7000	2nd Ref Pt
D	750	4th Ref Pt	750	4th Ref Pt	1000	3rd Ref Pt	7234	Be Prepared to Stop (CW21-8)
E	1000	5th Ref Pt	1000	5th Ref Pt	1250	4th Ref Pt	7350	3rd Ref Pt
F	1250	6th Ref Pt	1250	6th Ref Pt	1436	Flagger Station	8223	Flagger Station
G	1500	7th Ref Pt	1500	7th Ref Pt	6106	2nd Piezo	8650	4th Ref Pt
H	1750	8th Ref Pt	1750	8th Ref Pt			9000	5th Ref Pt
I	2000	9th Ref Pt	2000	9th Ref Pt			8350	6th Ref Pt
J	2250	10th Ref Pt	2200	Be Prepared to Stop (CW21-8)			9723	End of Construction
K	2350	Be Prepared to Stop (CW21-8)	2500	10th Ref Pt			13867	2nd Piezo
L	2500	11th Ref Pt	2750	11th Ref Pt				
M	2750	12th Ref Pt	3000	12th Ref Pt				
N	3000	13th Ref Pt	3250	Flagger Station				
O	3250	Flagger Station						

Table 9. Reference Points for Lane Closures.

Label	LC1		LC2		LC3		LC4		LC5	
	Dist	Description	Dist	Description	Dist	Description	Dist	Description	Dist	Description
A	0	1st Piezo	0	1st Piezo	0	Upstream Spot Speed Location	0	Upstream Spot Speed Location	0	1st Piezo
B	1995	Road Work Ahead - Traffic Fines Double (R20-5)	1000	1st Ref Pt	1000	1st Ref Pt	1000	1st Ref Pt	1000	1st Ref Pt
C	2170	1st Ref Pt	2000	2nd Ref Pt	1795	Road Work Ahead - Traffic Fines Double (R20-5)	1475	Road Work Ahead - Traffic Fines Double (R20-5)	1475	Road Work Ahead - Traffic Fines Double (R20-5)
D	2420	2nd Ref Pt	2775	Road Work Ahead - Traffic Fines Double (R20-5)	2000	2nd Ref Pt	2000	2nd Ref Pt	2000	2nd Ref Pt
E	2670	3rd Ref Pt	3000	3rd Ref Pt	2940	Road Work Ahead (CW20-1D)	3000	3rd Ref Pt	2251	Road Work Ahead (CW20-1D)
F	2985	Right Lane Closed Ahead (CW20-5)	3775	Road Work Ahead (CW20-1D)	3000	3rd Ref Pt	3355	Road Work Ahead (CW20-1D)	2299	Video Trailer
G	3170	4th Ref Pt	3900	Speed Trailer	3940	Right Lane Closed Ahead (CW20-5)	4000	4th Ref Pt	3000	3rd Ref Pt
H	3420	5th Ref Pt	4000	4th Ref Pt	4000	4th Ref Pt	4365	Left Lane Closed Ahead (CW20-5)	3097	Left Lane Closed Ahead (CW20-5)
I	3745	6th Ref Pt	4775	Right Lane Closed Ahead (CW20-5)	4865	Speed Trailer	5000	5th Ref Pt	3571	Radar Drone Location
J	3985	Arrow Panel	5000	5th Ref Pt	5000	5th Ref Pt	5400	Begin Taper	3826	Road Work - Traffic Fines Double (R20-5)
K	4170	7th Ref Pt	5805	Begin Taper	5285	Begin Taper	5600	Lane Closure and Arrow Panel	3978	Left Lane Closed Ahead (CW20-5)
L	4420	8th Ref Pt			6000	6th Ref Pt	6000	6th Ref Pt	4000	4th Ref Pt
M	4670	2nd Piezo	6005	Lane Closure and Arrow Panel	5485	Lane Closure and Arrow Panel	8240	Piezo	5149	Arrow Panel
N	4920	9th Ref Pt							6205	2nd Piezo
O	5170	Downstream Spot Speed Location	7915	2nd Piezo	8125	Piezo				
P	6170	3rd Piezo								

Speeds of vehicles at the reference points were determined using the spot speed data from the piezoelectric sensors and the speed profiles captured with the LIDAR guns. However, because the rate of data collection with the LIDAR guns is approximately three observations per second and the average speed of a vehicle is on the order of 100 fps, typical profiles contain speed measurements every 33 ft. Consequently, each station along the road does not necessarily have as many speed observations as vehicles recorded. Therefore, when descriptive statistics concerning the speeds at each reference point were calculated, all speeds within 49 ft. were used thus creating a 100 ft. bin. An example of this would be if a reference speed were at 500 ft. Then speeds from 451 to 549 ft. were used to determine the average, standard deviation, and other descriptive speed statistics associated with the reference point of 500 ft. Oversampling was eliminated by only using one observation for vehicles with multiple speed observations recorded in the 100 ft. bin. When more than one speed value was recorded, the median value was used.

Videotape Data Reduction

Video of the approach to each site was also collected. This effort was used to analyze traffic conflicts based on the various treatments. In year-two activities, the use of the video may be expanded to analyze brake light activations for flagger operations and lane occupancy rates as a function of upstream distance to the taper for lane closure work zones.

An analysis of crashes is traditionally performed in order to identify potential safety hazards associated with a location. However, crash analysis cannot be used for this project due to the temporary nature of the work zones studied. For this reason, conflicts were examined since they can be useful in identifying specific safety problems when no crash data are available.

A traffic conflict is defined as "an event involving the interaction of two or more road users, usually motor vehicles, where one or both drivers take evasive action such as braking or weaving to avoid a collision" (*37*). An FHWA study analyzed the relationship between traffic conflicts and crashes using the traffic conflicts technique methodology (*38*). This FHWA study found that traffic conflict studies could be good predictors of actual safety problems at a location.

Of the 14 separate conflict types used by the traffic conflicts technique, two are applicable to the work zones that were studied in this project: the slow vehicle conflict and the lane change conflict. The slow vehicle conflict involves a vehicle traveling at a faster speed overtaking a slow moving vehicle. The faster vehicle is then either forced to hit its brakes or to change lanes to avoid hitting the slow moving vehicle. Lane change conflicts involve either a vehicle being forced to brake in order to wait for a gap to change lanes, or a vehicle changing lanes when an insufficient gap exists, causing the vehicle it is moving in front of to hit its brakes or to swerve to avoid the vehicle.

The videotapes obtained during data collection were examined to identify the number of lane change and slow vehicle conflicts. Conflicts that could be attributed to the operations of the work zone were the only conflicts classified. The number of conflicts that occurred during the before-and-after period was then counted and analyzed.

CHAPTER 4
DATA ANALYSIS

The data obtained during first-year data collection were examined to determine which combinations of devices, treatments, and practices provided the most promise for further evaluation in year two. The sites were separated into flagger-controlled sites and lane-closure sites. The operational characteristics of these two types of work zones are fundamentally different, so devices may have different impacts depending on the type of work zone studied.

Speed and video data were collected and analyzed at all nine sites. Additionally, a motorist survey was conducted at sites F3 and F4 on SH 86 to assess drivers' opinions on the devices, treatments, and practices tested. Also, the TxDOT maintenance crews were interviewed to ascertain their opinions on the devices, treatments, and practices under evaluation. Conflict data and recorded CB radio conversations were also examined.

ANALYSIS RESULTS

The speed profile data for all nine sites are included in Appendix B. Summaries of descriptive speed statistics for each site and their reference points are provided in Appendix C. The cells in these tables with shaded backgrounds and bold text indicate a statistically significant difference between the before-and-after period (at a significance testing level of 0.05). It is worth noting, however, that reference points within the same table may have different numbers of actual speed observations. Consequently, for a given table, small differences at one reference point may show up as statistically significant (because many speed observations make up the data associated with the reference point) while larger differences at an adjacent reference point in the same table may not (because of relatively fewer data points).

These speed analysis results are discussed in the following sections. Flagger operation results are presented first followed by the lane closure operations. The data obtained from the driver survey, worker interviews, conflict analysis, and CB radio conversations are included after the speed analysis.

SPEEDS AT FLAGGER OPERATIONS

The speeds at the four sites with flagger operations were examined. Detailed descriptions of these sites and the work being performed are included in Appendix A. The devices, treatments, and practices under evaluation are summarized in Table 10.

Table 10. Devices Tested at Flagger Controlled Sites.

Site	Date	Highway	Treatments
F1	5/11/99	US 83	Fluorescent orange signs, radar drone, fluorescent yellow-green vests and hard hat covers, handheld strobe light attached to flagger vest, Safe-T-Spins
F2	5/12/99	US 83	Fluorescent orange signs, radar drone, fluorescent yellow-green vests and hard hat covers, handheld strobe light attached to flagger vest, Safe-T-Spins
F3	8/25/99	SH 86	Fluorescent orange signs, radar drone, fluorescent yellow-green vests and hard hat covers, retroreflective magnetic strips attached to flagger vehicle
F4	8/26/99	SH 86	Fluorescent orange signs, radar drone, fluorescent yellow-green vests and hard hat covers, retroreflective magnetic strips attached to flagger vehicle

Appendix B shows the speed profiles for these four sites, and Appendix C shows the summary of the statistical analysis for these four sites.

Sites F1 and F2

The speed profile data collected at the F1 site are shown in Figure 14. In this case, the speeds of cars and trucks are combined since some of the LIDAR data did not denote the vehicle type. The speeds collected during the after period were usually lower than those collected when no innovative measures were in place. However, the speed reduction from the before period to the after period was not found to be significant at any reference point. Vehicles begin to decelerate at a point approximately 2000 ft. in advance of the flagger station. Almost no vehicles were detected traveling over the speed limit.

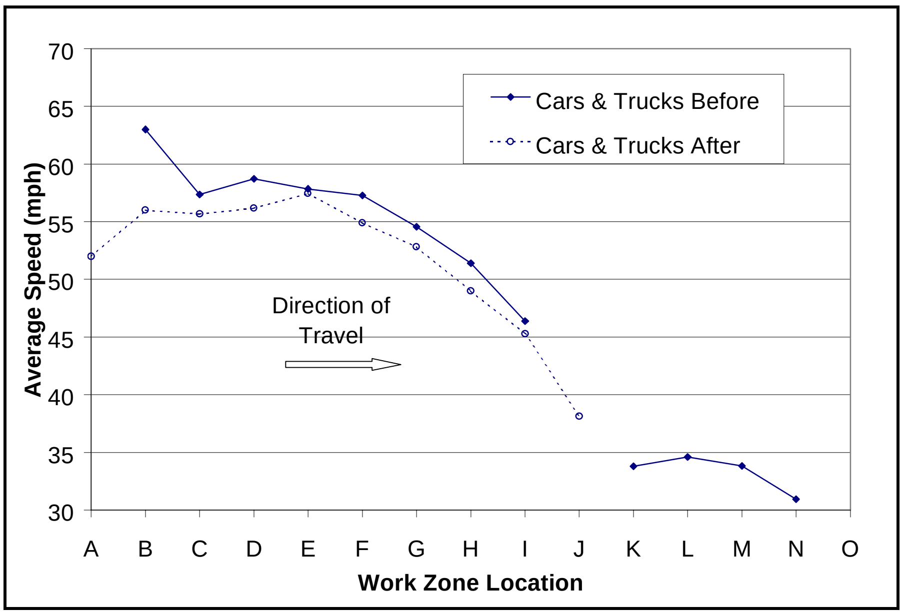

Figure 14. US 83 - May 11, 1999 Mean Speed Profile (F1).

While the speed reductions were not found to be statistically significant, the speeds in the after period were usually lower than in the before period. Speed reductions in the area prior to the start of the work zone averaged about 2.2 mph, which is consistent with previous research on radar drones. Figure 14 is shown in order to provide a representative sample of the speed profile data. All subsequent speed profiles are included in Appendix B.

The speed profile data collected at the F2 site is shown in Figure B-2 in Appendix B. The upstream LIDAR gun malfunctioned during data collection, causing all data collected upstream during the before period to be lost. The comparison of the available before and after speeds was not significant for any point for the passenger cars. Speed reductions were found to be significant at points I, K, and L for trucks, however. Points I, K, and L correspond to points 1250 ft., 750 ft., and 500 ft. before the flagging station, respectively. The speed reductions at these points range from 13.6 mph to 20.7 mph.

Although they were not significant, the speed reductions achieved averaged around 2 mph for passenger cars and around 14 mph for trucks. The speed reductions for the cars are consistent with prior research on radar drones. The speed reduction achieved for trucks was much larger than the reductions for cars. This may have been due to the smaller number of valid data points for trucks.

Sites F3 and F4

The speed profiles data collected at the F3 site is shown in Figure B-3 in Appendix B. Speed reductions were found to be statistically significant for passenger cars at reference points E and F. These points correspond to points 186 ft. upstream of the flagger station and the flagger station itself, respectively. The speed reductions were 11.5 mph at point E and 15.1 mph at point F. Additionally, the standard deviation during the after period was found to be significantly larger than the standard deviation during the before period, indicating more variation in the speeds at that point when the measures were being tested. No analyses could be performed on the trucks since there was no LIDAR data for trucks in the after period.

The speed reductions for passenger cars averaged about 7 mph just prior to the flagger station, and about 13 mph within the work zone. While the speed reductions within the work zone were found to be statistically significant, they represent a very limited sample size and should not necessarily be construed as being representative of the results that can be achieved with these devices.

The speed profile data collected at the F4 site is shown in Figure B-4 in Appendix B. No speed reductions were found to be statistically significant during this testing. Speeds through the work zone were typically slower than they were during the F3 data collection. The standard deviation of the data collected was found to be significantly different for both cars and trucks at the first piezo, with the standard deviation of the speed data being much larger during the before period than during the after period.

Speeds during the after period were actually an average of 4 mph higher prior to the work zone for passenger cars and 10 mph lower for trucks. Speed reductions within the work zone showed an average of a 1 mph decrease in speeds for passenger cars and a 1 mph increase for trucks. None of these changes were found to be statistically significant, most likely due to limited sample size.

Speed Reduction Comparisons

Figures B-5 and B-6 show the speed reductions obtained for passenger cars and trucks at the four sites with flagger control. Speed reductions for passenger cars prior to the flagging station are fairly consistent for F1 and F2, averaging around 2 mph. Speed reductions at F3 and F4 are more variable, most likely due to the limited number of data points.

SPEEDS AT LANE CLOSURE OPERATIONS

The speeds at the five sites with lane closures were examined. Descriptions of these sites and the work being performed are included in Appendix A. The devices, treatments, and practices tested are shown in Table 11.

Table 11. Devices Tested at Lane Closure Sites.

Site	Date	Highway	Treatments
LC1	5/13/99	US 287	Fluorescent orange signs, radar drone, fluorescent yellow-green vests and fluorescent yellow-green hard hat covers, Safe-T-Spins
LC2	6/16/99	US 287	Speed trailer with advisory speed sign
LC3	6/17/99	US 287	Speed trailer with advisory speed sign
LC4	6/18/99	US 287	Radar drone, advisory speed sign
LC5	8/24/99	US 287	Fluorescent orange signs, radar drone, fluorescent yellow-green vests and fluorescent yellow-green hard hat covers, retroreflective magnetic strips on work vehicles

Appendix B shows the speed profiles for these five sites, and Appendix C shows the summary of the statistical analysis for these five sites.

Radar Drones with Supplemental Measures

Several different combinations of supplemental devices were tested in combination with the radar drone. For the most part, the results of these evaluations appear to produce results that are consistent with earlier research on radar drones.

Figure B-7 in Appendix B shows the speed profile data collected at LC1. No speed reductions were found to be statistically significant. Standard deviations were found to be significantly different for reference points C, G, H, and P for passenger cars, and for points M and P for trucks. In all of these cases, the standard deviation increased during the after period, signifying more variability in speeds.

Although they were not found to be statistically significant, the passenger car speed reductions prior to the work zone averaged about 2 mph. This is consistent with the results of prior studies that tested radar drones. The speed reductions within the work zone averaged to less than 0.5 mph. Trucks showed an increase in speed prior to the work zone during the after period, and less than a 0.5 mph decrease in speed within the work zone. The percent of vehicles exceeding the speed limit decreased for both vehicle types prior to the taper. However, the percent of trucks exceeding the speed limit actually increased within the work zone.

At LC4, a radar drone and 55 mph speed advisory signs were tested. Figure B-8 shows the speed profile for LC4. Appendix C summarizes the descriptive speed statistics associated with this site. Changes in mean speeds for passenger cars approaching the work zone are inconclusive. However, there is a general trend for decreased speeds as trucks approach the work zone. Anecdotal information from the recorded CB radio conversations indicate that most truckers use radar detectors and "their watchdogs were barking" as they approached the work zone (i.e., the truckers' radar detectors were activated by the radar drone's signal). Consequently, reduced speeds by the truckers is not surprising. The variability in speeds approaching the work zone shows no trends or patterns indicating effectiveness of the treatment.

Within the work zone speeds were reduced with the radar drone and advisory speed signs. The passenger car speed reduction was significant with a 3.1 mph reduction (from 63.4 to 60.3 mph). The truck speed reduction was not significant at 0.7 mph (from 57.6 to 56.9) but considerably lower than the passenger car speeds. These reductions correspond well to previous research on radar drones (*18*). The speed variability within the work zone did not change much at all between the before-and-after periods (6.8 to 6.9 mph for passenger cars and 5.2 to 4.7 mph for trucks).

The radar drone and speed advisory signs also reduced the percentage of speeders in the work zone. The percent of passenger cars speeding in the work zone decreased from 17.8 to 12.6. The percentage of trucks speeding decreased from 33.0 to 21.8.

Figure B-8 in Appendix B shows the speed profile data collected at LC5. The only speed difference that was found to be significant was for passenger cars at the sensor location within the work zone where the speeds during the after period were found to be larger than the speeds during the before period. The standard deviations in the speeds were found to be significantly different at point A for passenger cars, and points A, D, E, F, and H for trucks. For the trucks, the standard deviation increased during the after period, indicating more variability in the speeds.

No consistent trends in speed reductions were observed at this site. This may be due to the presence of an adjacent long-term work zone. Drivers that are familiar with the area may have been expecting construction on the nearby work zone and already altered their behavior in preparation for it.

Speed Trailer Testing

The data collected at LC2 and LC3 was used to determine if speed trailers reduce vehicle speeds at rural high-speed temporary work zones. The data summarized in Appendix C provide adequate evidence that speed trailers reduce vehicle speeds. Figures B-10 and B-11 show the speed profiles for these sites. Where both before-and-after data are available to compare, there is an evident trend of decreasing speeds during the after period as compared to the before. This trend holds true for passenger cars and trucks and for both sites. Additional evidence concerning the effectiveness of speed trailers is the general decrease in percent speeders between before-and-after periods. In summary, general observations show that speed trailers do reduce speeds. However, the next question is how they affect speeds spatially. This next section will focus on three different parts of the work zone; upstream of the speed trailer, at the speed trailer, and downstream of the speed trailer.

Upstream of Trailer Location

The speed trailer used in this study was equipped with a 24 in. LED speed display. Using a crude and general rule-of-thumb for legibility distance (50 ft. of legibility distance for every inch of letter height), the speed display of the trailer should be legible at about 1200 ft. From observations made by the researchers in the field, the speed display under daytime conditions with sunny skies is somewhat less than 1200 ft. (about 800 to 1000 ft.). Therefore, approaching motorists at LC2 should have been able to first read the speed display of the speed trailer at point E. Motorists at LC3 should have been able to first begin to read the speed display at about point I. Therefore, this part of the discussion is focused on two areas, both upstream of the speed trailer. The first is upstream of the speed trailer until about 1000 ft. before the speed trailer, in other words, at the point where the speed trailer's LED display becomes visible. The second area is the approximately 1000 ft. before the speed trailer where the LED speed display is visible.

LED Display not Legible The data indicate that there was an overall increase in passenger car speeds upstream of the speed trailer where the display was not visible. This finding is likely caused by the random nature of the data since there is no reasonable explanation of this trend. However, in the same upstream area where the speed display was not visible, the trucker data showed an overall decrease in speeds. With their advanced communication ability through CB radio, the truckers are able to warn approaching truckers of the speed trailer's presence.

LED Display Legible The large LED speed display featured with the trailer used for this study was thought to have the capability to slow traffic before entering the work zone (because of the increased legibility distance). This theory was tested by comparing before-and-after speeds and speed variability at points E and F at LC2 and points G and H at LC3 (all points within the legibility distance of the speed trailer). For both passenger cars the findings were mixed and therefore inconclusive. For trucks the speeds were reduced when the speed trailer was present. In fact, for both reference points at LC3 the reduction in truck speeds was statistically significant (from 66.5 and 65.6 to 63.1 and 62.4 mph, respectively). The variability at these reference points for both sites was mixed. For passenger cars, the speed variability was reduced in all cases but the truck speed variability showed an overall increase.

The data for percent speeders show no conclusive evidence that suggest speed trailers influence speeds upstream. However, as motorists approach the speed trailer and the device and its display become legible, the percent speeders is generally reduced. A difference in the reduction trends and amount of reduction between passenger cars and trucks is evident in the tables in Appendix C. The percent truckers speeding begins to be affected further upstream than the passenger cars, and the reduction is more pronounced. The recorded CB conversations indicated that approaching truckers were well aware of the speed trailer before it was within sight distance. However, what is not known is the extent of their knowledge. They may have been aware of its presence but unsure of whether they were in risk of receiving a speeding citation. In this case, it is assumed they would reduce their speed significantly. However, if they knew that it was being used only to display speeds of approaching vehicles and there was no risk of being issued a citation, then they may have disregarded the threat of being issued a citation.

Speed Trailer Location

For purposes of this evaluation, the speed trailer location (reference point G for LC2 and LC3) and the next reference point immediately downstream (reference points H and J for LC2 and LC3, respectively) were used for the evaluation. The distance between the reference points is small enough (100 and 135 ft., respectively) that the reference points can be considered as being in practically the same location.

Mean speeds measured for both passenger cars and trucks were reduced during the after period. Although the differences were not statistically significant, passenger car speeds decreased about 2 mph and truck speeds decreased about 4 mph. The speed variability results are mixed. While passenger car speed variability was slightly reduced, truck speed variability increased.

Downstream of Trailer Location

Probably the most important aspect of the speed trailer is how it influences speeds downstream or in the work zone. Because of the restrictive space available in work zones, the most appropriate location for the speed trailer is upstream of the taper. This spacing can leave ample space for motorists to accelerate to levels near their original speeds shortly after passing the speed trailer and before entering the work zone taper. This phenomenon is called the “halo” effect and is essentially when speeds quickly rebound to or near their original level.

Speeds were captured just downstream of the trailer and then again about 0.5 mi. into the work zones. The largest speed reductions occurred just past the speed trailer. At LC2, the largest passenger car speed reduction (7.0 mph) occurred about 1000 ft. past the speed trailer. This location was also about 1000 ft. upstream of the beginning of the lane taper. Likewise, the largest truck speed reduction for LC2 occurred at the same location but this time with a mean speed reduction of 8.8 mph. At LC3, the largest speed reduction occurred at the beginning of the taper (only 500 ft. past the speed trailer). This was consistent for both passenger cars and trucks. The mean speed reductions at this point were 7.2 and 4.4 mph, respectively.

Further downstream, approximately 0.5 mi. into the work zone, all mean speeds for passenger cars and trucks for both sites were statistically lower during the after period as compared to the before period. At LC2, mean speeds of passenger cars and trucks were reduced 5.7 and 4.4 mph, respectively, while similar reductions, 4.5 and 2.8 mph for passenger cars and trucks, occurred at LC3.

Changes in speed variability downstream of the speed trailer are somewhat inconclusive. Immediately following the speed trailer passenger car speed variability is reduced but truck variability increases. Further downstream and in the work zone, speed variability is slightly reduced for most cases.

While the mean speed reductions downstream of the speed trailer show effective results, definite patterns do not exist with speed variance. However, one conclusive measure of effectiveness is reduction of the numbers of speeders downstream of the speed trailer. Appendix C contains data indicating that for each site and each vehicle class, the percentage of speeders in the work zone decreased considerably. The percent passenger cars speeding dropped from 9.6 and 7.9 to 2.0 and 2.4 for LC2 and LC3, respectively. Truck percentages dropped from 32.6 and 17.1 during the before period to 7.6 and 7.4 during the after period.

Speed Trailer Comparisons to Radar Drone

Speed reductions in the three work zones are shown in Figures B-12 and B-13. The data were adjusted so that the beginning of the taper corresponded to the same point for all three work zones. This change allows the speed profiles from all three work zones to be superimposed.

All speed reductions inside the work zone at LC2 and LC3 are statistically significant with the LC2 site having slightly greater speed reductions than LC3 (5.7 versus 4.5 and 4.4 versus 2.8, for passenger cars and trucks, respectively). Both sites where the speed trailer was tested produced speed reductions that were larger in the work zone than the three sites where drone radar was tested. The changes in speed at the three sites were a reduction of 0.3 mph at LC1, a decrease of 3.1 mph at LC4, and an increase of 2.6 mph at LC5. The speed changes for trucks were reductions of 0.4 mph at LC1, 0.7 mph at LC4, and 0.5 mph at LC5.

The profiles in Figures B-12 and B-13 show that the speed trailers produce lower speeds in the work zone than the radar drone. However, upstream of the work zone the results are inconclusive. The speed trailer location with respect to the beginning of the taper changed about 1500 ft. between LC2 and LC3 data collection. The location of the speed trailer appears to have a significant impact on the speeds through the taper and into the early area of the work zone. When the speed trailer was located about 2000 ft. upstream of the taper, the speeds entering the work zone and throughout the length of the work zone were reduced. The cause of this increased reduction is difficult to associate with any one factor such as speed trailer location because of such a limited study effort. Nonetheless, the profiles in Appendix B indicate the effectiveness of speed trailers in rural high-speed temporary work zones. Conservatively, at rural high-speed temporary work zones, speed reductions in the work zone when a speed trailer is used upstream can be expected to be about 2 to 3 mph greater than when radar drone and speed and supplemental measures are used. Overall, and based on this reduced effort, speed trailers used at rural high-speed temporary work zones can be expected to produce speed reductions of about 5 mph inside the work zone.

DRIVER SURVEY RESULTS

During the data collection at F3 and F4, a driver survey was conducted to ascertain motorists' opinions on the devices tested. This was done to obtain some qualitative information on the devices from the driving public. Note that this survey gathered information only on devices that were currently being tested in the work zone on the days in question.

A total of 26 surveys was administered during the afternoon testing, and six of the 26 drivers surveyed (23 percent) identified at least one of the devices being tested. The majority of the drivers surveyed did not identify any of the measures tested. The radar drone was mentioned twice, the fluorescent signs were mentioned four times, and the fluorescent yellow vests were mentioned once. The drivers stated that their behavior changed in the following ways:

- *Radar Drone (2 responses)* - Both drivers stated that they slowed down.
- *Fluorescent Signs (4 responses)* - All drivers stated that the signs were more visible, and that they were more prepared for the upcoming work zone.
- *Fluorescent Vests (1 response)* - The driver stated he was more aware of the presence of the workers.

MAINTENANCE CREW COMMENTS

Workers were also questioned about the devices used from August 24-26 in order to ascertain their opinions on the devices tested. The comments received from the workers included:

- All workers liked the fluorescent yellow vests. They felt that they improved their visibility and were not noticeably warmer than mesh vests.
- None of the workers cared for the hard hat covers, primarily because they did not care for their appearance.
- They indicated that the high-visibility magnetic strips for worker vehicles were beneficial. Workers indicated a preference for permanent mounting on the vehicle, rather than magnetic strips. They also felt that it was only really needed on the tailgate of pickup trucks.
- The workers also liked the fluorescent signs. They felt they were much more visible.

CONFLICT ANALYSIS

Only three sites were identified to have any conflicts that could be attributable to work zone operations: LC1, LC3, and LC4. None of the flagger-controlled sites were found to have any conflicts during the data collection period, and video data were unavailable for the LC2 site. The conflicts are shown as a rate per 1000 entering vehicles in order to account for differences in volume during the data collection periods. The video data for the LC4 site ended at 2:15 p.m., although speed data was collected until 3:00 p.m.

Given the limited duration of the data collection activities, it is difficult to make any statements about whether conflicts increased or decreased during testing. At sites LC1 and LC4, the conflict rate decreased during the after period, but it increased at LC3. Lane change conflicts were more prevalent than slow vehicle conflicts at all three sites.

Table 12. Conflict Summary.

Site	Time Period	Elapsed Time	Entering Vehicles	Slow Vehicles		Lane Change	
				Number	Conflicts per 1000 Entering Vehicles	Number	Conflicts per 1000 Entering Vehicles
LC1	Before	1:35	384	1	2.6	4	10.4
	After	1:34	405	0	0	0	0
LC3	Before	1:30	326	0	0	5	15.3
	After	2:55	862	0	0	6	7.0
LC4	Before	1:40	484	1	2.1	3	6.2
	After	1:00	243	0	0	3	12.3

CB RADIO CONVERSATIONS

CB radio conversations were monitored in order to determine if truck drivers were receiving advance warning of the radar drone or speed trailer. Review of these conversations showed that truckers did receive early warning of the presence of radar transmissions or the speed trailer. Some examples of the comments recorded include:

- "Watch out you got one of those portable computerized speed limit things up there before you get to town."
- "They have those radar machines to see how fast you're going up there in that construction."
- "There's radar. Watch out or he's gonna stop you."
- "They're using something on the top of the pole that tells them how fast everyone is running."
- "My whistle's blowing."
- "Extra points for the cones with spinners."

The conversations showed that many truck drivers were aware of the presence of the speed trailer or radar drone prior to arriving at the work zone.

SUMMARY

Table 13 summarizes the results of the data analysis for year one of the project. Again, site descriptions can be found in Appendix A. The sites labeled with an F represent flagger sites, while those labeled with an LC represent lane closure sites. The change in speed, change in percent speeders, and change in conflict rate between standard traffic control and the test period are shown. Negative value represent a decrease during the after period, meaning that speeds, the percent of vehicles speeding, or the number of conflicts decreased when the innovative traffic control was tested. Similarly, a positive number denotes an increase in the measure of effectiveness. The label “No Data” signifies that there was not data during both the before and after period to make a comparison.

Table 13. Summary of Results.

Site	Vehicle Type	Speed				Change in Conflict Rate (Per 1000 Entering Vehicles)
		Taper		In Work Zone		
		Speed Change (mph)	Change in Percent Speeders	Speed Change (mph)	Change in Percent Speeders	
F1	Car	No Data	No Data	No Data	No Data	0
	Truck	No Data	No Data	No Data	No Data	
F2	Car	-1.7	0	No Data	No Data	0
	Truck	-3.5	0	No Data	No Data	
F3	Car	-15.1	0	No Data	No Data	0
	Truck	No Data	No Data	No Data	No Data	
F4	Car	+7.9	0	-1.4	0	0
	Truck	No Data	No Data	-6.5	0	
LC1	Car	-2.1	-3.1%	-0.4	-3.8%	-10.4
	Truck	-0.2	5.3%	-0.4	5.1%	
LC2	Car	-6.8	-6.8%	-5.7	-7.6%	No Data
	Truck	-8.8	-47.3%	-4.4	-25.0%	
LC3	Car	-2.6	6.7%	-4.5	-5.5%	-8.3
	Truck	-2.4	-5.7%	-2.8	-9.7%	
LC4	Car	+3.1	14.3%	-3.1	-5.2%	+6.1
	Truck	-5.5	-32.5%	-0.7	-11.2%	
LC5	Car	+0.4	18.9%	+2.7	2.0%	0
	Truck	+0.9	5.8%	-0.5	-0.2%	

CHAPTER 5
FIRST-YEAR FINDINGS AND SECOND-YEAR ACTIVITIES

The research activities performed in year one of the project provided insight into the effectiveness of the various measures tested and helped determine future activities for the project. The first year findings are based on analyses of the speed data, conflicts, driver surveys, maintenance crew surveys, and recorded CB conversations. The recommended second-year activities are based on promising devices, treatments, and practices not yet tested and lessons learned from year one activities.

FIRST-YEAR FINDINGS - FLAGGER OPERATIONS

Table 14 summarizes the specific device findings from the flagger-controlled work zones. Additional findings related to the flagger-controlled work zones are described in further detail below. It should be emphasized here that the traffic volumes on SH 86 (sites F1 and F2) and US 83 (sites F3 and F4) were low, limiting the number of valid data points for rigorous statistical analyses.

1. Speeds approaching the flagger station were reduced for all sites except F4.
2. At sites F1 and F2, a speed reduction of approximately 2 mph was achieved for passenger cars. This finding is consistent with previous research on radar drones.
3. The F3 and F4 data did not show consistent trends although the devices tested and conditions at the sites were very similar. The low volume of traffic on SH 86 was the likely cause of this inconsistency.
4. The F2 truck and passenger car data showed very large speed reductions approaching the flagging station. These reductions were between 10 and 15 mph. While these reductions were determined to be statistically significant, these results are most likely due to a limited sample size. These results should be interpreted carefully.
5. Very few vehicles were found to be exceeding the speed limit at any of the four sites during the before or after period.
6. No significant conflicts were found at any of the flagger-controlled sites.
7. Only the radar drone was identified by motorists as actually influencing them to slow down. The fluorescent orange signs, fluorescent yellow-green vests, vehicle visibility improvements, Safe-T-Spins, and flagger strobes seem to have a negligible impact on vehicle speeds. This does not mean that these devices are not necessarily beneficial, only that speed during the daytime conditions is not a good measure of their effectiveness.
8. Workers felt that the flourescent orange signing was more visible and should be used. The flourescent orange signs were mentioned by several drivers in the driver survey. Workers also felt that the fluorescent yellow-green vests improved their visibility.
9. The recorded CB conversations demonstrated the effectiveness of the unofficial advance warning system the truck drivers use through their communication with the CB radios. Truckers were well aware of the radar drone before entering the work zone.

Table 14. Device-Specific Findings at Flagger Operations.

Devices	Use of Devices				Measures of Effectiveness						
	F1	F2	F3	F4	Conflict Analysis	Speeds		Driver Survey	Maintenance Crew Survey	CB Radios	Researcher Observations
						At Taper	In WZ				
Fluorescent orange signs	✔	✔	✔	✔	○	○	○	✚	✚	○	✚
Radar drone	✔	✔	✔	✔	○	○	✚	✚	○	✚	✚
Fluorescent yellow-green vest	✔	✔	✔	✔	○	○	○	✚	✚	○	✚
Fluorescent yellow-green hard hat covers	✔	✔	✔	✔	○	○	○	○	○	○	✚
Strobes	✔	✔			○	○	○		—	○	—
Safe-T-Spins	✔	✔			○	○	○		○	○	○
Vehicle conspicuity markings			✔	✔	○	○	○	○	✚	○	✚

NOTES: Blank cells represent devices not used and/or measures of effectiveness not evaluated. Otherwise:
✚ Positive results/comments
○ Inconclusive results/comments
— Negative results/comments

FIRST-YEAR FINDINGS - LANE CLOSURE OPERATIONS

Table 15 summarizes the specific device findings from the lane closure work zones. Additional findings related to the lane closure work zones are described in further detail below.

1. The locations where the radar drone was used resulted in speed reductions of no more than 2 mph approaching the taper for passenger cars. This is consistent with previous research on the effectiveness of radar drones. Passenger car speed reductions within the work zone were no larger than about 3 mph.
2. Truck speed reductions approaching the taper were observed at sites LC4 and LC5. Speed reductions in the work zone were no larger than 1 mph for trucks when the radar drone was in use.
3. The speed trailer resulted in the largest reductions at the beginning of the work zone and within the work zone. Speed reductions at the speed trailer were between 2 and 7.5 mph, and reductions within the work zone ranged from 3 to 6 mph.
4. The speed trailer affected the standard deviation of the speeds of cars and trucks differently. The standard deviation for cars was typically less during the test period than when standard traffic control was in place, indicating that there was less variation among the speeds. The standard deviation for trucks was larger when the speed trailer was in place, indicating larger variations in speeds.
5. The speed trailer successfully reduced the percentage of vehicles exceeding the speed limit approaching the taper and within the work zone.
6. The conflict analyses showed the use of the speed display trailers increased conflict rates approaching the work zone. When radar drone were used, the conflict rates decreased slightly.
7. The TxDOT maintenance crews felt that the fluorescent yellow-green vests and speed display trailer provided the best safety-related improvement.
8. The recorded CB conversations demonstrated the effectiveness of the unofficial advance warning system the truck drivers use through their communication with the CB radios. Truckers were well aware of the radar drone and speed display trailer before entering the work zone.
9. The Safe-T-Spins tested were not appropriate for high-speed facilities. They experienced frequent blow-down and required constant attention from maintenance personnel to keep them in an upright position.

Table 15. Device-Specific Findings at Lane Closure Operations.

Devices	Use of Devices					Measures of Effectiveness					
	LC 1	LC 2	LC 3	LC 4	LC 5	Conflict Analysis	Speeds		Maintenance Crew Survey	CB Radios	Researcher Observations
							At Taper	In WZ			
Fluorescent orange signs	✔				✔	○	○	○	✚	○	✚
Radar drone	✔			✔	✔	✚	○	✚	○	✚	✚
Fluorescent yellow-green vest	✔				✔	○	○	○	✚	○	✚
Fluorescent yellow-green hard hat covers	✔				✔	○	○	○	○	○	✚
Safe-T-Spins	✔					○	○	○	—	—	—
Vehicle conspicuity markings					✔	○	○	○	○	○	○
Speed display trailer		✔	✔			—	✚	✚	✚	✚	✚
Advisory speed signing		✔	✔	✔		○	✚	✚	✚	○	✚

NOTES: Blank cells represent devices not used and/or measures of effectiveness not evaluated. Otherwise:
✚ Positive results/comments
○ Inconclusive results/comments
— Negative results/comments

SECOND-YEAR ACTIVITIES

Based on the results of the first year's activities, several future activities were identified. These activities will provide better insight into the measures that were shown to be effective during the first year testing and will explore several new options that may improve worker safety.

1. The measures tested at the flagger-controlled work zone sites for the most part resulted in relatively small speed reductions. Cases where larger speed reductions were achieved are likely attributable to the small sample size of the data. Additional data need to be collected at flagger work zones on higher volumes roads.
2. It is unlikely that several of the measures tested in the flagger work zones would have a large impact on speeds, but may improve safety by increasing the conspicuity of workers, vehicles, and traffic signs. Measurements will be made of the fluorescent orange signs, fluorescent yellow-green vests, and magnetic retroreflective vehicle markings in order to determine the extent to which they improve the visibility of workers, vehicles, and signs.
3. Since the speed reductions achieved in the flagger work zones were relatively small, additional measures will be tested. Specifically, portable stop bars and portable rumble strips will be tested in order to ascertain their effect on traffic.
4. The speed trailer was found to have a larger impact on speeds through the lane closure work zones than either of the radar drone alternatives. The San Angelo District has recently purchased a number of speed trailers for use in their maintenance activities. Further research into the proper placement of the trailers may be very beneficial in order to determine their optimal location during maintenance activities.

CHAPTER 6
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APPENDIX A
WORK ZONE STUDY SITE LAYOUTS

Study Site Location Map

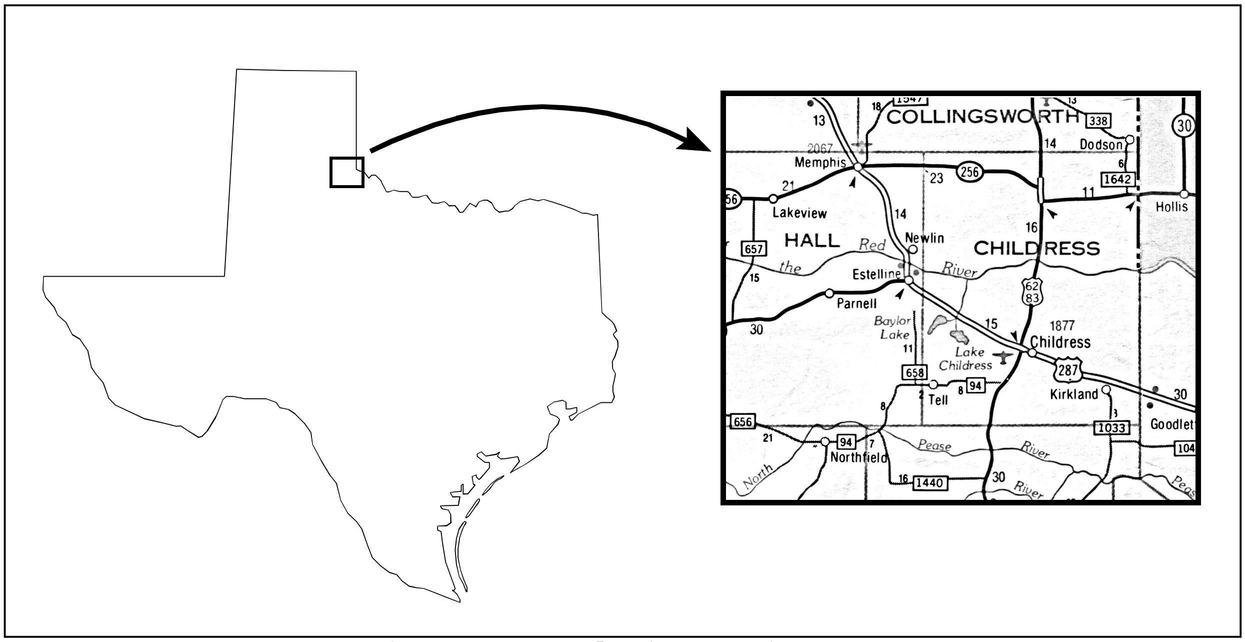

Figure A-1. Study Site Location Map.

Features common to all study sites

- Temporary rural high-speed work zones
- Dry pavement conditions
- Daytime data collection only
- TxDOT maintenance crews (no contract work)
- Traffic control in accordance with TMUTCD and TxDOT Work Zone Compliant List
- Horizontal alignment: gentle to non-existent
- Vertical alignment: 2 percent or less
- Regulatory speed limits were in effect (speed limits were not reduced other than advisory speed signing tested as part of the experimental plan)

F1 – US 83 - May 11, 1999

Location: US 83, approximately 0.25 mi. south of the intersection of US 83 with FM 2042.

AADT (1998): 1500 (17% trucks)

Description of Work: Repair and resurface approximately 0.5 mile stretch of southbound lane.

Device(s) Tested: Fluorescent orange signs, Safe-T-Spins, radar drone, fluorescent yellow-green vests, fluorescent yellow-green hard hat covers, and handheld strobe light.

Site Description: US 83 runs north-south through Childress and is a two-lane rural highway. US 83 had a differential posted speed limit at the time of data collection, with a daytime speed limit of 70 mph for passenger cars and 60 mph for trucks.

Data Collection Comments: The two LIDAR data collection stations were located 3250 ft. in advance of the flagger and 1000 ft. in advance of the flagger.

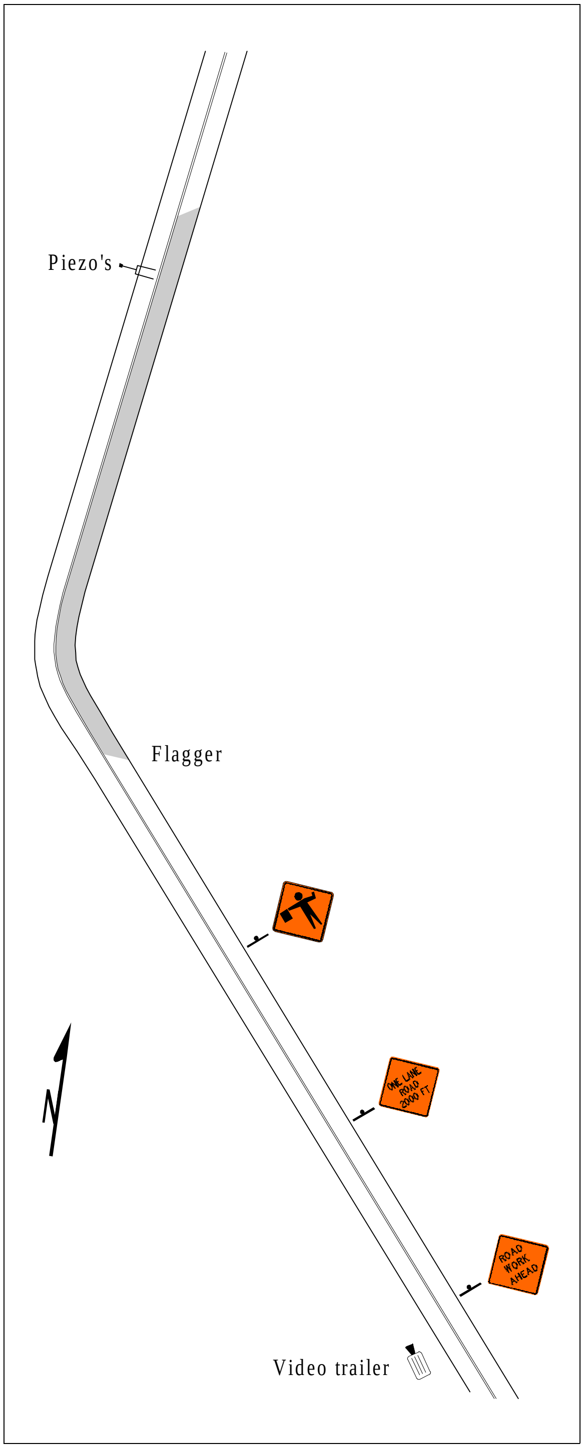

Figure A-2. F1 Site Layout (Not to Scale).

F2 – US 83 - May 12, 1999

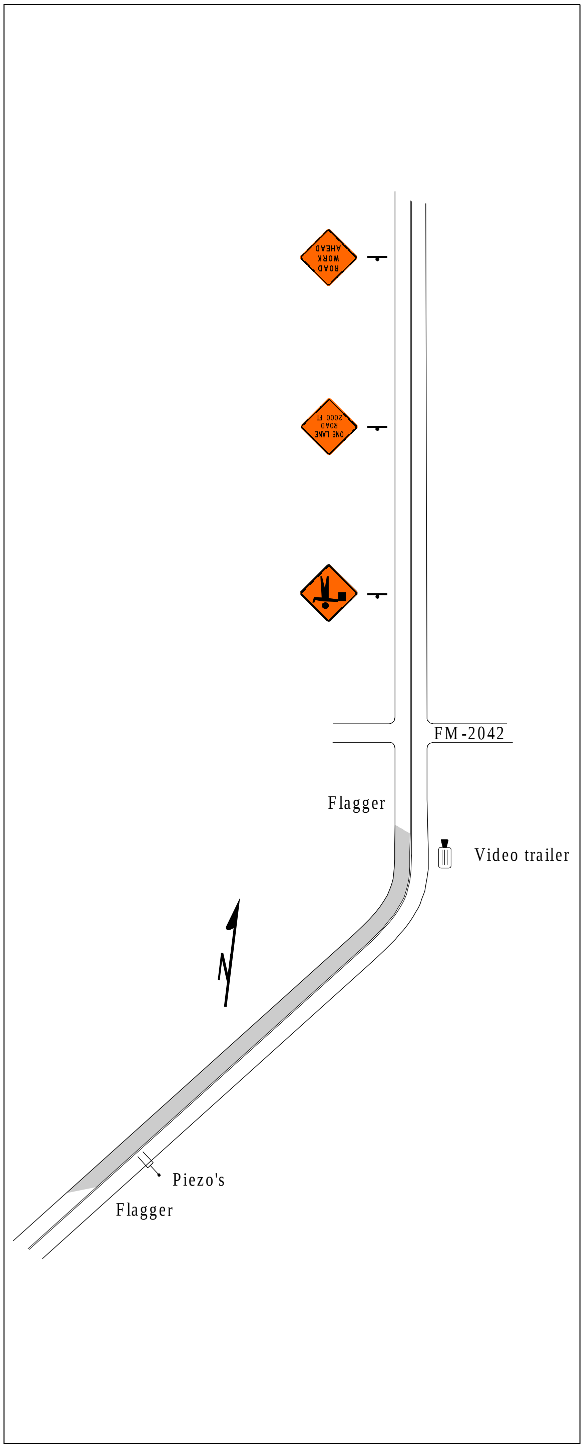

Figure A-3. F2 Site Layout (Not to Scale).

Location: US 83, approximately 0.25 mi. south of the intersection of US 83 with FM 2042.

AADT (1998): 1500 (17% trucks)

Description of Work: Repair and resurface approximately 0.5 mi. stretch of northbound lane.

Device(s) Tested: Fluorescent orange signs, Safe-T-Spins, radar drone, fluorescent yellow-green vests, fluorescent yellow-green hard hat covers, and handheld strobe light.

Site Description: US 83 runs north-south through Childress and is a two-lane rural highway. US 83 had a differential posted speed limit at the time of data collection, with a daytime speed limit of 70 mph for passenger cars and 60 mph for trucks.

Data Collection Comments: The two LIDAR data collection stations were located at the "Flagger Ahead" sign and at the flagging station.

LC1 – US 287 WB - May 13, 1999

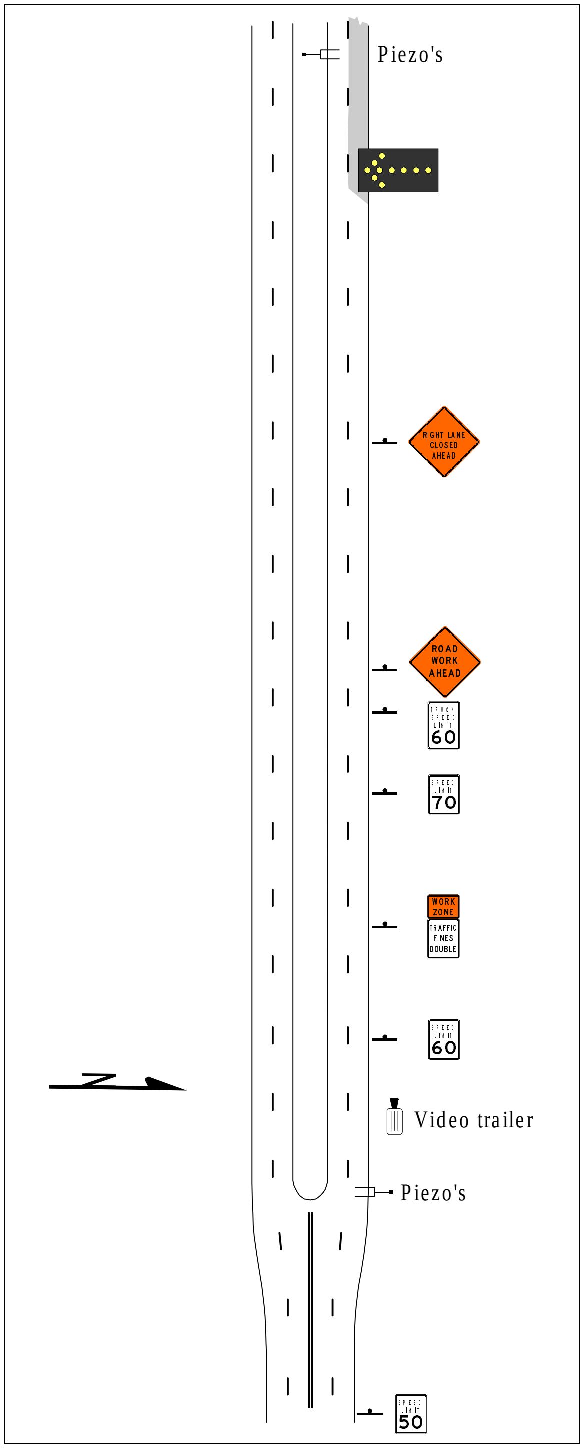

Figure A-4. LC1 Site Layout (Not to Scale).

Location: Approximately 0.3 mi. west of US 83, at the corporate limits of Childress.

AADT (1998): 8900 (33% trucks)

Description of Work: Repair and resurface westbound lane.

Device(s) Tested: Fluorescent orange signs, Safe-T-Spins, radar drone, fluorescent yellow-green vests, and fluorescent yellow-green hard hat covers.

Site Description: US 287 runs east-west through Childress and is a four-lane divided highway in a rural environment. The work zone was located approximately 0.4 mi. from where US 287 transitions from a four-lane undivided highway to a four-lane divided highway.

This site was located near the city limits of Childress, heading out of town. The posted speed limit was 50 mph near the beginning of the work zone, 60 mph 900 ft. downstream from the 50 mph speed limit sign, and then a differential speed limit was posted 1000 ft. downstream from the 60 mph speed limit sign. The differential speed limit sign showed a daytime speed limit of 70 mph for passenger cars and 60 mph for trucks.

Data Collection Comments: Piezo sensors were set up 500 ft. east of the initial work zone sign. The LIDAR data collection station was located 250 ft. east of the arrow panel.

The Safe-T-Spins tested at this site were frequently blown over by passing trucks. This required that TxDOT workers be almost constantly resetting the cones with the spinners.

LC2 – US 287 EB - June 16, 1999

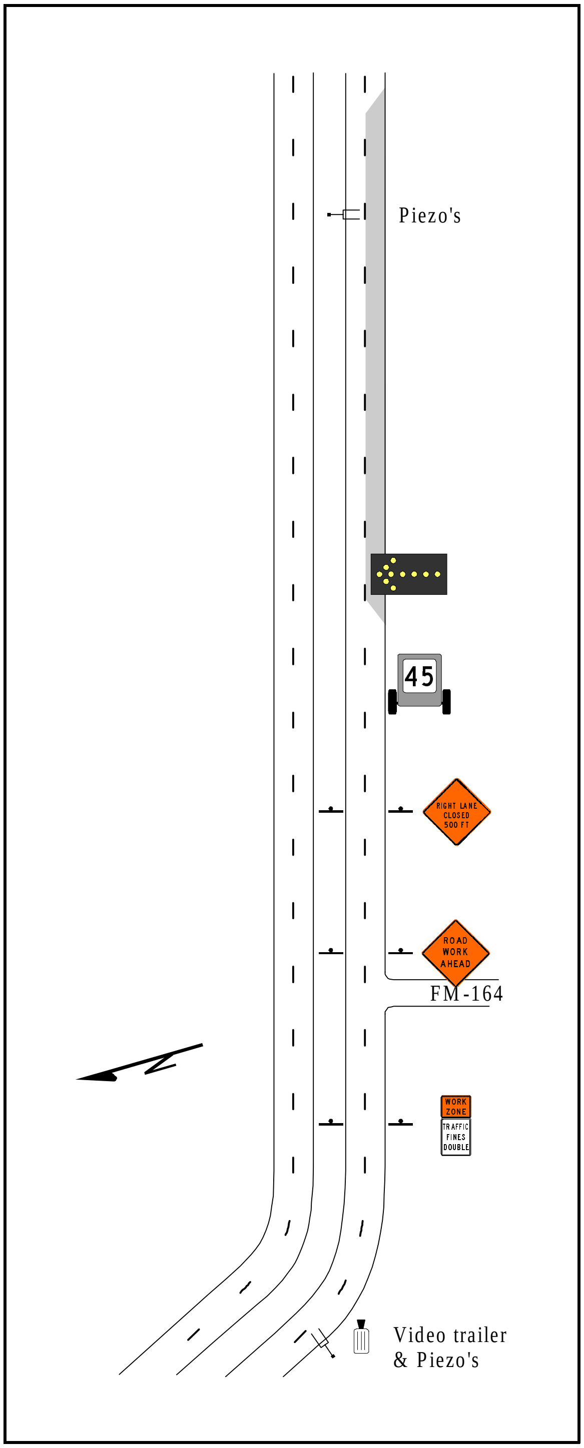

Figure A-5. LC2 Site Layout (Not to Scale).

Location: Approximately 3 mi. west of the corporate limits of Childress.

AADT (1998): 8900 (33% trucks)

Description of Work: A TxDOT crew with heavy earth-moving equipment was clearing debris from the right roadside slope in order to increase drainage capacity.

Device(s) Tested: Speed trailer with 55 mph advisory speed signing.

Site Description: US 287 runs east-west through Childress and is a four-lane divided highway in a rural environment. US 287 had a differential posted speed limit at the time of data collection, with a daytime speed limit of 70 mph for passenger cars and 60 mph for trucks. The right lane was closed for approximately 0.75 mi.

Data Collection Comments: The two LIDAR data collection stations were located 2775 ft. in advance of the "Road Work Ahead" sign and approximately 500 ft. before the arrow panel. The piezos were located 2775 ft. before the "Road Work Ahead" sign and 1900 ft. after the arrow panel.

LC3 – US 287 EB - June 17, 1999

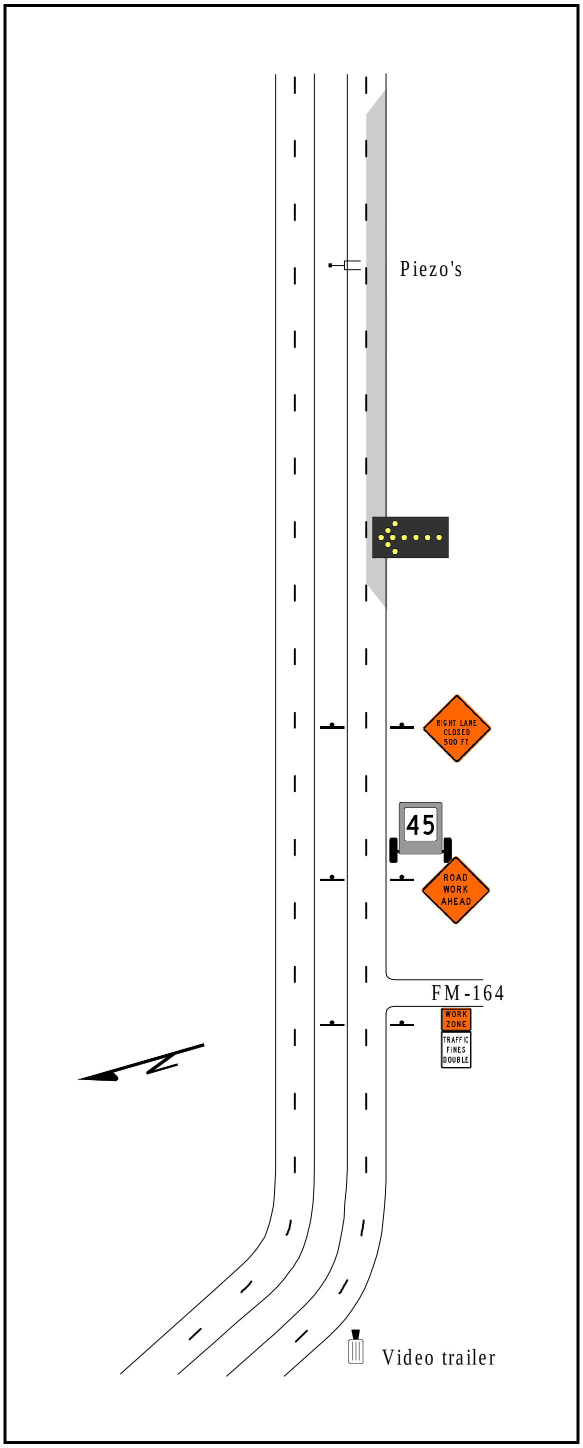

Figure A-6. LC3 Site Layout (Not to Scale).

Location: Approximately 3 mi. west of the corporate limits of Childress.

AADT (1998): 8900 (33% trucks)

Description of Work: A TxDOT crew with heavy earth-moving equipment was clearing debris from the right roadside slope in order to improve drainage capacity.

Device(s) Tested: Speed trailer with 55 mph advisory speed signing.

Site Description: US 287 runs east-west through Childress and is a four-lane divided highway in a rural environment. US 287 had a differential posted speed limit at the time of data collection, with a daytime speed limit of 70 mph for passenger cars and 60 mph for trucks. The right lane was closed for approximately 0.75 mi.

Data Collection Comments: The two LIDAR data collection stations were located 1800 ft. in advance of the "Road Work Ahead" sign and approximately 500 ft. before the arrow panel. The piezo was located 2600 ft. after the arrow panel.

LC4 – US 287 WB - June 18, 1999

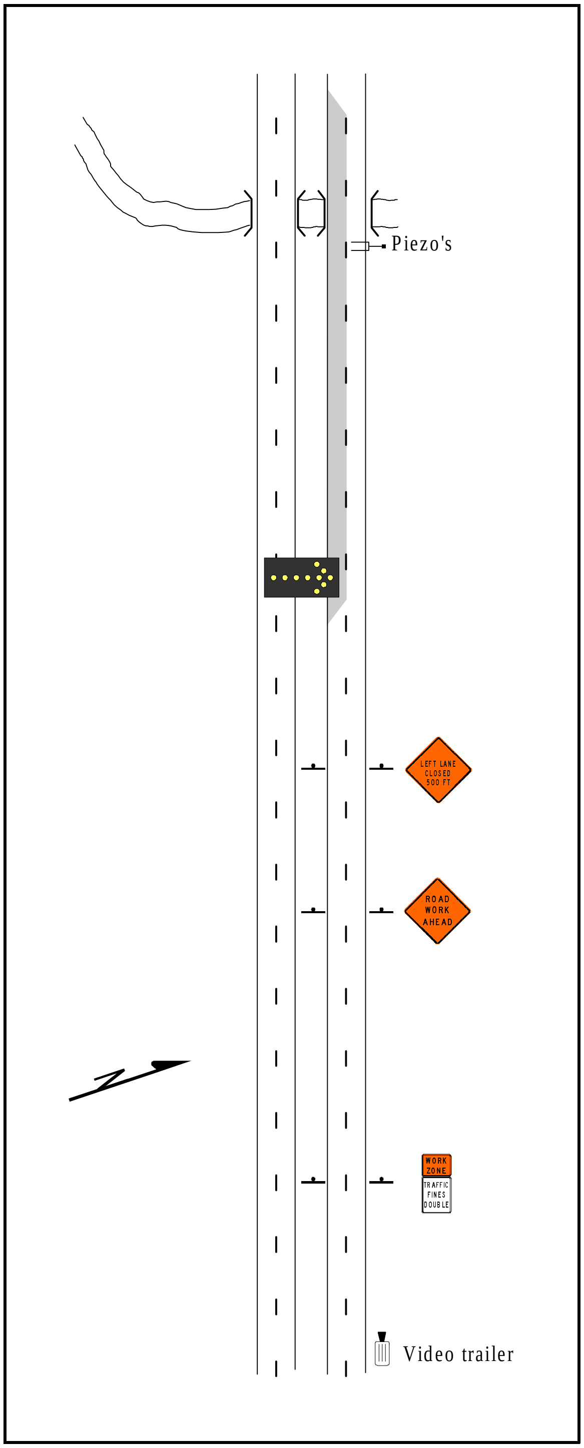

Figure A-7. LC4 Site Layout (Not to Scale).

Location: Approximately 4 mi. east of the corporate limits of Childress.

AADT (1998): 6900 (35% trucks)

Description of Work: A TxDOT crew with heavy earth-moving equipment was clearing debris in the median that was restricting drainage capacity.

Device(s) Tested: Radar drone on arrow panel with 55 mph advisory speed signs.

Site Description: US 287 runs east-west through Childress and is a four-lane divided highway in a rural environment. US 287 had a differential posted speed limit at the time of data collection, with a daytime speed limit of 70 mph for passenger cars and 60 mph for trucks. The left lane was closed for approximately 0.75 mi.

Data Collection Comments: The two LIDAR data collection stations were located 1475 ft. in advance of the "Road Work Ahead" sign and approximately 800 ft. before the "Left Lane Closed" sign. The piezo was located 2600 ft. after the arrow panel.

LC5 – US 287 WB - August 24, 1999

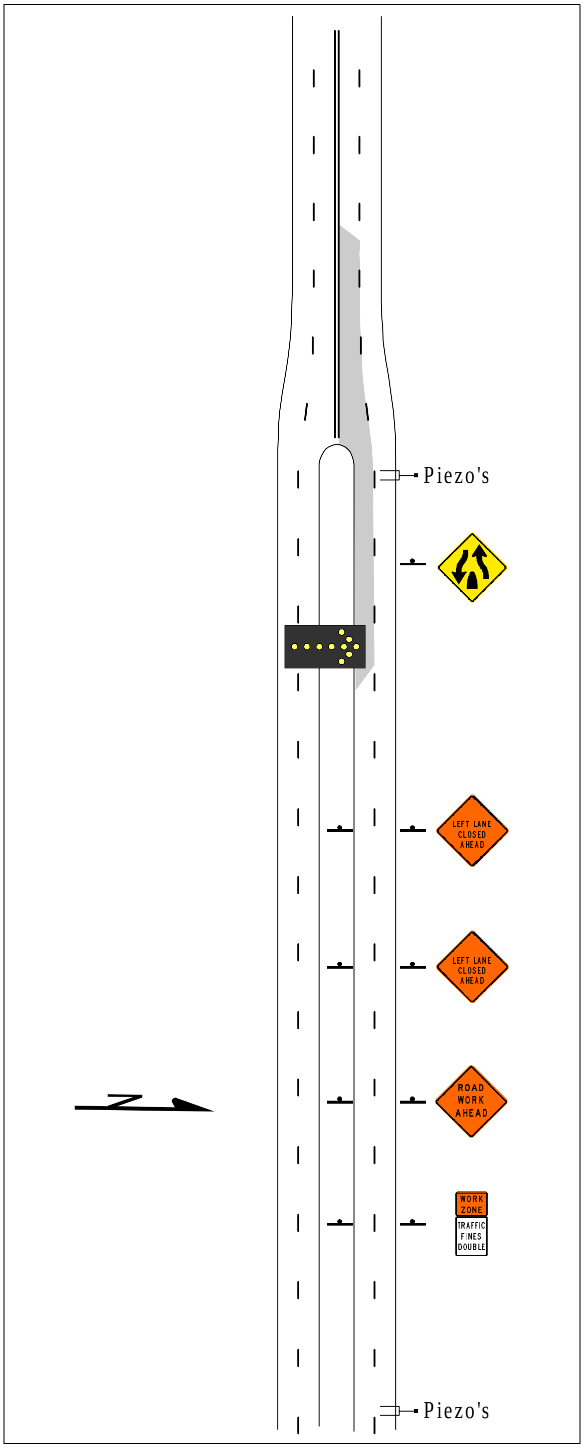

Figure A-8. LC5 Site Layout (Not to Scale).

Location: US 287, 0.5 mi. south of Hedley.

AADT (1998): 7800 (34% trucks)

Description of Work: A TxDOT crew with heavy earth-moving equipment was attempting to stabilize pavement in the left lane.

Device(s) Tested: Radar drone, fluorescent orange signs, fluorescent yellow-green vests, fluorescent yellow-green hard hat covers, and high-visibility retroreflective magnetic strips for vehicles.

Site Description: US 287 runs east-west through Hedley. At this location, US 287 transitions from a four-lane divided highway to a four-lane undivided highway. The work being performed was near the transition from a divided to an undivided facility. The posted daytime speed limit was 70 mph. The left lane was closed for approximately 0.5 mi.

The site was located just prior to a long-term construction project that went through the town of Hedley. This project was not active during the day data was collected, but signage was still in place to warn motorists of the upcoming construction. This construction may have influenced speeds at the site since drivers familiar with the area may have been familiar with the long-term construction site.

Data Collection Comments: The two LIDAR data collection stations were located 640 ft. before the "Road Work Ahead" sign and 400 ft. before the "Left Lane Closed Ahead" sign. Piezos were positioned 1475 ft. before the "Work Zone - Traffic Fines Double" sign.

The radar drone and high-visibility magnetic vehicle strips were located at the LIDAR data collection station before the "Left Lane Closed Ahead" sign.

F3 – SH 86 - August 25, 1999

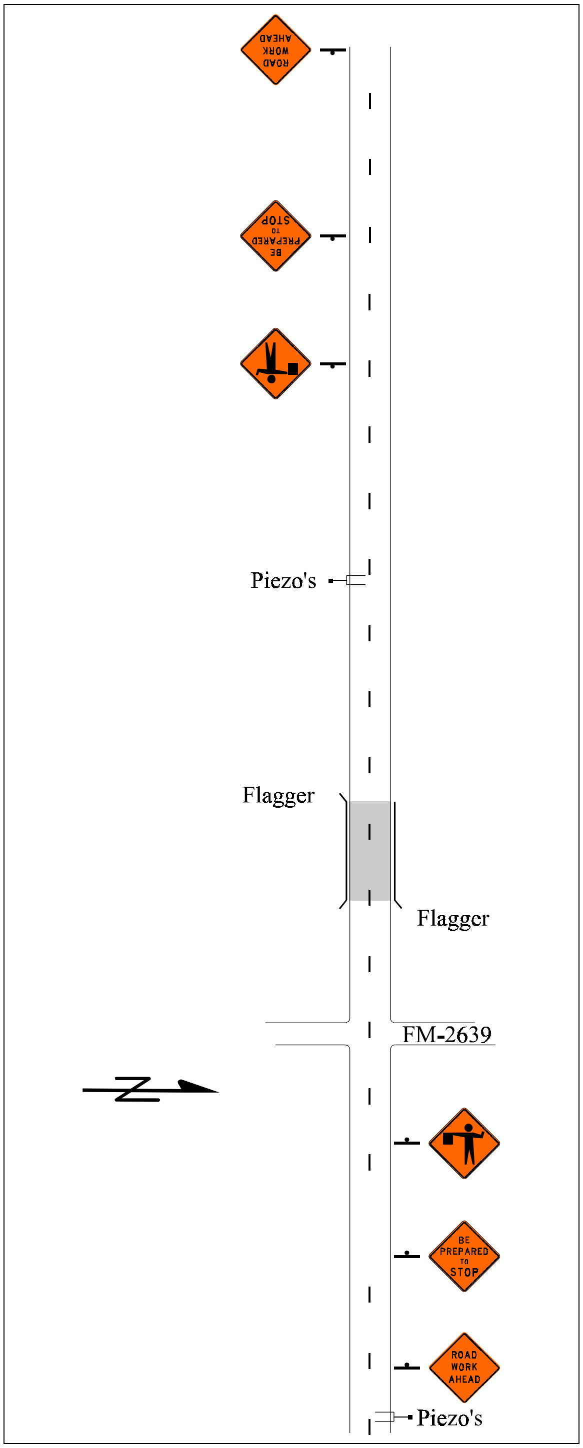

Figure A-9. F3 Site Layout (Not to Scale).

Location: Approximately 10 mi. west of Estelline.

AADT (1998): 410 (30% trucks)

Description of Work: A TxDOT crew was blade patching a 0.5 mi. westbound section of the road.

Device(s) Tested: Radar drone, fluorescent orange signs, fluorescent yellow-green vests, fluorescent yellow-green hard hat covers, and high-visibility retroreflective magnetic strips for vehicles.

Site Description: SH 86 runs east-west between Estelline and Turkey in Hall County. SH 86 is a two-lane rural highway with full shoulders and a speed limit of 70 mph.

Data Collection Comments: The two LIDAR data collection sites were located at the "Road Work Ahead" sign and at approximately 1400 ft. past the work zone. Piezos were located approximately 460 ft. in advance of the "Road Work Ahead" sign.

The radar drone was located at the flagging station, and the flagger's vehicle had the magnetic visibility strips applied to it during the "after" period.

A traffic survey station was set up approximately 400 ft. from the flagger on the east side of the work zone. At this point, vehicles were stopped, and the traffic survey was administered.

F4 – SH 86 - August 26, 1999

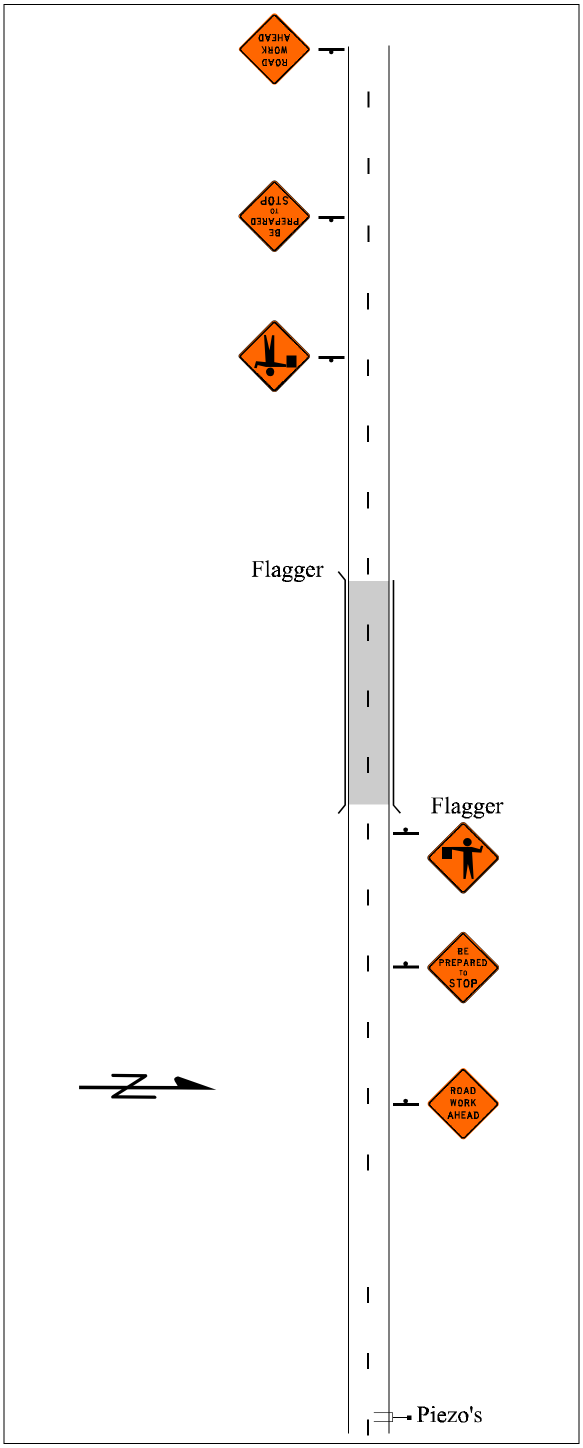

Figure A-10. F4 Site Layout (Not to Scale).

Location: Approximately 10 mi. west of Estelline.

AADT (1998): 410 (30% trucks)

Description of Work: A TxDOT crew was blade patching a 0.3 mi. westbound section of the road.

Device(s) Tested: Radar drone, fluorescent orange signs, fluorescent yellow-green vest, fluorescent yellow-green hard hat covers, and high-visibility retroreflective magnetic strips for vehicles.

Site Description: SH 86 runs east-west between Estelline and Turkey in Hall County. SH 86 is a two-lane rural highway with full shoulders and a speed limit of 70 mph.

Data Collection Comments: The two LIDAR data collection sites were located at the "Road Work Ahead" sign and at the flagging station. Peizo sensors were located approximately 1.2 mi. in advance of the "Road Work Ahead" sign.

The radar drone was located at the flagging station, and the flagger's vehicle had the magnetic visibility strips applied to it during the "after" period.

A traffic survey station was set up approximately 300 ft. from the flagger on the east side of the work zone. At this point, vehicles were stopped, and the traffic survey was administered.

APPENDIX B
SPEED PROFILES

This appendix contains the speed profile data collected with the LIDAR guns at the test sites. Tables B-1 and B-2 summarize the reference point information used in the speed profile graphs.

Table B-1. Reference Points for Flagger Control Operations.

Label	F1		F2		F3		F4	
	Dist	Description	Dist	Description	Dist	Description	Dist	Description
A	0	1st Ref Pt	0	1st Ref Pt	0	1st Piezo	0	1st Piezo
B	250	2nd Ref Pt	250	2nd Ref Pt	500	1st Ref Pt	6366	1st Ref Pt
C	500	3rd Ref Pt	500	3rd Ref Pt	750	2nd Ref Pt	7000	2nd Ref Pt
D	750	4th Ref Pt	750	4th Ref Pt	1000	3rd Ref Pt	7234	Be Prepared to Stop (CW21-8)
E	1000	5th Ref Pt	1000	5th Ref Pt	1250	4th Ref Pt	7350	3rd Ref Pt
F	1250	6th Ref Pt	1250	6th Ref Pt	1436	Flagger Station	8223	Flagger Station
G	1500	7th Ref Pt	1500	7th Ref Pt	6106	2nd Piezo	8650	4th Ref Pt
H	1750	8th Ref Pt	1750	8th Ref Pt			9000	5th Ref Pt
I	2000	9th Ref Pt	2000	9th Ref Pt			8350	6th Ref Pt
J	2250	10th Ref Pt	2200	Be Prepared to Stop (CW21-8)			9723	End of Construction
K	2350	Be Prepared to Stop (CW21-8)	2500	10th Ref Pt			13,867	2nd Piezo
L	2500	11th Ref Pt	2750	11th Ref Pt				
M	2750	12th Ref Pt	3000	12th Ref Pt				
N	3000	13th Ref Pt	3250	Flagger Station				
O	3250	Flagger Station						

Table B-2. Reference Points for Lane Closures.

Label	LC1		LC2		LC3		LC4		LC5	
	Dist	Description	Dist	Description	Dist	Description	Dist	Description	Dist	Description
A	0	1st Piezo	0	1st Piezo	0	Upstream Spot Speed Location	0	Upstream Spot Speed Location	0	1st Piezo
B	1995	Road Work Ahead - Traffic Fines Double (R20-5)	1000	1st Ref Pt	1000	1st Ref Pt	1000	1st Ref Pt	1000	1st Ref Pt
C	2170	1st Ref Pt	2000	2nd Ref Pt	1795	Road Work Ahead - Traffic Fines Double (R20-5)	1475	Road Work Ahead - Traffic Fines Double (R20-5)	1475	Road Work Ahead - Traffic Fines Double (R20-5)
D	2420	2nd Ref Pt	2775	Road Work Ahead - Traffic Fines Double (R20-5)	2000	2nd Ref Pt	2000	2nd Ref Pt	2000	2nd Ref Pt
E	2670	3rd Ref Pt	3000	3rd Ref Pt	2940	Road Work Ahead (CW20-1D)	3000	3rd Ref Pt	2251	Road Work Ahead (CW20-1D)
F	2985	Right Lane Closed Ahead (CW20-5)	3775	Road Work Ahead (CW20-1D)	3000	3rd Ref Pt	3355	Road Work Ahead (CW20-1D)	2299	Video Trailer
G	3170	4th Ref Pt	3900	Speed Trailer	3940	Right Lane Closed Ahead (CW20-5)	4000	4th Ref Pt	3000	3rd Ref Pt
H	3420	5th Ref Pt	4000	4th Ref Pt	4000	4th Ref Pt	4365	Left Lane Closed Ahead (CW20-5)	3097	Left Lane Closed Ahead (CW20-5)
I	3745	6th Ref Pt	4775	Right Lane Closed Ahead (CW20-5)	4865	Speed Trailer	5000	5th Ref Pt	3571	Radar Drone Location
J	3985	Arrow Panel	5000	5th Ref Pt	5000	5th Ref Pt	5400	Begin Taper	3826	Road Work - Traffic Fines Double (R20-5)
K	4170	7th Ref Pt	5805	Begin Taper	5285	Begin Taper	5600	Lane Closure and Arrow Panel	3978	Left Lane Closed Ahead (CW20-5)
L	4420	8th Ref Pt			6000	6th Ref Pt	6000	6th Ref Pt	4000	4th Ref Pt
M	4670	2nd Piezo	6005	Lane Closure and Arrow Panel	5485	Lane Closure and Arrow Panel	8240	Piezo	5149	Arrow Panel
N	4920	9th Ref Pt							6205	2nd Piezo
O	5170	Downstream Spot Speed Location	7915	2nd Piezo	8125	Piezo				
P	6170	3rd Piezo								

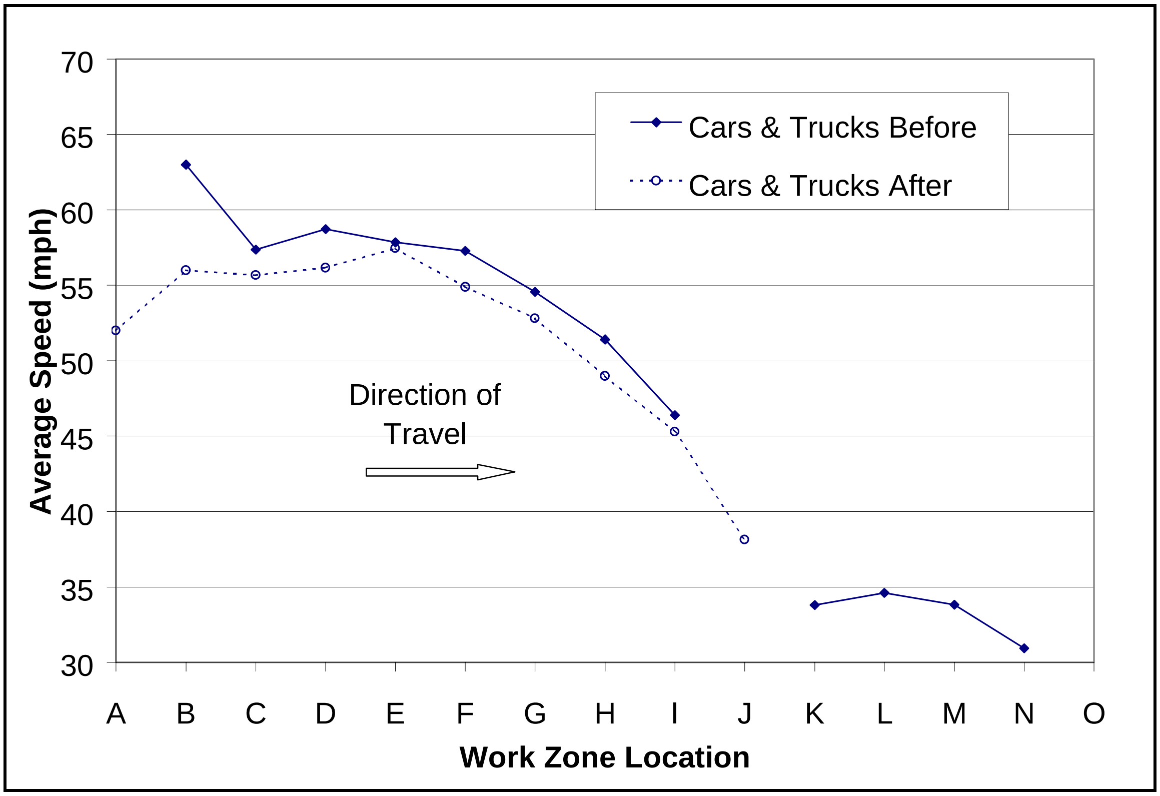

Figure B-1. US 83 - May 11, 1999 Mean Speed Profile (F1).

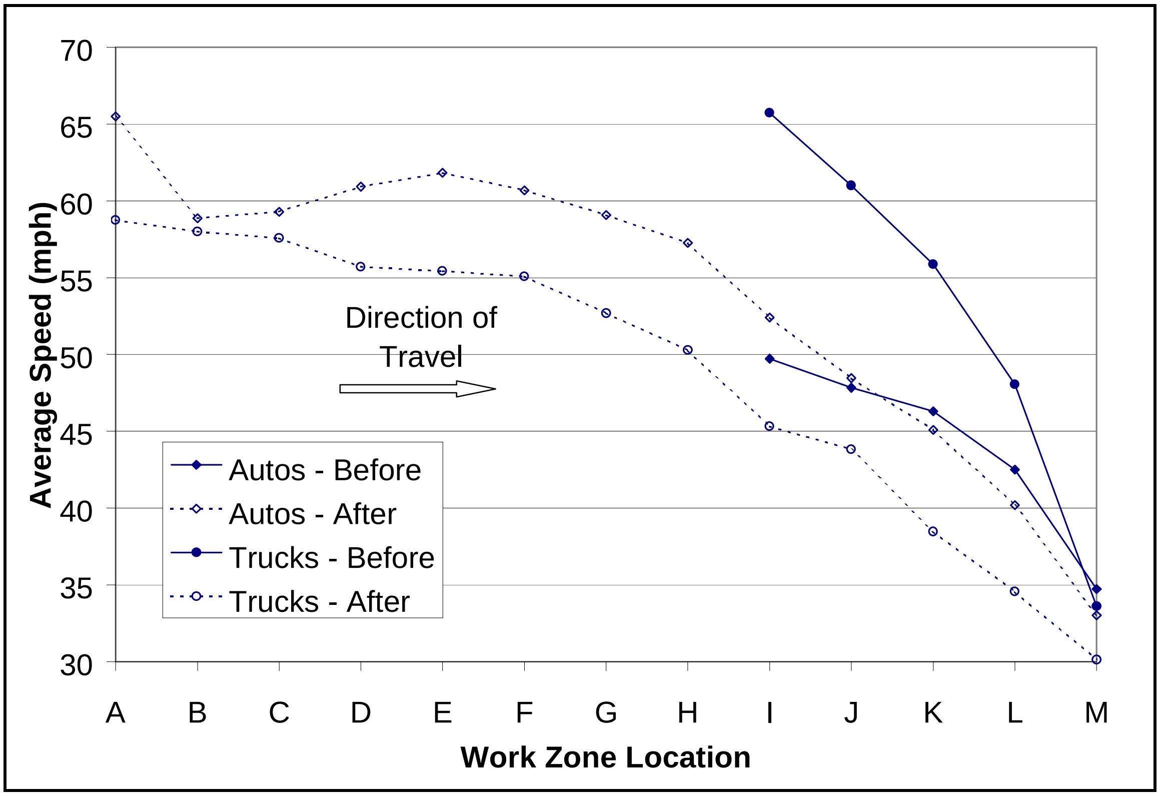

Figure B-2. US 83 - May 12, 1999 Mean Speed Profile (F2).

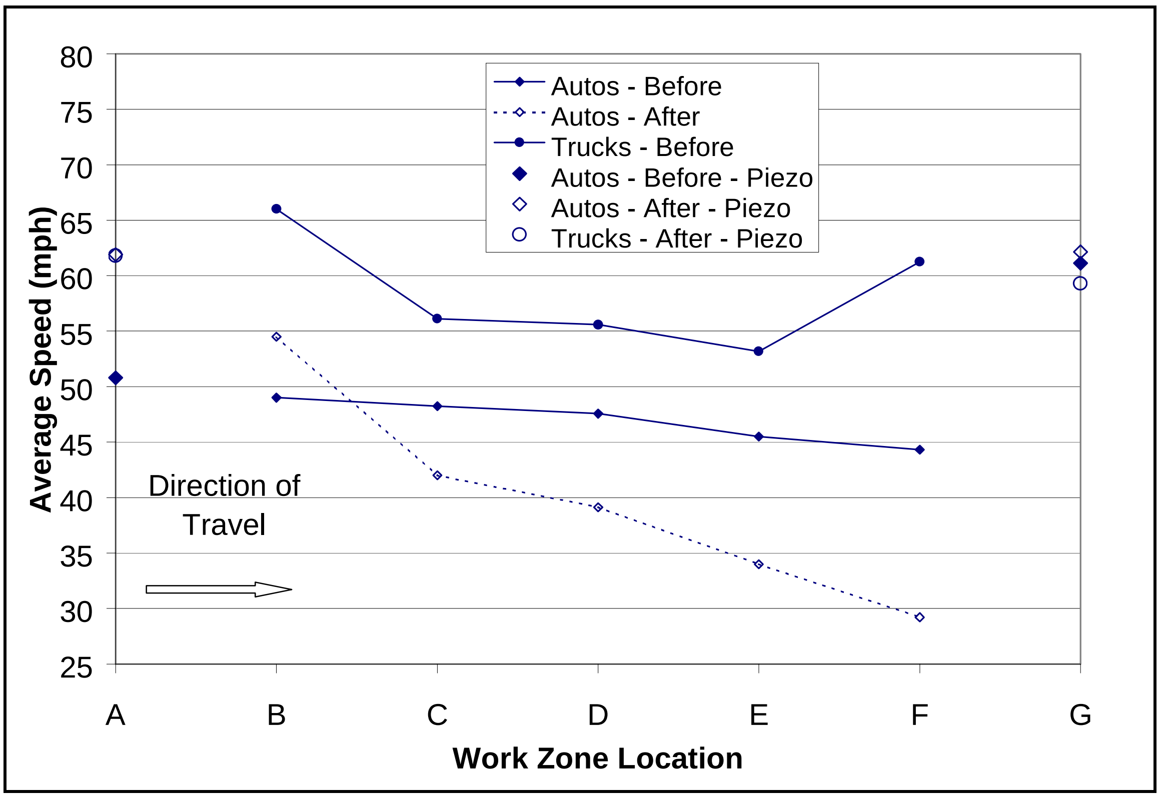

Figure B-3. SH 86 - August 25, 1999 Mean Speed Profile (F3).

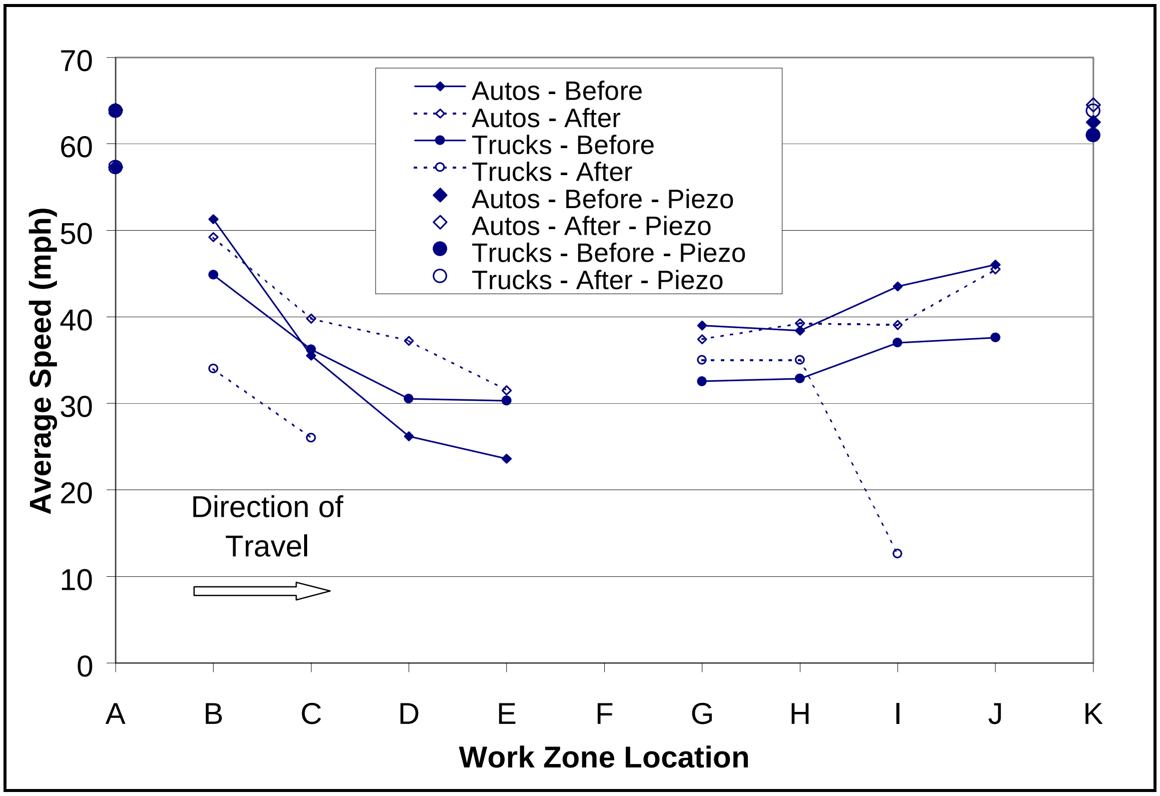

Figure B-4. SH 86 - August 26, 1999 Mean Speed Profile (F4).

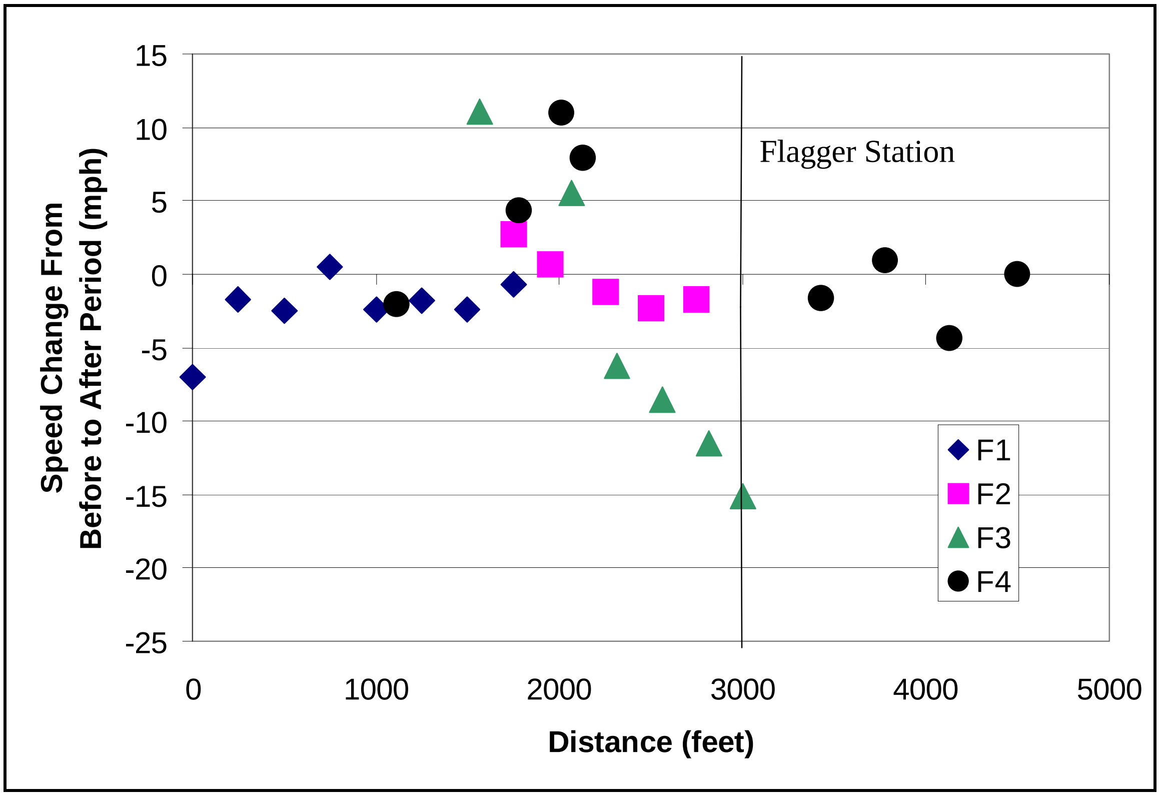

Figure B-5. Passenger Car Speed Differential - Flagger Control.

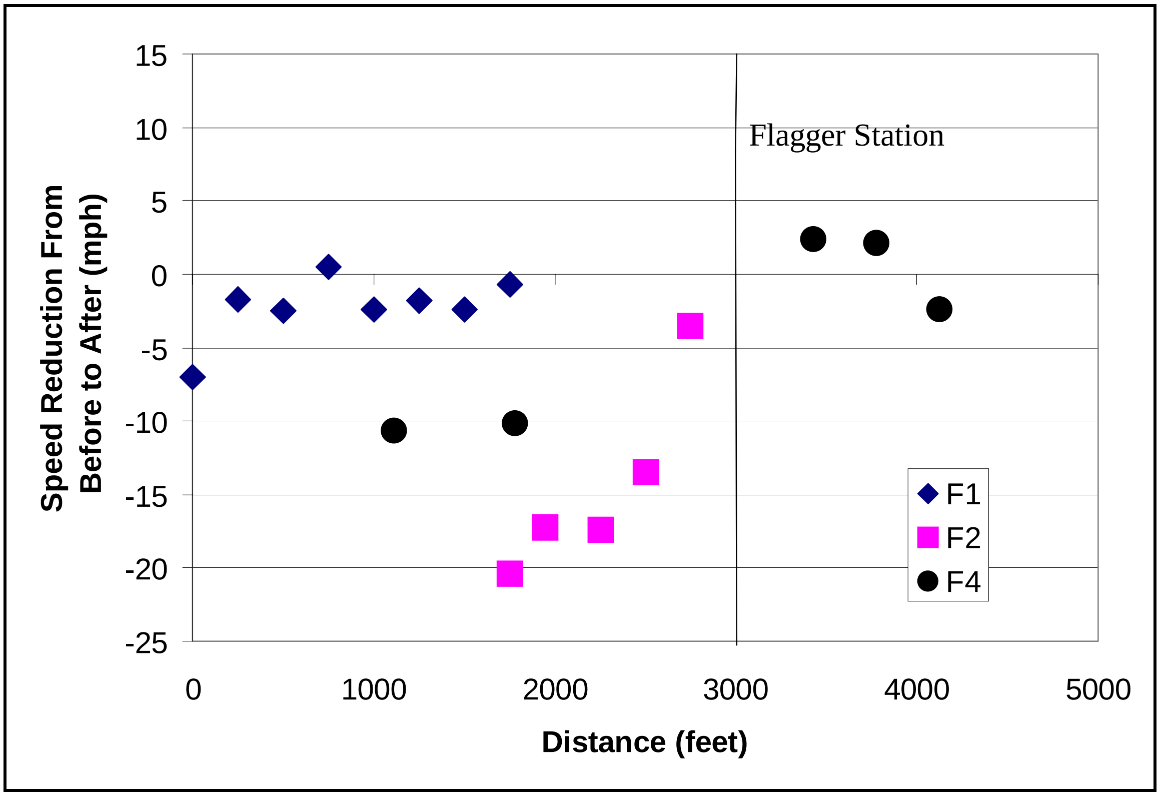

Figure B-6. Truck Speed Differential - Flagger Control.

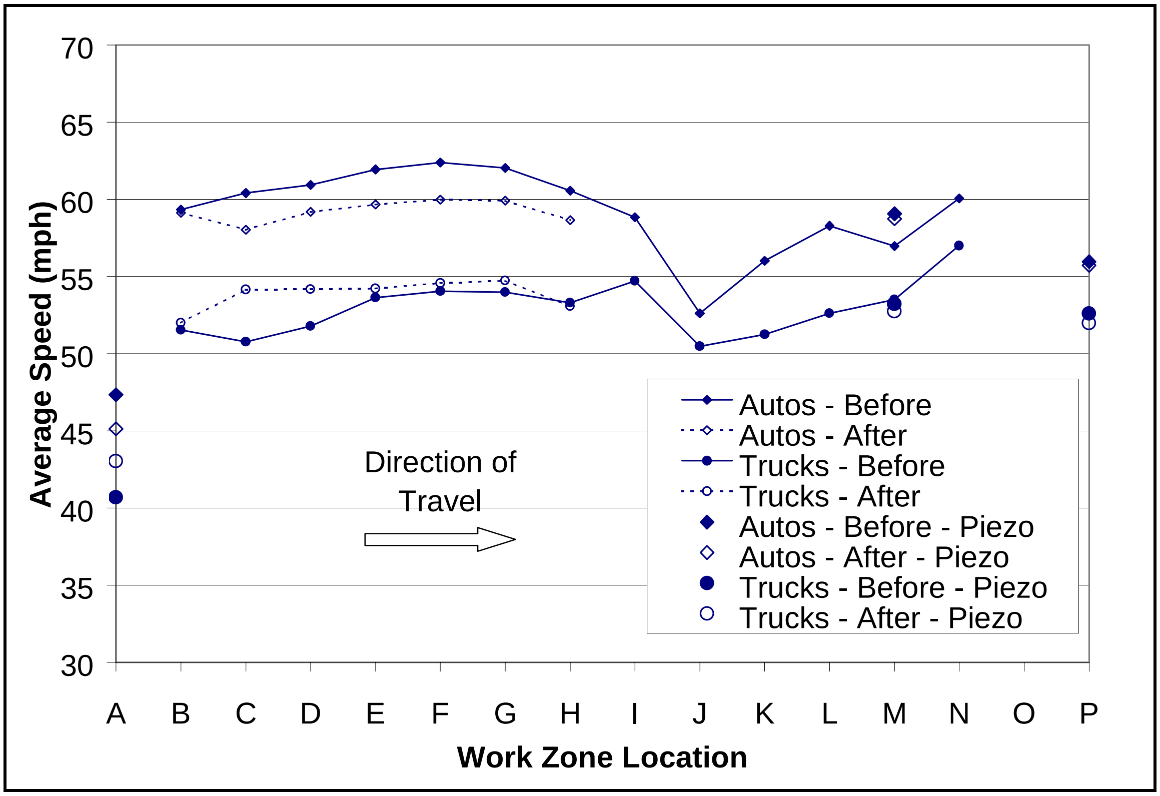

Figure B-7. US 287 - May 13, 1999 Mean Speed Profile (LC1).

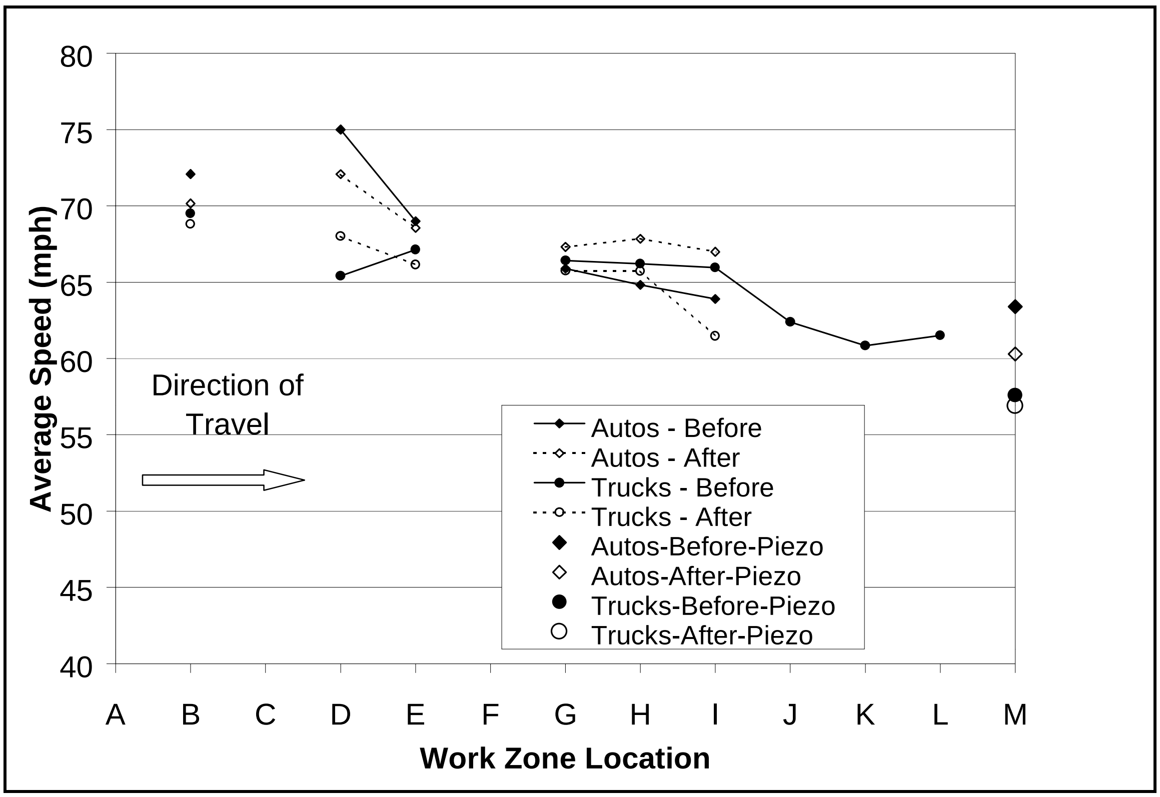

Figure B-8. US 287 - June 18, 1999 Mean Speed Profile (LC4).

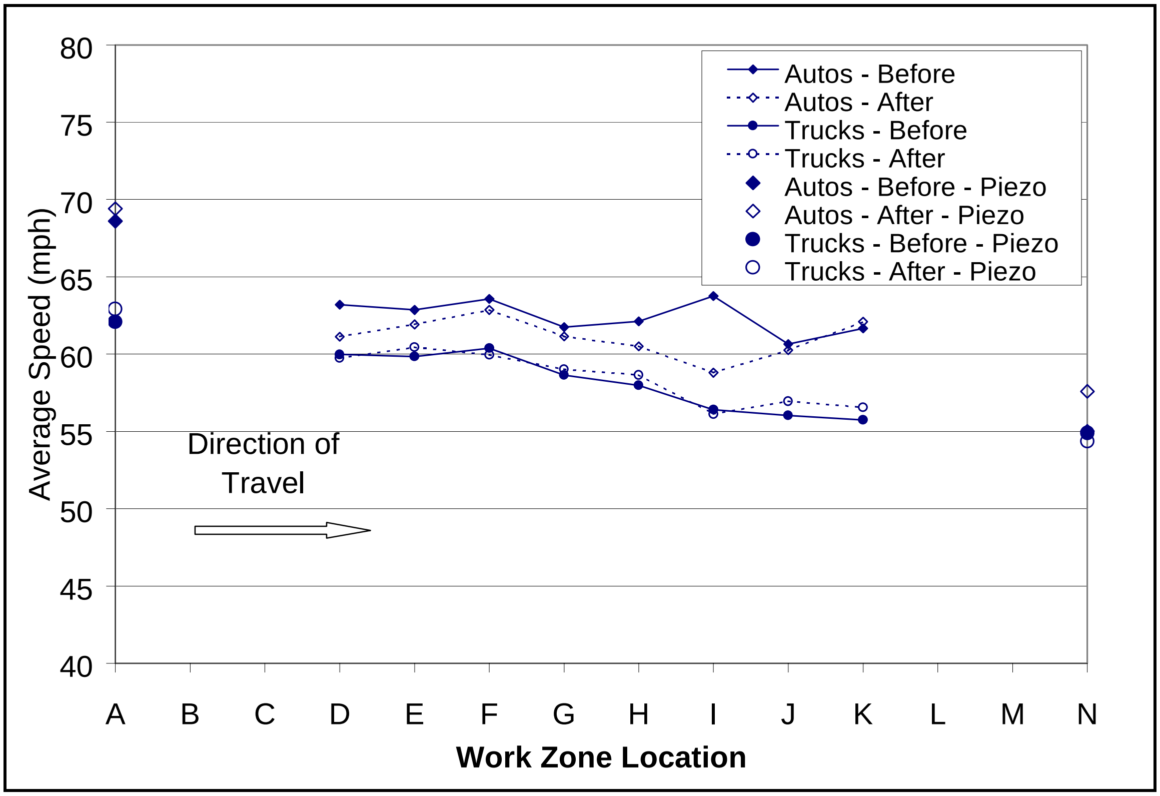

Figure B-9. US 287 - August 24, 1999 Mean Speed Profile (LC5).

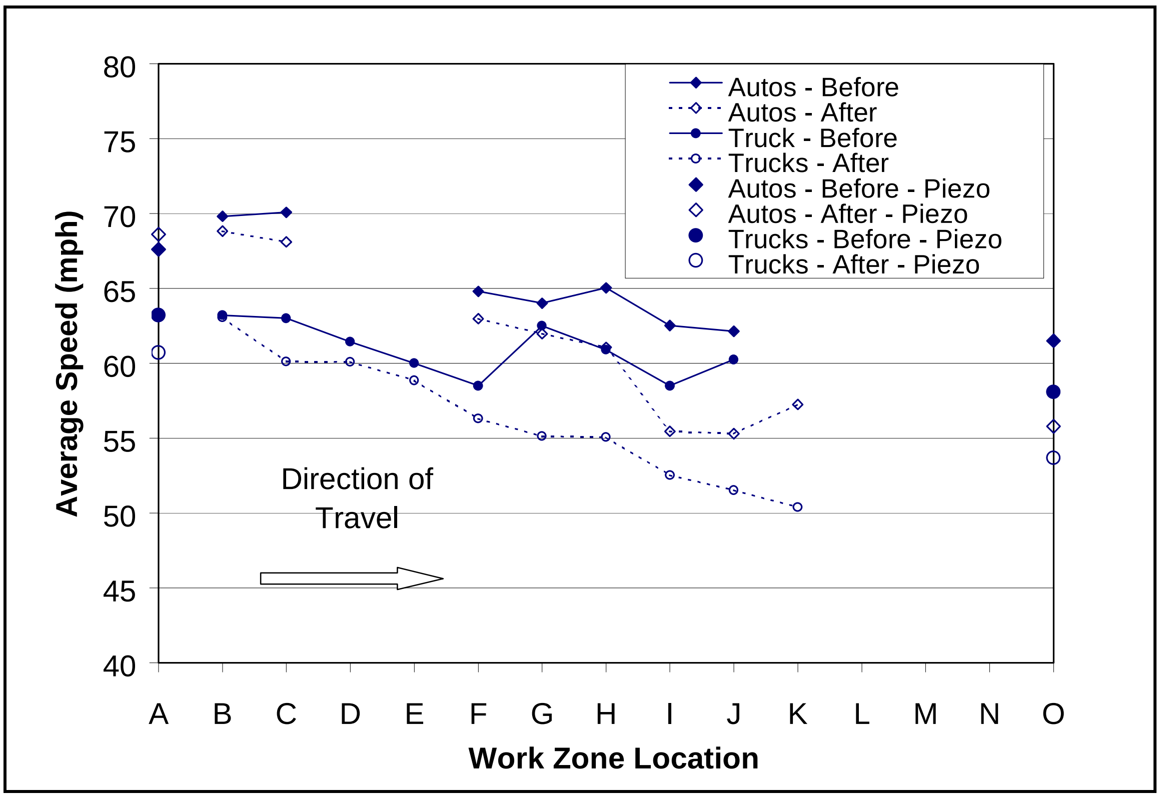

Figure B-10. US 287 - June 16, 1999 Mean Speed Profile (LC2).

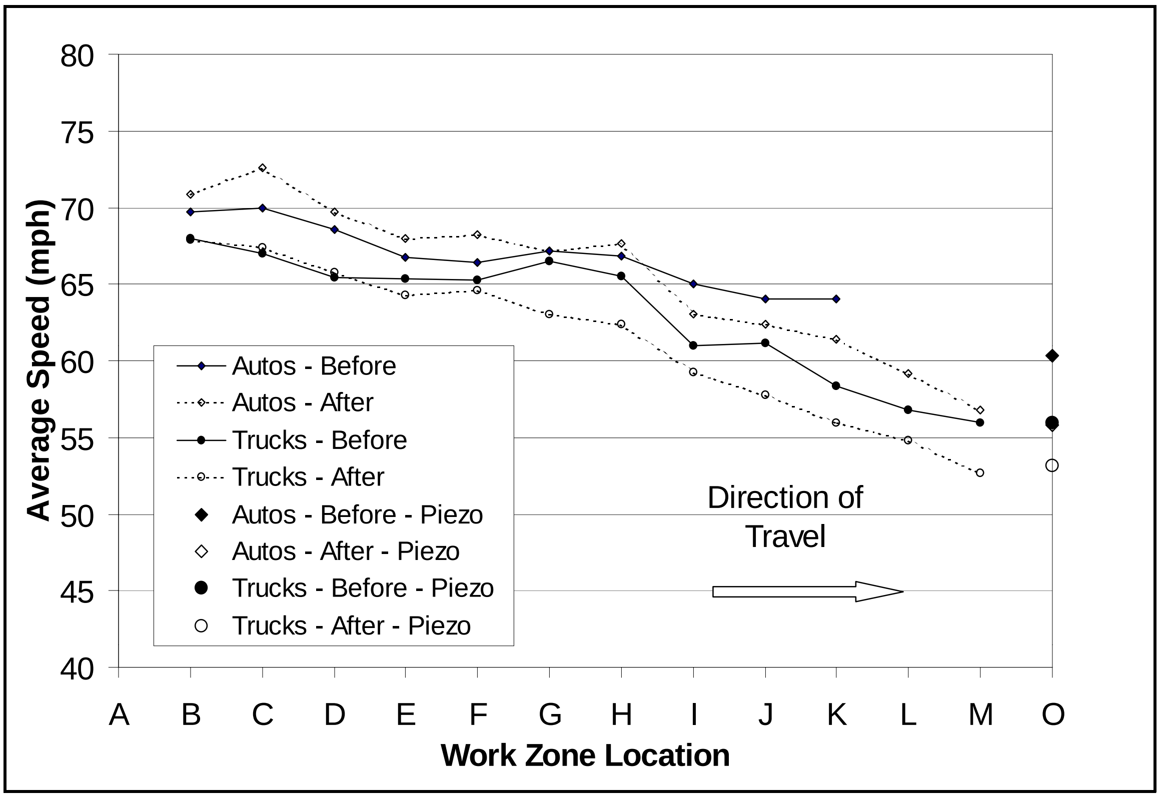

Figure B-11. US 287 - June 17, 1999 Mean Speed Profile (LC3).

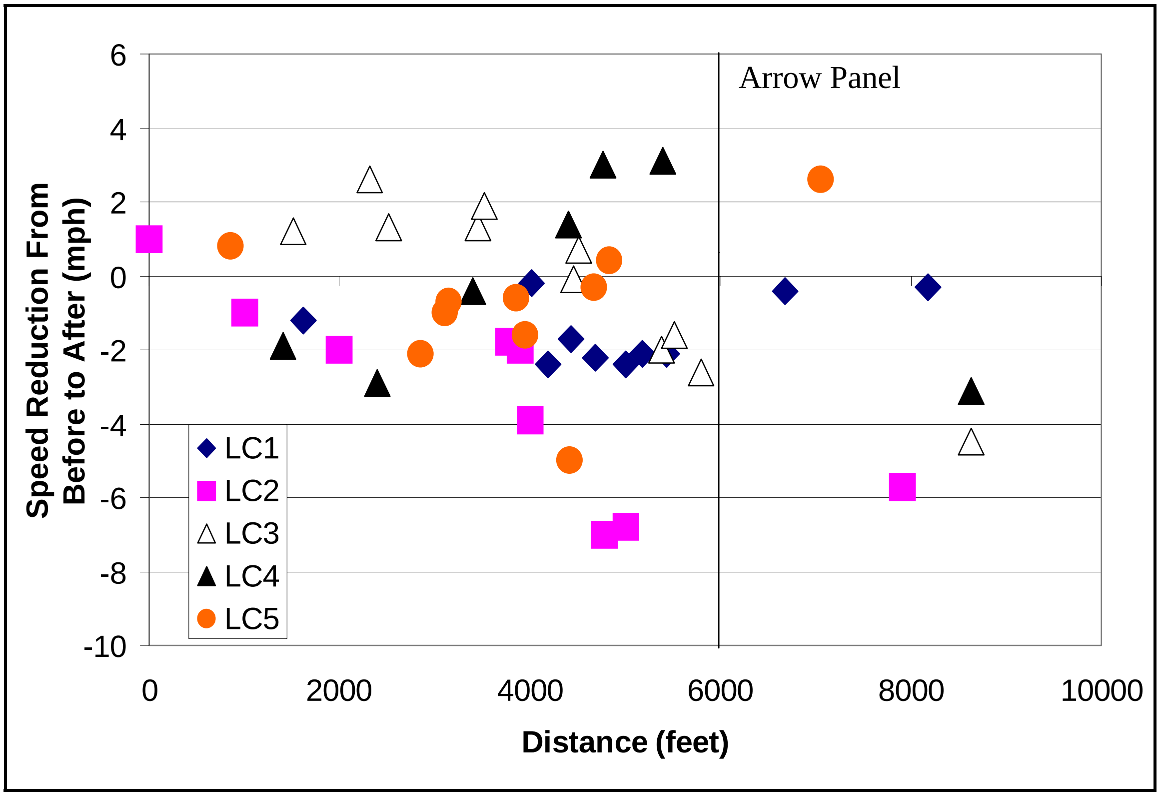

Figure B-12. Passenger Car Speed Differential - Lane Closure on Multilane Road.

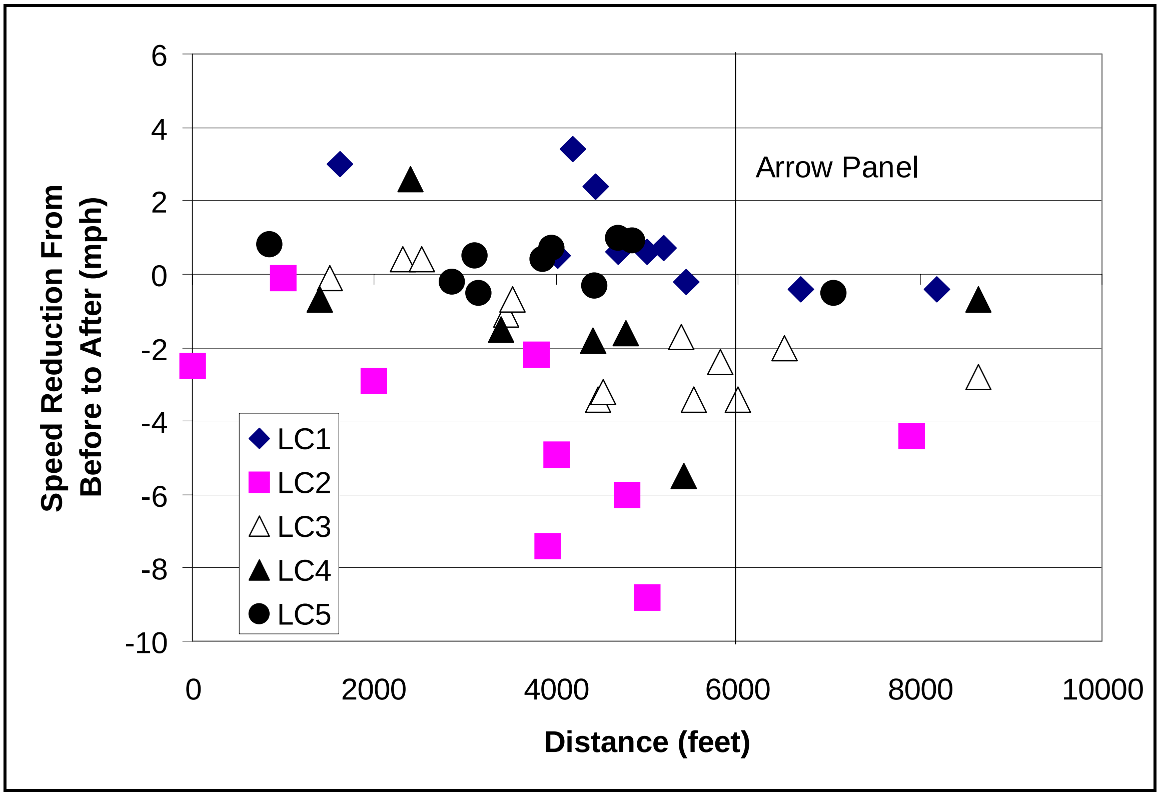

Figure B-13. Truck Speed Differential - Lane Closure on Multilane Road.

APPENDIX C
SUMMARY TABLES

Table C-1. US 83 - May 11, 1999 Descriptive Speed Statistics (F1) ①.

Ref Pts	Study Period	Passenger Cars				
		Mean	**Std Dev**	**Min**	**Max**	**% > 70**
A	Before After	② 52.0	② ②	② 52	② 52	② 0
B	Before After	63.0 56.0	7.1 11.1	58 46	68 68	0 0
C	Before After	57.4 55.7	8.3 7.8	44 48	69 68	0 0
D	Before After	58.7 56.2	7.8 6.6	43 47	70 69	0 0
E	Before After	57.8 58.3	7.4 7.7	42 49	68 69	0 0
F	Before After	57.3 54.9	6.6 5.9	39 47	67 67	0 0
G	Before After	54.6 52.8	7.5 5.8	36 44	74 63	3.3 0
H	Before After	51.4 49.0	7.3 6.3	36 39	68 61	0 0
I	Before After	46.4 45.7	7.5 8.2	29 33	64 69	0 0
J	Before After	② 38.1	② 8.9	② 27	② 65	② 0
K	Before After	② 33.8	② 8.1	② 23	② 44	② 0
L	Before After	② 34.6	② 5.8	② 27	② 42	② 0
M	Before After	② 33.8	② 5.3	② 28	② 43	② 0
N	Before After	② 31.0	② 5.0	② 26	② 41	② 0
O	Before After	② ②	② ②	② ②	② ②	② ②

① Before (mph)⁄⁄After (mph)
② Insufficient amount of data
③ Shaded cells with bold text indicate statistically significant difference at α=0.05. Min and max not analyzed

Table C-2. US 83 - May 12, 1999 Descriptive Speed Statistics (F2) ①.

Ref Pts		Passenger Cars					Trucks				
		Mean	**Std Dev**	**Min**	**Max**	**% > 70**	**Mean**	**Std Dev**	**Min**	**Max**	**% > 60**
A	Before After	65.5 ②	3.5 ②	63 ②	68 ②	0 ②	55.4 ②	1.3 ②	54 ②	57 ②	0 ②
B	Before After	58.9 ②	12.9 ②	50 ②	68 ②	0 ②	58.8 ②	4.4 ②	55 ②	63 ②	33.3 ②
C	Before After	59.3 ②	8.0 ②	50 ②	68 ②	0 ②	58.0 ②	3.6 ②	56 ②	64 ②	25.0 ②
D	Before After	60.9 ②	8.0 ②	49 ②	73 ②	7.1 ②	55.7 ②	2.9 ②	53 ②	60 ②	0 ②
E	Before After	61.8 ②	8.7 ②	49 ②	74 ②	22.2 ②	57.6 ②	4.9 ②	51 ②	66 ②	14.3 ②
F	Before After	60.7 ②	8.3 ②	47 ②	72 ②	10.5 ②	55.1 ②	5.8 ②	48 ②	65 ②	12.5 ②
G	Before After	59.1 ②	8.1 ②	46 ②	72 ②	5.0 ②	52.7 ②	6.5 ②	43 ②	63 ②	12.5 ②
H	Before After	57.3 ②	8.3 ②	43 ②	71 ②	4.8 ②	50.3 ②	6.7 ②	41 ②	58 ②	0 ②
I	Before After	49.7 52.4	3.8 8.6	46 40	55 71	0 4.3	**65.7** **45.3**	7.0 6.7	61 38	71 56	100.0 0
J	Before After	47.8 48.5	10.8 9.3	36 35	73 70	11.1 0	61.0 43.8	2.8 8.9	59 37	63 55	50.0 0
K	Before After	46.3 45.1	10.8 8.7	32 33	67 65	0 0	**55.9** **38.5**	2.7 7.7	54 30	58 50	0 0
L	Before After	42.5 40.2	8.2 7.9	27 30	59 61	0 0	**48.1** **34.6**	3.5 6.7	46 28	51 44	0 0
M	Before After	34.7 33.0	7.4 8.6	23 24	47 58	0 0	33.6 30.1	9.8 7.3	27 23	41 41	0 0
N	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②

① Before (mph)//After (mph)
② Insufficient amount of data
③ Shaded cells with bold text indicate statistically significant difference at α=0.05. Min and max not analyzed

Table C-3. US 287 - May 13, 1999 Descriptive Speed Statistics (LC1) ①.

Ref Pts		Passenger Cars					Trucks				
		Mean	Std Dev	Min	Max	% > 70	Mean	Std Dev	Min	Max	% > 60
A	Before After	47.3 46.1	11.9 12.3	18 14	111 71	2.0 0.8	40.0 43.0	10.3 10.8	11 18	68 61	3.6 1.9
B	Before After	59.3 59.1	4.9 6.7	52 46	67 73	0 11.1	51.5 52.0	4.8 5.0	47 48	60 59	0 0
C	Before After	60.4 58.0	**4.6** **6.8**	52 41	70 72	0 2.6	50.8 54.2	5.0 5.6	42 48	60 62	0 12.5
D	Before After	60.9 59.2	6.1 7.1	47 45	73 74	9.4 7.5	51.8 54.2	4.9 4.7	41 48	61 62	7.7 10.0
E	Before After	61.9 59.7	6.0 7.1	49 42	76 74	10.5 6.2	53.6 54.2	5.1 4.4	42 48	62 62	18.8 5.6
F	Before After	62.4 60.0	6.2 7.7	50 37	77 74	13.0 6.2	54.0 54.6	4.5 4.6	44 47	61 63	12.5 5.9
G	Before After	62.0 59.9	**5.9** **7.7**	50 36	76 78	9.3 3.1	54.0 54.7	4.4 4.5	44 47	61 63	12.5 6.7
H	Before After	60.8 58.7	**5.4** **7.8**	51 37	71 79	7.0 3.9	53.3 53.1	3.9 4.6	46 46	60 62	0 5.3
I	Before After	58.8 ②	7.9 ②	54 ②	68 ②	0 ②	54.7 ②	3.5 ②	50 ②	60 ②	0 ②
J	Before After	52.6 ②	7.4 ②	32 ②	62 ②	0 ②	50.5 ②	5.8 ②	42 ②	59 ②	0 ②
K	Before After	56.0 ②	8.9 ②	23 ②	70 ②	0 ②	51.2 ②	4.8 ②	43 ②	58 ②	0 ②
L	Before After	58.3 ②	7.4 ②	34 ②	77 ②	5.3 ②	52.6 ②	4.8 ②	43 ②	61 ②	2.9 ②
M	Before After	59.1 58.7	6.5 6.4	44 35	75 74	4.9 1.1	53.2 52.8	**4.8** **5.9**	33 35	66 67	3.3 8.4
N	Before After	60.1 ②	6.8 ②	41 ②	72 ②	6.5 ②	57.0 ②	② ②	57 ②	57 ②	0 ②
O	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②
P	Before After	56.0 55.7	**7.8** **9.5**	33 16	74 76	3.9 3.4	52.6 52.2	**5.7** **8.1**	20 19	67 68	5.7 8.4

① Before (mph)//After (mph)
② Insufficient amount of data
③ Shaded cells with bold text indicate statistically significant difference at α=0.05. Min and max not analyzed

Table C-4. US 287 - June 16, 1999 Descriptive Speed Statistics (LC2) ①.

Ref Pts		Passenger Cars					Trucks				
		Mean	Std Dev	Min	Max	% > 70	Mean	Std Dev	Min	Max	% > 60
A	Before After	67.6 68.6	6.2 6.5	46 38	78 87	42.6 47.4	**63.2** **60.7**	4.7 4.2	51 50	72 73	68.8 49.1
B	Before After	69.8 68.8	5.8 4.0	57 61	81 74	45.5 52.9	63.2 63.1	2.9 1.7	59 61	67 65	80.0 100.0
C	Before After	70.1 68.1	**6.5** **4.3**	63 57	83 77	44.4 32.6	63.0 60.1	3.5 5.7	59 52	65 68	66.7 55.6
D	Before After	② 67.2	② 5.6	② 53	② 80	② 30.4	② 60.1	② 4.9	② 52	② 69	② 50.0
E	Before After	② 65.9	② 6.9	② 33	② 79	② 21.4	② 58.9	② 4.3	② 52	② 65	② 46.7
F	Before After	64.8 63.0	8.0 6.1	53 46	74 75	20.0 10.0	58.5 56.3	2.1 5.3	57 49	60 66	0.0 26.1
G ④	Before After	64.0 62.0	8.2 6.6	53 44	74 75	20.0 11.7	62.5 55.1	3.5 5.2	60 46	65 65	50.0 18.2
H	Before After	65.0 61.1	6.9 6.6	52 44	74 75	25.0 10.3	60.9 55.1	3.7 5.3	58 45	65 69	33.3 19.4
I	Before After	**62.5** **55.5**	6.8 6.4	49 39	74 77	13.6 1.2	**58.5** **52.5**	3.8 5.0	56 39	64 69	25.0 3.7
J	Before After	**62.1** **55.3**	6.9 6.0	49 40	72 73	9.1 2.3	**60.3** **51.5**	3.2 4.4	58 42	63 69	50.0 2.7
K ⑤	Before After	② 57.3	② 7.4	② 52	② 63	② 0.0	② 50.4	② 3.0	② 47	② 54	② 0.0
L	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②
M	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②
O	Before After	**61.5** **55.8**	7.1 6.0	40 40	80 76	9.6 2.0	**58.1** **53.7**	4.9 5.0	45 40	69 73	32.6 7.6
P	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②

① Before (mph)//After (mph)
② Insufficient amount of data
③ Shaded cells with bold text indicate statistically significant difference at α=0.05. Min and max not analyzed
④ Speed trailer and 55 mph advisory sign location
⑤ Begin taper

Table C-5. US 287 - June 17, 1999 Descriptive Speed Statistics (LC3) ①.

Ref Pts		Passenger Cars					Trucks				
		Mean	Std Dev	Min	Max	% > 70	Mean	Std Dev	Min	Max	% > 60
A	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②
B	Before After	69.7 70.9	3.3 3.2	65 63	79 79	33.3 61.4	68.0 67.9	6.2 5.9	58 52	82 83	90.7 86.1
C	Before After	**70.0** **72.6**	3.9 3.8	63 66	77 85	52.0 72.4	67.0 67.4	6.8 5.9	52 53	83 80	82.4 89.8
D	Before After	68.5 69.8	5.0 2.6	59 67	78 73	31.8 50.0	65.4 65.8	6.7 5.2	50 55	79 77	76.0 85.3
E	Before After	66.7 68.0	**6.0** **2.5**	55 65	80 73	27.3 10.0	65.4 64.3	6.0 6.1	51 48	77 76	81.0 71.1
F	Before After	66.4 68.3	**5.1** **2.6**	57 65	77 72	17.6 12.5	65.3 64.6	5.9 6.1	50 54	77 75	81.6 68.3
G	Before After	67.2 67.1	5.9 3.9	55 58	75 73	40.0 17.6	**66.5** **63.1**	7.0 7.1	54 40	89 75	84.8 68.6
H	Before After	66.9 67.6	**6.8** **2.6**	54 62	74 72	42.9 12.5	**65.6** **62.4**	7.2 7.1	54 40	89 75	81.5 65.2
I	Before After	65.0 63.0	② 6.3	65 53	65 75	0.0 6.3	61.0 59.3	**4.3** **7.6**	52 45	69 74	60.0 40.0
J	Before After	64.0 62.4	② 6.1	64 54	64 75	0.0 6.7	61.2 57.8	**4.0** **7.1**	53 44	69 73	63.6 25.0
K	Before After	64.0 61.4	② 5.7	64 54	64 76	0.0 6.7	58.3 55.9	5.7 6.2	52 44	63 67	33.3 27.6
L	Before After	② 59.2	② 6.2	② 47	② 74	② 5.9	56.8 54.8	4.1 5.1	52 45	59 65	0.0 12.9
M	Before After	② 56.8	② 6.1	② 50	② 71	② 10.0	56.0 52.6	5.7 4.3	52 44	60 59	0.0 0.0
N	Before After	**60.3** **55.8**	7.1 6.3	45 40	77 77	7.9 2.4	**56.0** **53.2**	5.2 4.9	42 37	68 68	17.1 7.4
O	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②

① Before (mph)/After (mph)
② Insufficient amount of data
③ Shaded cells with bold text indicate statistically significant difference at α=0.05. Min and max not analyzed

Table C-6. US 287 - June 18, 1999 Descriptive Speed Statistics (LC4) ①.

Ref Pts		Passenger Cars					Trucks				
		Mean	**Std Dev**	**Min**	**Max**	**% > 70**	**Mean**	**Std Dev**	**Min**	**Max**	**% > 60**
A	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②
B	Before After	72.1 70.2	**5.6** **4.4**	58 55	90 83	66.7 49.4	69.5 68.8	5.1 4.9	56 53	80 77	96.1 92.3
D	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②
C	Before After	75.0 72.1	4.2 4.0	72 66	78 79	100.0 63.6	65.4 68.0	8.7 6.0	58 57	78 75	66.7 92.3
E	Before After	69.0 68.6	7.4 5.8	57 57	83 76	46.2 45.5	67.1 65.6	6.1 5.9	54 54	79 76	87.2 79.6
F	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②
H	Before After	65.9 67.3	5.3 6.1	56 54	77 79	20.2 32.1	66.4 64.6	5.8 5.9	55 53	78 73	86.0 68.6
I	Before After	64.8 67.8	7.1 6.5	52 54	80 79	23.8 41.4	66.2 64.6	5.7 6.2	55 52	78 76	81.6 67.3
J	Before After	63.9 67.0	10.0 6.2	47 59	81 75	14.3 28.6	**66.0** **60.5**	5.5 5.5	56 55	77 71	79.2 46.7
K	Before After	② ②	② ②	② ②	② ②	② ②	62.4 ②	3.6 ②	60 ②	68 ②	40.0 ②
M/N	Before After	② ②	② ②	② ②	② ②	② ②	60.8 ②	4.3 ②	57 ②	65 ②	66.7 ②
L	Before After	② ②	② ②	② ②	② ②	② ②	61.5 ②	2.1 ②	60 ②	63 ②	50.0 ②
O	Before After	**63.4** **60.3**	6.8 6.9	46 42	81 79	17.8 12.6	57.6 56.9	5.2 4.7	46 46	68 68	33.0 21.8
P	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②

① Before (mph)//After (mph)
② Insufficient amount of data
③ Shaded cells with bold text indicate statistically significant difference at α=0.05. Min and max not analyzed

Table C-7. US 287 - August 24, 1999 Descriptive Speed Statistics (LC5) ①.

Ref Pts		Passenger Cars					Trucks				
		Mean	Std Dev	Min	Max	% > 70	Mean	Std Dev	Min	Max	% > 60
A	Before After	68.6 69.4	**8.6** **6.2**	10 50	85 102	50.0 48.9	62.1 62.9	**3.7** **6.0**	50 23	76 75	75.5 74.3
B	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②
C	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②
D	Before After	63.2 61.1	6.8 7.2	50 49	72 68	17.6 0	60.0 59.8	**2.5** **4.7**	57 48	64 65	46.7 64.3
E	Before After	62.9 61.9	7.4 6.1	49 49	73 72	18.8 5.9	59.9 60.4	**2.7** **6.3**	54 48	64 74	42.9 50.0
F	Before After	63.6 62.9	6.7 7.0	49 50	73 75	11.5 11.8	60.4 59.9	**3.2** **5.9**	54 48	65 73	50.0 45.2
G	Before After	61.7 61.1	8.5 7.7	50 51	72 74	22.2 14.3	58.6 59.0	5.4 7.3	52 48	65 74	42.9 45.0
H	Before After	62.1 60.5	6.1 8.2	51 46	71 74	4.3 11.8	58.0 58.7	**4.0** **6.5**	52 48	65 74	29.4 31.3
I	Before After	63.8 58.8	8.7 7.9	50 46	75 73	30.0 10.0	56.4 56.1	3.7 4.4	51 47	63 65	25.0 21.7
J	Before After	60.6 60.3	6.9 7.2	49 49	71 74	5.9 11.1	56.0 57.0	3.8 5.2	50 47	63 70	18.8 18.8
K	Before After	61.7 62.1	6.5 7.8	49 50	70 74	0 18.9	55.7 56.6	4.0 5.3	49 48	64 72	20.0 25.8
L	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②
M	Before After	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②	② ②
N	Before After	**55.0** **57.6**	6.8 7.2	36 38	72 77	2.2 4.2	54.9 54.4	4.0 4.8	44 38	64 69	9.5 9.3

① Before (mph)//After (mph)
② Insufficient amount of data
③ Shaded cells with bold text indicate statistically significant difference at α=0.05. Min and max not analyzed

Table C-8. SH 86 - August 25, 1999 Descriptive Speed Statistics (F3) ①.

Ref Pts		Passenger Cars					Trucks				
		Mean	**Std Dev**	**Min**	**Max**	**% > 70**	**Mean**	**Std Dev**	**Min**	**Max**	**% > 60**
A	Before After	50.8 61.9	4.4 11.4	48 42	54 87	0 11.1	② 61.8	② 1.6	② 60	② 64	② 80.0
B	Before After	49.0 54.5	② 12.4	49 43	49 72	0 12.5	66 ②	② ②	66 ②	66 ②	100.0 ②
C	Before After	48.2 42.0	3.8 6.4	45 36	52 53	0 0	56.1 ②	17.2 ②	36 ②	67 ②	66.7 ②
D	Before After	47.6 39.1	2.9 8.0	45 29	51 53	0 0	55.6 ②	18.8 ②	34 ②	68 ②	66.7 ②
E	Before After	**45.5** **34.0**	**0.5** **6.4**	45 27	46 46	0 0	53.2 ②	19.1 ②	32 ②	69 ②	33.3 ②
F	Before After	**44.3** **29.2**	2.0 6.2	42 21	46 40	0 0	61.3 ②	12.4 ②	53 ②	70 ②	50.0 ②
G	Before After	61.1 62.2	7.1 8.0	50 48	68 74	0 20.0	② 59.3	② 6.4	② 56	② 69	② 25.0

① Before (mph)/After (mph)
② Insufficient amount of data
③ Shaded cells with bold text indicate statistically significant difference at α=0.05. Min and max not analyzed

Table C-9. SH 86 - August 26, 1999 Descriptive Speed Statistics (F4) ①.

Ref Pts		Passenger Cars					Trucks				
		Mean	**Std Dev**	**Min**	**Max**	**% > 70**	**Mean**	**Std Dev**	**Min**	**Max**	**% > 60**
A	Before	57.3	**16.3**	18	67	0	63.8	**13.3**	47	74	60.0
	After	63.9	**8.7**	50	78	20	57.3	**0.7**	57	58	0
B	Before	51.3	2.4	50	53	0	44.7	12.2	26	60	0
	After	49.2	11.1	34	58	0	34.0	②	34	34	0
C	Before	35.5	1.1	35	36	0	36.2	9.4	20	45	0
	After	39.8	14.3	24	59	0	26.0	②	26	26	0
D	Before	26.2	4.9	23	30	0	30.5	5.9	20	36	0
	After	37.2	11.2	25	53	0	②	②	②	②	0
E	Before	23.6	3.8	21	26	0	30.3	5.3	22	36	0
	After	31.5	10.4	20	45	0	②	②	②	②	②
F	Before	②	②	②	②	②	②	②	②	②	②
	After	②	②	②	②	②	②	②	②	②	②
G	Before	39.0	7.0	32	47	0	32.6	6.3	28	37	0
	After	37.4	4.2	34	42	0	35.0	2.1	34	37	0
H	Before	38.4	9.2	27	50	0	32.9	5.4	29	37	0
	After	39.3	7.8	31	46	0	35.0	②	35	35	0
I	Before	43.5	6.3	37	50	0	37.0	②	37	37	0
	After	39.1	11.2	31	47	0	13.0	②	13	13	0
J	Before	46.0	4.7	41	50	0	38.0	②	38	38	0
	After	46.0	②	46	46	0	②	②	②	②	0
K	Before	62.5	6.3	53	76	6.7	61.0	2.4	59	63	50.0
	After	64.5	9.7	34	81	15.8	63.8	5.3	60	68	50.0

① Before (mph)//After (mph)
② Insufficient amount of data
③ Shaded cells with bold text indicate statistically significant difference at α=0.05. Min and max not analyzed