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16. Abstract

This report documents the second year of a two-year project to evaluate the effectiveness of innovative work zone traffic control devices. Researchers evaluated these devices at short-term rural work zones. During the second year of the project, seven devices were tested at eight work zones. The devices evaluated included portable rumble strips, portable variable message signs (VMSs), radar drones, fluorescent yellow-green worker vests, retroreflective vehicle visibility improvements, fluorescent orange signs, and speed display trailers. A radar activated flagger paddle was evaluated, but on a more limited basis.

The effectiveness of these devices was assessed based on the vehicle speeds in the work zone, the ease of installation and removal, the impact of the device on vehicle conflicts, and worker comments. Analysis of the data collected revealed that the speed display trailer had the largest impact on speeds. The VMS had a positive benefit in reducing conflicts. The fluorescent orange signs, vehicle visibility improvements, and yellow-green worker vests all acted to improve the conspicuity of the workers.

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EVALUATION OF TRAFFIC CONTROL DEVICES FOR RURAL HIGH-SPEED MAINTENANCE WORK ZONES: SECOND YEAR ACTIVITIES AND FINAL RECOMMENDATIONS

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DISCLAIMER

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Project Advisory Panel

- Greg Brinkmeyer, Traffic Operations Division, Texas Department of Transportation
- David Casteel, Childress District, Texas Department of Transportation
- Terry Keener, Childress District, Texas Department of Transportation

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CHAPTER 1
INTRODUCTION AND SUMMARY

As the transportation system has grown older, roadway maintenance has become increasingly more common. As a result, drivers are increasingly coming into closer contact with workers. Maintenance work zones are usually set up to allow traffic to continue to use the facility while work is being performed. Since maintenance crews and traffic are sharing the same right-of-way, there is a potential for increased conflicts between workers and motorists.

According to Department of Public Safety data, 10,273 crashes occurred in work zones on the state road system in 1998 (*1*). This figure represents 6 percent of all crashes on the state system. These crashes resulted in 132 fatalities and 11,514 injuries. Excessive speed was cited as a contributing factor in about 38 percent of these cases.

Traffic control devices can be used to increase safety in work zones by either altering motorist behavior or simply heightening awareness of potential hazards in the work zone. In Texas, the *Texas Manual on Uniform Traffic Control Devices* (MUTCD) details standard practices for work zone traffic control (*2*). Even though TxDOT has followed the protocols in the MUTCD, safety in work zones still remains a concern. As a result, new traffic control devices that may improve work zone safety are constantly being developed.

BACKGROUND

Many of the work zone safety concerns experienced in Texas are seen nationwide. As a result, a number of research projects have been conducted that have tested the effectiveness of these innovative devices. To date, TxDOT has made limited use of this research, and there are opportunities to implement innovative devices relatively easily.

This research project identified existing and new devices that could improve work zone safety. Limited field evaluations of the most promising devices were conducted, and this report makes recommendations for the use of the various devices. The research specifically focused on the application of innovative traffic control devices to rural maintenance work zones. These work zones typically occur on low-volume roads with a posted speed limit of 70 mph. The maintenance activities occur during daylight hours, with traffic control being set up in the morning and removed by dusk. The nature of maintenance work zones presents a number of challenges. Traffic control must be able to be set up quickly and easily to ensure that sufficient time is available to perform actual work activities. Set up of traffic control should not be labor-intensive, since a limited number of workers are usually available for this task. Due to the short term nature of these sites, regulatory speeds cannot be reduced for the maintenance work zone, and limited resources exist for police enforcement. Finally, workers at these sites typically are in a more exposed position than at a long-term work zone. Therefore, it is important that workers are visible to motorists and that motorists are aware of the upcoming work zone.

This report documents the findings from the second year of a two-year research project. In the first year, the research team developed a preliminary list of devices to be examined and conducted some field testing of promising devices. The devices to be tested during the second year of the project were determined based on the results of the first year activities and input from the Project Advisory Panel. This report describes the second year activities and provides final recommendations based on the results of both years of the project.

PROJECT OBJECTIVES

This project is intended to provide information that will allow TxDOT to choose which innovative treatments are most likely to provide a significant increase in work zone safety. In order to achieve this goal, the research team established the following objectives:

- 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;
- 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; and
- document the activities and findings of the research project in annual reports.

Each year of the project was intended to meet these objectives. The results of the first year activities were used to determine the devices to be evaluated during the second year of the project. In order to accomplish the objectives of the year two evaluation, the work plan established during year one was followed. Table 1 shows the work plan tasks. This report summarizes the results of tasks 10 through 15.

Table 1. Work Plan Tasks.

Task	Description	Year Performed
1	Conduct kick-off meeting with TxDOT project advisors	1
2	Determine the state-of-the-art	1
3	Conduct survey of state transportation agencies	1
4	Identify and classify innovative devices, treatments, and/or practices	1
5	Select potential devices, treatments, or practices for preliminary field evaluations	1
6	Develop plan for preliminary field evaluations	1
7	Conduct preliminary field evaluations	1
8	Analyze preliminary field evaluation data	1
9	Prepare first research report	1
10	Meet with project advisors	2
11	Select potential devices/treatments/practices for final field evaluation	2
12	Develop plan for final field evaluations	2
13	Conduct final field evaluations	2
14	Analyze field data and develop recommendations	2
15	Prepare second research report and project summary report	2

RESEARCH SUMMARY

Eight major research tasks were completed during the first year of the project, and an additional six tasks were completed during the second year. The major activities and results from each year's activities are summarized in this section. More detailed information of the first year activities can be found in the report summarizing year one results (*3*).

First Year Activities

During the first year of the project, 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. Researchers administered a survey of state transportation agencies to determine other states' experience with new or innovative devices, treatments, and practices. In addition to the state DOT survey, the members of the Advisory Panel and research team met at the Annual American Traffic Safety Services Association (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 Federal Highway Administration (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.

Identification and Selection of Devices, Treatments, and Practices

The Advisory Panel and research team agreed to structure the first year efforts on the devices, 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^{TM} (visibility improvement attachments for cones), and

- 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^{TM} (visibility improvement attachments for cones),
- speed display,
- advisory speed signing, and
- retroreflective magnetic strips on work vehicles.

Safe-T-Spin is a trademark of Safe-T-Spin, Inc.

Research Methodology

The research methodology included developing the experimental plan, selecting data collection sites, developing data collection procedures and activities, and performing data reduction. Essentially, three data collection trips were made to the Childress District during the first year. 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.

Data Analysis

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 citizens' band (CB) radio conversations.

First Year Findings

The findings for each device tested during the first year of the project 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 statistical analyses.

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 are made of prismatic retroreflective sheeting. Consequently, if work crews used the signs during nighttime conditions, they would appear brighter than the beaded retroreflective material normally used.

Figure 1. Fluorescent Orange Sign.

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.

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.

Figure 2. Fluorescent Yellow-Green Vests and Hard Hat

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.

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.

- Being retroreflective, the strips' main benefit would occur at night.

Figure 3. Vehicle Visbility Improvments.

Safe-T-Spins (Figure 4)

Figure 4. Safe-T-Spins.

- 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 used on the cones located at the work zone taper and then intermittently throughout 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.

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 (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 Display.

Second Year Activities

Following the completion of the first year activities, researchers held a meeting with the Project Advisory Panel to determine the research activities for the final year of the project. The second year of the project focused on the evaluation of devices that showed promise in year one of the project and also served to evaluate additional devices that were not examined in the first year. A meeting was held on March 1, 2000, in order to determine the second year activities. The panel elected to gather more detailed data on the following devices that were examined during the first year:

- speed display,
- radar drone,
- fluorescent yellow-green vests,
- fluorescent orange signs, and
- retroreflective magnetic strips on work vehicles.

In addition to field testing, researchers measured the fluorescent vests to determine their photometric performance as compared to the standard orange TxDOT vest. This comparison was done in order to provide objective data on the performance of the garments.

The panel also elected to examine several new devices. These devices included:

- portable rumble strips,
- portable variable message signs, and
- radar-activated flagger paddle.

These devices were not evaluated during the first year of the project either due to time constraints, or because the equipment was not available.

Research Methodology

The research methodology included developing the experimental plan, selecting data collection sites, developing data collection procedures, performing data collection activities, and reducing the data. Data were collected at eight work zones in the Childress District. Six of these were located on two-lane roads, and the remaining two sites were located on an Interstate.

The research team collected the data on the relative performance of the various worker garments at the Texas A&M Riverside campus. The procedures used to determine the performance of the garments are described in a separate chapter.

Data Analysis

Several analyses were performed to determine the effectiveness of each device. A series of analysis of variance tests were performed 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. The analysis is summarized by measure of effectiveness for each device tested.

The various worker garments were evaluated based on several criteria. The luminance, contrast ratio and color of each garment were examined to determine the relative performance characteristics of the vests.

Second Year Findings and Final Recommendations

The effectiveness of devices evaluated during the second year of the project is 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.

Portable rumble strips (Figure 6)

- The portable rumble strips had little impact on passenger car speeds but reduced truck speed by 3-5 mph.
- The percentage of vehicles exceeding the speed limit tends to be reduced following the rumble strip installations.
- Installation time for the rumble strips was probably too lengthy to justify their use at rural maintenance work zones.

Figure 6. Portable Rumble Strips.

Portable Variable Message Sign (VMS)

- The VMS produced speed reductions of 1-2 mph within the work zone.
- The VMS also reduced the percentage of vehicles exceeding the speed limit inside the work zone.
- Portable VMSs have a number of applications beyond work zone traffic control and can be used for other purposes when needed.
- The VMS seemed to cause vehicles to move out of the closed lane earlier than when the VMS was not operational, which resulted in fewer observed conflicts.

Fluorescent orange signing

- Maintenance crew opinions were 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 are made of prismatic retroreflective sheeting. Consequently, if crews used the signs during nighttime conditions, they would appear brighter than the beaded retroreflective material normally used.

Fluorescent yellow-green worker vests

- 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.
- Testing showed that the fluorescent yellow-green vests with solid fabric panels provided the best luminance and contrast ratios.
- The TxDOT fluorescent yellow-green vests were the best performing mesh vests evaluated.

High-visibility retroreflective magnetic strips on work vehicles

- 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.
- Being retroreflective, the strips' main benefit would occur at night.

Radar drone

- The use of the radar drone generally reduced speeds. Speeds approaching the work zones were about 2 mph less with the radar drone compared to when the radar drone was not present.

Speed display trailer

- The speed display reduced passenger car speeds by 7-9 mph at the first test site and 2-3 mph at the second test site.
- The speed display reduced truck speeds by 3-10 mph at both sites.
- The speed display had a positive impact on the percent of vehicles speeding.
- Set-up and removal of the display was easily accomplished.

CHAPTER 2
DEVICES EVALUATED DURING THE SECOND YEAR

This chapter is divided into two sections. The first section describes the process used to determine which devices researchers would evaluate in year two of the project. The second section provides a detailed description of each device and how the device was used during second year activities.

SELECTION OF DEVICES TO BE EXAMINED

Following the first year of the project, it was necessary to determine which devices should be evaluated further, and if any new devices should be evaluated during the second year of the project. A meeting was held with the project advisors at the Childress District office on March 1, 2000, to discuss first year results and data collection activities for the second year of this project. The first year of data collection yielded results on the following devices:

- speed displays,
- radar drones,
- fluorescent orange signs,
- fluorescent yellow-green vests, and
- retroreflective magnetic strips on work vehicles.

Based on the discussions at this meeting, it was determined that the following devices should be investigated during the second year of the project:

- portable rumble strips,
- portable variable message signs,
- speed displays, and
- radar-activated flagger paddle.

Due to the limited amount of data collected during the first year of the project, an additional day of data collection was needed for the radar drone, fluorescent signs, and vehicle visibility strips. In addition to these evaluations, visibility measurements would be performed on the worker vests to determine if they would improve worker visibility over the garments currently used by TxDOT.

DEVICE DESCRIPTIONS

Based on the comments received at the March 1 meeting, the research team planned a series of data collection trips to test the devices selected for evaluation. A literature review of the devices had previously been performed during year one of this project, and this information will not be repeated in this report. Readers interested in past studies of the devices tested are urged to consult the report summarizing the first year activities of this project *(3)*. Information from new research is included in this report. Descriptions of the devices tested in year two of this project and details as to how they were installed at the sites are included below.

Portable Rumble Strips

Description

The portable rumble strips evaluated were manufactured by Advance Traffic Markings. The rumble strips were shipped as individual 12 feet long strips that are 4 inches wide and 0.125 inch thick. The strips are colored bright orange and have an adhesive backing. When these strips are placed perpendicular to the direction of traffic, they create an auditory and vibratory warning to drivers. These particular strips were selected since they had been successfully tested in a study performed in Kansas in 1999 (*4*).

Installation and Use

Researchers tested two sets of rumble strips at each data collection site. Since the Kansas study showed that the initial 0.125 inch thickness produced minimal speed reductions, the thickness of the strips was doubled by adhering one strip to the face of another. Each set was composed of six individual rumble strips that were placed at 18 inch intervals parallel to one another. The adhesive backing was simply peeled from the back of the strip, and the strip was placed on the pavement. A tamping cart was used to ensure that there was good adhesion between the strip and the road surface. Figure 7 shows an example of the tamping process.

Figure 7. Portable Rumble Strips Installation.

Two sets of six rumble strips were used at all of the work zones studied. The first set was located approximately halfway between the “Work Zone – Traffic Fines Double” and the “Road Work Ahead” signs in the work zone. Workers placed the second set of rumble strips about halfway between the “Road Work Ahead” and “Left/Right Lane Closed” or “Flagger Ahead” signs. Figures A-1 to A-3 in Appendix A show the locations of the rumble strips. These locations were selected since they allow workers to easily locate the appropriate installation position and also provide adequate warning to the driver to read the messages on the signs.

Removal of the rumble strips was accomplished by simply peeling them off the road surface. If the surface of the road was not clean, or was composed of loose pavement, some debris could still be attached to the back of the rumble strip. In these cases, the rumble strips were not reusable. Figure 8 shows the aftermath of removing the rumble strips from the pavement.

Figure 8. Removal of Rumble Strips.

Portable Variable Message Sign

Description

This project utilized a TxDOT standard trailer-mounted solar variable message sign. The VMS could display up to three lines of text with eight characters on each line. Light emitting diodes (LEDs) were used to display the characters. The message board met the MUTCD visibility and legibility requirements.

Installation and Use

The portable VMS was placed approximately 0.5 mile prior to the work zone taper at both sites. The display was set up on the right shoulder and displayed a three-panel message. The message was (1) “ROAD WORK AHEAD,” (2) “RIGHT LANE CLOSED,” and (3) “REDUCE SPEED.”

The VMS was easily set up and removed. A towing vehicle brought the VMS to the site and placed it on the right shoulder. Once the VMS was leveled, the message board was rotated from its towing position to face traffic. Workers then extended the message board mast so that the bottom of the message board was at least 7 feet above the road surface.

Fluorescent Yellow-Green Vests

Description

During the first year of the project, evaluation of worker vests focused on subjective field evaluations of yellow-green vests. During the second year, a more quantitative evaluation was conducted in order to determine the performance of a wide variety of worker garments. This evaluation compared a total of five different worker vests. The garments are shown in Figure 9. The vests examined from left to right are:

- TxDOT orange mesh vest,
- TxDOT yellow-green mesh vest,
- mesh yellow-green vest,
- solid panel yellow-green vest, and
- yellow-green garment with sleeves.

Figure 9. Worker Garments Evaluated.

These garments were evaluated based on their visual performance and the wearer's anticipated comfort level. In order to determine an acceptable procedure for objectively determining a garment's visibility, a great deal of research was conducted into how humans process visual information and requirements for worker garments. This research is described below.

Prior Research

Research has shown that fluorescent colors are more conspicuous than ordinary colors during overcast days and during dawn and dusk conditions. However, research has not quantified the impacts of fluorescent materials during cloudless midday conditions. One of the main fluorescent issues remaining is to determine the quantified benefits of fluorescent material during cloudless midday conditions. Under these conditions, luminance contrast ratio is the critical measure of effectiveness. Luminance contrast ratio helps define the conspicuity of objects in the periphery. Luminance contrast ratio is the difference in the luminance (i.e., brightness) of an object versus the immediate surroundings of that object. In the daytime, luminance is dependent on color, fluorescence, and ambient light. Luminance can be measured and has a strong association with perceived brightness. The larger the luminance contrast ratio, the more conspicuous or visible an object is.

Daytime Visibility. A motorist needs to be able to detect the highway worker against various backgrounds. These backgrounds could have high luminance, low luminance, or intermediate luminance. Backgrounds could be made up of a variety of colors, be man-made, or be natural. When increasing conspicuity by means of luminance contrast, as in the case of daytime conditions, the use of headlamps enhances passive materials such as non-illuminated worker vests (e.g., those vests being studied herein), which leaves color contrast as the most promising avenue. A number of studies have shown fluorescent colors to be the most universally effective colors for improving overcast and dawn/dusk visibility measured in terms of conspicuity (*5*-*13*) and increased safe driving behavior (*14*-*16*).

Another factor to consider is older drivers and their increasing proportion of the drivers on the road. Aging brings with it a deterioration in physical and cognitive performance. As a result, older drivers need two to three times the color contrast during the day to match the performance of their younger counterparts (*17*).

Sufficient surface area of contrasting colored materials is needed to produce the desired or adequate conspicuity, which means covering the torso and hard hat in order to maximize the coverage area. Traditionally, the torso has been covered with a safety vest, usually made from a mesh material to reduce the insulation impact. It is important that the torso area of the highway worker be covered with highly visible material because the torso provides the largest area for display of the highly visible material. However, typical temporary traffic control (excluding advance signing) is less than 5 feet high. Assuming the average highway worker is 6 feet tall, this average puts the torso area of the highway worker at the same height as much of the work zone traffic control. The next largest area of the highway worker that may have the most potential to improve visibility is the head protection.

In Texas, workers are required to wear a hard hat whenever they are on the road. The color of this hard hat is currently white and includes the option of adding white retroreflective material for improved nighttime visibility. To date, most studies have overlooked this option for improved worker visibility. However, because of the height advantage, the research team feels that this option is potentially one of the most promising for improving worker visibility. In fact, subjective evaluations in temporary work zones have shown that the fluorescent yellow-green hard hat tested in year one was well accepted as a potential improvement for increased highway worker safety (*3*).

Nighttime Visibility. The focus of this research effort is on daytime maintenance work zones. However, nighttime visibility of worker clothing is also a main concern. Retroreflective material is usually added to worker clothing to improve nighttime visibility. In general, the color of the non-retroreflective material does not improve nighttime detection (regardless of the fluorescence of the non-retroreflective material), rather, the retroreflective material is meant to improve nighttime detection. Standards for minimum retroreflectivity have recently been approved and published (*18*). Interested readers are encouraged to review the American National

Standards Institute (ANSI) standard for retroreflectivity requirements of highway worker vests (*18*).

Highway Worker Safety Clothing Research. The Minnesota Department of Transportation (MnDOT) first formulated the idea of safety clothing with orange and yellow-green. In 1990, The MnDOT conducted a survey of colored safety vests at the Minnesota State Fair (*19*). Four difference fluorescent color safety vests (fluorescent yellow, fluorescent green, fluorescent orange, and fluorescent pink) were placed on mannequins. Fair attendees were asked to indicate which of the four vests was most visible. Fluorescent yellow was selected as the most visible color (45.5 percent), followed by fluorescent green (21.2 percent), then fluorescent orange (17.5 percent), and finally fluorescent pink (15.8 percent).

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[(1)] 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 inch in width and be at least 0.25 inch 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/lx/m^2 at an entrance angle of -4 degrees and an observation angle of 0.2 degrees and of 165 cd/lx/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 (*20*).

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 flagger's vest, shirt, or jacket shall be orange, yellow, strong yellow-green, or fluorescent versions of these colors" (*2*).

A MnDOT survey taken in 1995 issued samples of retroreflective vests and shirts to workers in MnDOT district 7, which were a yellow-green combination (*21*). 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 (*21*).

One of the more realistic studies on worker garments was reported by Turner et al. (*7, 8*). This effort included a field study to determine the most conspicuous color of safety clothing for daytime use in work zones. Researchers evaluated eleven different colors including eight

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[1] Photometric data is now discussed almost exclusively in metric terms. If English units are desired, the following conversion factors can be used:

- 1 foot-Lambert = 3.426 candela (cd)/m^2
- 1 foot-Lambert/foot-candle = 0.318 cd/lux/m^2

fluorescent colors (green, yellow-green, yellow, yellow-orange, red-orange, a combination of red-orange with yellow-green, red mesh [over a white background], and pink), two non-fluorescent colors (yellow and orange), and one semi-fluorescent color (yellow). Two work zone configurations were set up on a closed-course facility, one with tapered barrels and one with a symmetrical configuration of cones. No machinery was used and the background was light colored buildings. Subjects were required to look through a shutter which opened for 300 msec at 100 feet intervals as the researcher drove 20 mph towards a work zone. Subjects were instructed to indicate the point at which they first identified safety clothing in the scene. These detection distances were recorded for each color in each of the four work zones. Detection distances for each color are shown in Table 2.

Table 2. Detection Distances (ft).

Color	Mean	Median	Minimum	Maximum	85th Percent
Fluor. Green	656	500	200	1800	300
Fluor. Yellow-Green	853	700	200	2000	500
Fluor. Yellow	794	700	200	2000	400
Semi-Fluor. Yellow	709	500	200	2000	400
Yellow	702	500	100	2200	400
Fluor. Yellow-Orange	781	700	100	2000	475
Fluor. Red-Orange	984	1000	0	2100	575
Fluor. Red-Orange with Fluor. Yellow-Green	830	700	0	2200	475
Fluor. Red Mesh on White	892	800	0	2200	500
Orange	666	600	100	1900	300
Fluor. Pink	843	800	200	2000	400

Older drivers were not able to perform the tasks associated with the data collection activities and were therefore eliminated from the sample (the older drivers were unable to identify objects located more than 100-300 ft in front of the vehicle).

The vest material was applied to flat aluminum substrate with an area of 0.46 ft^2 (the approximate area of a worker vest). Because the material was flat, no shadowing effects were possible. In a realistic environment, the material would not be flat and shadowing effects would decrease the brightness of the material. Furthermore, only one type of material was mesh, which is the preference with states in warmer climates such as Texas.

Fluorescent red-orange was found to have the highest mean detection distance. Other colors that were found to perform statistically equal to the fluorescent red-orange color were red mesh, yellow-green, and red-orange with the yellow-green combination.

The report recognizes that the fluorescent red-orange may not perform as well when the work zone includes a great deal of orange traffic control and machinery (a situation not covered in the field study). Fluorescent yellow and fluorescent red-orange with fluorescent yellow-green are two colors recommended as alternatives to the fluorescent red-orange. Although red mesh was shown to have relatively large detection distances, it was not recommended for additional use since the detection distance may vary significantly depending on the clothing color worn underneath the mesh vest.

A study by the University of Illinois in 1997 indicated that motorists do not see flaggers very well in construction zones *(22)*. 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 *(22)*.

In 1998, Brich conducted research aimed at improving the full-body jumpsuit design for the Virginia DOT safety service patrol *(6)*. At that time, the Virginia DOT used several different jumpsuit designs. The purpose of this study was to identify and evaluate various colors and configurations of retroreflective materials for use on the full-body jumpsuits to maximize worker safety and develop one consistent design to be used throughout the state.

The jumpsuits selected for testing were evaluated under controlled conditions in the field. The evaluation consisted of photographing the then current designs along with the improved designs. Each jumpsuit was videotaped to represent the driver's perspective. Photometric measurements were also made of the materials under daytime and nighttime conditions, including colorimetric measurements made in the laboratory.

The report concludes that fluorescent colors enhance daytime conspicuity of highway worker's clothing. Fluorescent orange and fluorescent yellow-green were identified as the best colors for use on high-visibility clothing. The fluorescent yellow-green garment was determined to be the most visible. Fluorescent orange and retroreflective strips were also included in the recommended design.

Another study performed by Michon was aimed at determining the influence of color and size on conspicuity of safety clothing *(23)*. The colors evaluated were white, yellow, fluorescent yellow, and fluorescent orange against backgrounds of trees, heather, sky, and road. Viewing distances were 328 ft and 656 ft. Overall, fluorescent orange scored the best followed by yellow, fluorescent yellow, and white. The results indicate that an area of 3.3 ft^2 provides sufficient conspicuity, which is roughly equivalent to a 12-inch wide band around the upper part of the body.

Fluorescence Research. Zwahlen and Vel studied the conspicuity of fluorescent and nonfluorescent colors in terms of peripheral vision *(9)*. They found that fluorescent colors are more easily and more successfully detected and recognized than similar nonfluorescent colors (against all three evaluated background colors). Fluorescent yellow provided the highest peripheral detection performance while fluorescent orange provided the highest peripheral recognition performance of the three different backgrounds. Table 3 summarizes their detection and recognition findings.

Table 3. Percent Average Detection of Fluorescent versus Non-Fluorescent Targets.

Color	**Background**	**City**			**Fall Foliage**			**Spring Foliage**		
	Peripheral Angle (deg)	**20**	**30**	**40**	**20**	**30**	**40**	**20**	**30**	**40**
Fluor. Orange and Yellow	Detection	98.6	84.7	70.8	88.9	87.5	72.2	98.6	94.4	73.6
	Recognition	69.4	57.0	37.3	73.6	56.7	37.4	80.6	68.0	36.1
Standard Orange and Yellow	Detection	97.9	75.0	45.6	83.3	79.2	58.3	97.9	83.3	52.1
	Recognition	52.1	32.9	12.5	64.6	47.9	39.6	80.2	43.8	27.1

In 1995, Burns and Pavelka evaluated the daytime visibility of fluorescence for signing applications (*10*). Although the main intent of their research was for signing, their research results apply to fluorescent worker garments as well. In field studies, Burns et al. looked at detection and recognition of fluorescent and non-fluorescent colors. Figure 10 shows how much more detectable fluorescent yellow-green is over similar non-fluorescent colors. The background material was a camouflage made up of 23 percent light green, 34 percent green, 25 percent brown, and 18 percent black. Similar findings, not shown here, were obtained for fluorescent orange versus standard orange.

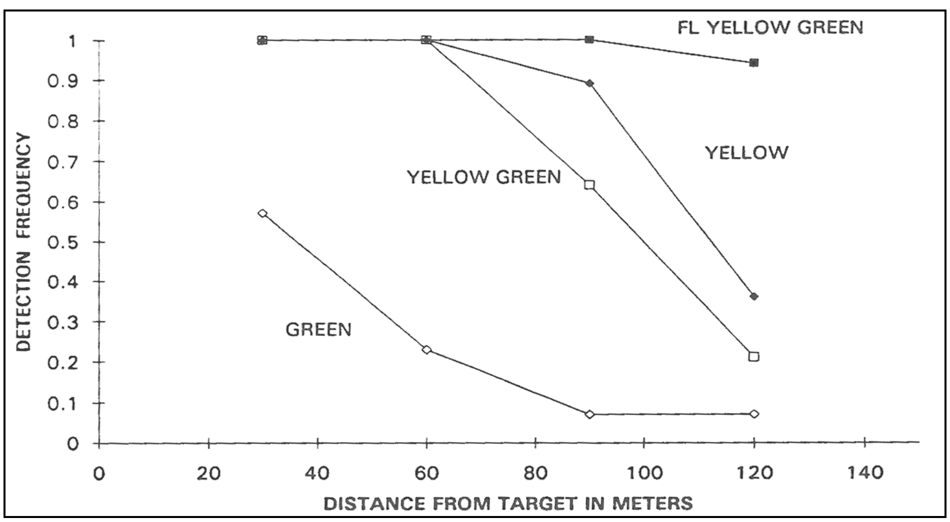

Figure 10. Detection (*10*).

Figure 11 shows similar results for color recognition of fluorescent versus non-fluorescent colors. Again, the findings comparing fluorescent orange and non-fluorescent orange showed similar results.

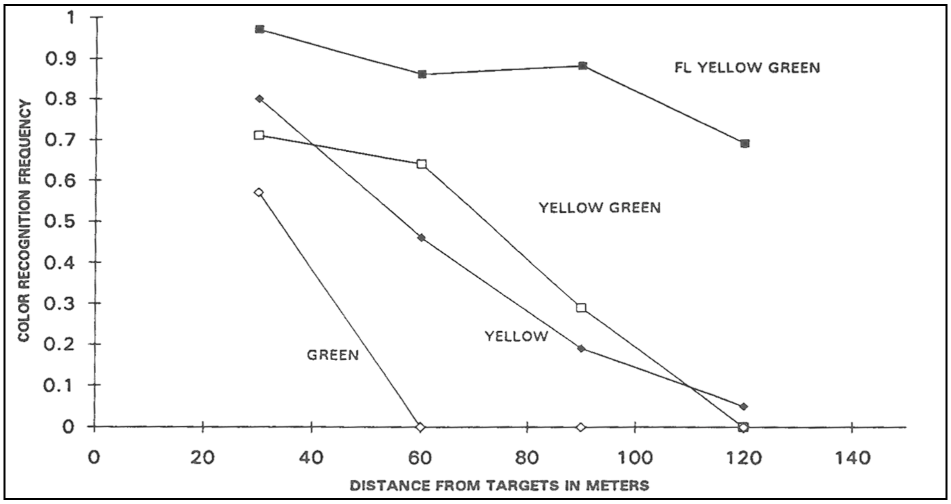

Figure 11. Color Recognition (*10*).

In another fluorescent experiment, Burns and Johnson asked observers to rate the perceived brightness of several colors, both fluorescent and non-fluorescent (*11*). They also measured the luminance contrast ratio of the targets. Figure 12 shows their findings. Figure 12a shows the observer rating of sign brightness according to time of day. Figure 12b displays the luminance contrast ratio of the target luminance (L_T) to the luminance of the background (L_B) by the time of day. The solid vertical bars represent the approximate time of local sunset.

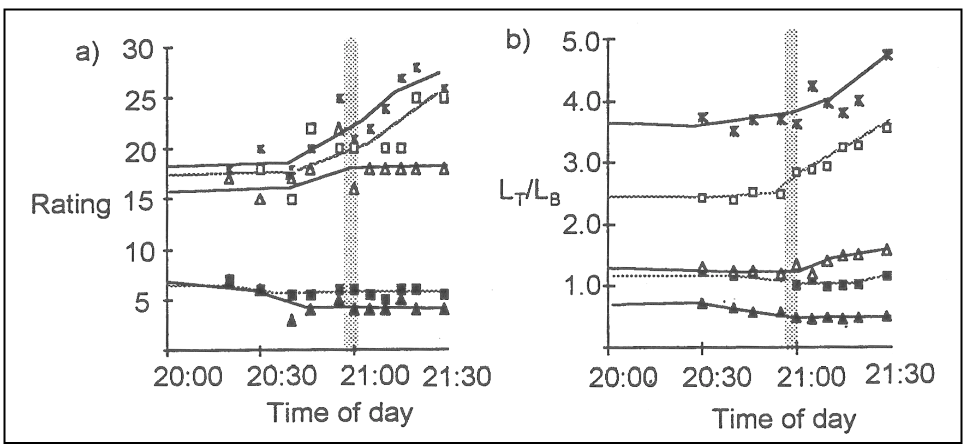

Figure 12. Brightness Perception (*11*).

Figure 12a shows how the observers rated the brightness of the signs, and Figure 12b shows how the measured luminance contrast ratio compares to observer ratings. Fluorescent yellow-green is shown with an '×', fluorescent yellow is shown with a '□', ordinary yellow is shown with a '■', fluorescent orange is shown with a '▲', and ordinary orange is shown with a '△'. Together, Figures 12a and 12b illustrate a direct correlation between the perceived brightness of the targets and the luminance contrast ratio. These results indicate that the photometric properties of fluorescent materials do play a significant role in their relative increased visibility and conspicuity over non-fluorescent colors. Figure 13 demonstrates typical luminance contrast ratio of various colors, measured during an overcast day and compared to a camouflage background. All three fluorescent colors showed the best detection rate.

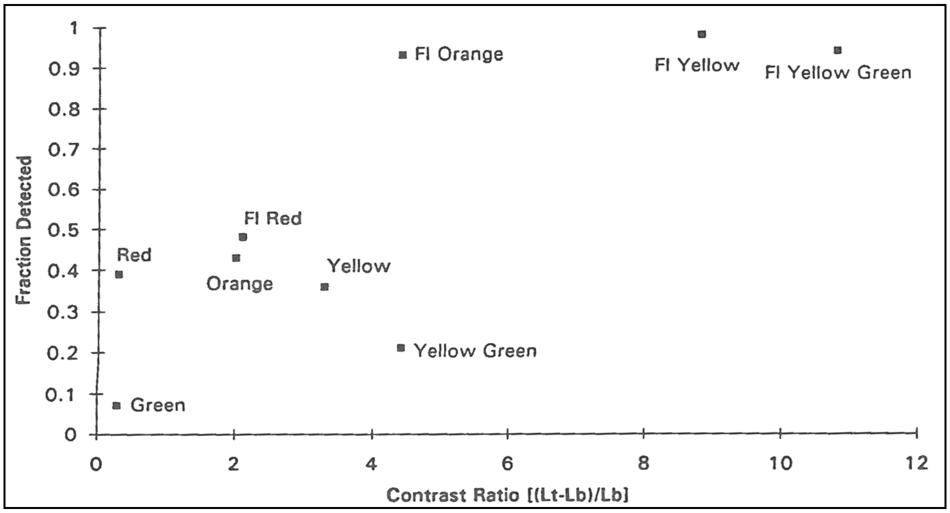

Figure 13. Contrast Ratio of Various Colors (*10*).

Installation and Use

The research team evaluated the worker garments two ways. First, the solid panel fluorescent yellow-green vest was evaluated in the field by asking members of the maintenance crew to wear the garment. The workers were then asked their opinions on the vest. All of the vests were also evaluated based on their luminance, contrast ratio, and color. The testing procedures are described in detail in Chapter 5.

Fluorescent Orange Signs

Description

Fluorescent orange roll-up construction signs were also used in this project. The signs used were constructed of microprismatic material and were 48 inches square. Signs were available for all common work zone legends.

Installation and Use

The fluorescent signs were inserted into the roll-up sign bases that were used for the standard TxDOT construction signs. The signs were set up and installed in the same manner as normal roll-up signs.

Retroreflective Magnetic Strips for Work Vehicles

Description

The retroreflective strips tested consisted of an 8-inch wide strip of sheeting on a magnetic backing. The strips were produced in lengths of 3 feet. Four inch square blocks were alternated along the strip to produce a checkerboard pattern. Orange and fluorescent orange microprismatic sheeting was used for the alternating boxes. The magnetic strips were manufactured specifically for this project.

Installation and Use

The magnetic strips were applied to the TxDOT flagger vehicle. Strips were placed on both sides of the pickup truck and along the tailgate of the truck. The truck was angled so that the right side and tailgate of the truck were visible to traffic entering the work zone. Installation and removal of the magnetic strips was accomplished very quickly.

Radar Activated Flashing Flagger Paddle

Description

A prototype radar-activated flashing flagger paddle was developed by the Texas Transportation Institute for this project. The existing device is currently very fragile and is not suitable for extended field use. The paddle consists of an 18 inch stop and slow sign made of prismatic sheeting mounted on a 5 feet tall plastic pipe. Figure 14 shows the front of the paddle.

Figure 14. Radar-Activated Flagger Paddle.

The unit is composed of a flashing stop/slow paddle that was obtained from TxDOT and some components from an older radar gun. The radar unit is mounted at the base of the sign face. A profile view of the radar unit is shown in Figure 15. The radar continuously emits a radar beam out of the copper cone mounted below the sign face. Some of the radar unit components are exposed and are very fragile. If the device is to be made into a field-ready product, some sort of casing will be required to protect these components.

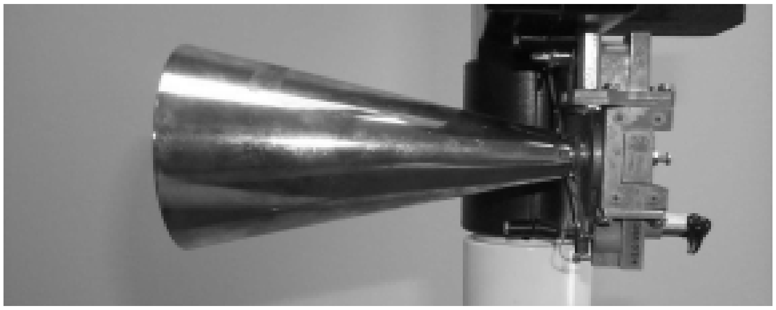

Figure 15. Profile of Radar Unit.

There are three white and 15 red light emitting diodes (LEDs) above and below the legend of the stop sign. These LEDs are extremely bright, but also very directional. If the flagger points the stop paddle directly at an oncoming vehicle, the LEDs can be seen from quite a distance during the day. The battery is included in the sign face and is rechargeable. The radar and LEDs can operate for more than a day on a single battery charge.

When the radar is active, the LEDs in the face of the sign will blink when a vehicle is detected traveling over a set speed threshold. The speed threshold can be set at 50, 55, 60, or 65 mph. When the radar detects a vehicle above the speed threshold, the red and white LEDs blink alternatively. The radar can only detect speeds when the stop legend is facing traffic. An indicator is located on the face of the slow sign that will provide the flagger with an indication as to how fast oncoming traffic is traveling. LEDs can still be activated manually without being triggered by the radar gun should the flagger desire additional visibility. Figure 16 shows the controls used to operate the sign.

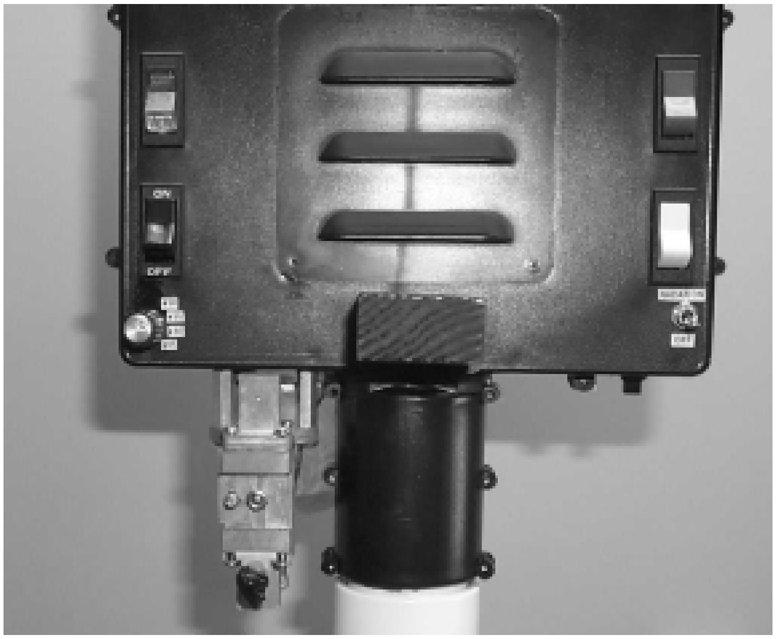

Figure 16. Flagger Paddle Controls.

Prior Research

No prior research on radar- activated stop/slow paddles was found, but there is a great deal of experience nationally with non-radar-activated flashing flagger paddles. It is anticipated that this device will combine the effects of a radar drone and a normal flashing stop/slow paddle. A summary of prior research on radar drones and flashing flagger paddles can be found in the report summarizing the first year activities of this project (*3*).

Installation and Use

Since the flagger paddle can only detect speeds when the stop indication is facing traffic, it was necessary to find a test site where volumes were large enough that vehicles would be forced to stop at the work zone. Since this device was developed relatively late in the project, researchers were unable to locate an adequate site to test the device. No results on this device are included in this report since researchers did not conduct any field testing. A preliminary assessment of the paddle's effectiveness is made purely based on the experiences of the researchers.

Radar Drone

Description

This evaluation utilized a commercially available radar drone. The radar drone emits a K-band radar signal that can be detected up to a mile away. The radar signal will activate radar detectors, potentially decreasing vehicles' speeds as they approach the drone site.

Installation and Use

Installation of the drone involved plugging it into the flagger vehicle cigarette lighter. The drone then operated continuously. The drone was placed in the flagger vehicle during testing.

Speed Display

Description

This evaluation utilized a trailer-mounted speed display provided by TxDOT. Figure 17 shows the front of the speed display, and Figure 18 shows the profile of the display. The unit features a 24 inch LED display and uses Ka-band radar to detect oncoming vehicles. The display has a strobe lamp that flashes when a vehicle is detected traveling over a preset speed threshold. This feature is intended to simulate the operation of photo enforcement, possibly decreasing speeds through the threat of automated enforcement. During this evaluation, the speed threshold for the strobe light was set at 75 mph. The display also has a 130 decibel siren that can be activated by vehicles traveling over a preset speed. This option is intended to warn workers when an extremely high-speed vehicle is approaching but was not used in this evaluation due to concerns about battery drain. Figure 19 shows the controls for the speed display.

Figure 17. Speed Display (Front View).

Installation and Use

The speed display was set up within the work zone at two different locations. The speed display testing from year one indicated that placing the display too close to the work zone taper may reduce its effectiveness. Therefore, two new locations were selected for the speed display. These locations were:

- approximately halfway between the "Work Zone – Traffic Fines Double" sign and the "Road Work Ahead" sign, and
- approximately halfway between the "Road Work Ahead" and the Reverse Curve signs.

These locations were selected since they would be relatively easy for a maintenance crew to locate and would not obstruct the message of any of the work zone signs.

The set up and removal of the sign could be accomplished in under 10 minutes. A towing vehicle brought the sign to the desired location. The display was disconnected from the towing vehicle and placed perpendicular to traffic. Workers leveled the display by adjusting the legs attached to the trailer. The front of the display was then opened, and the power was turned on. Speed thresholds for the strobe light and siren could be set by simply dialing the correct speed. The display was then closed, and the speeds were verified using Light Detection and Ranging (LIDAR) guns. Removal of the display involved turning the power off and connecting the display to the towing vehicle.

Figure 18. Speed Display (Side View).

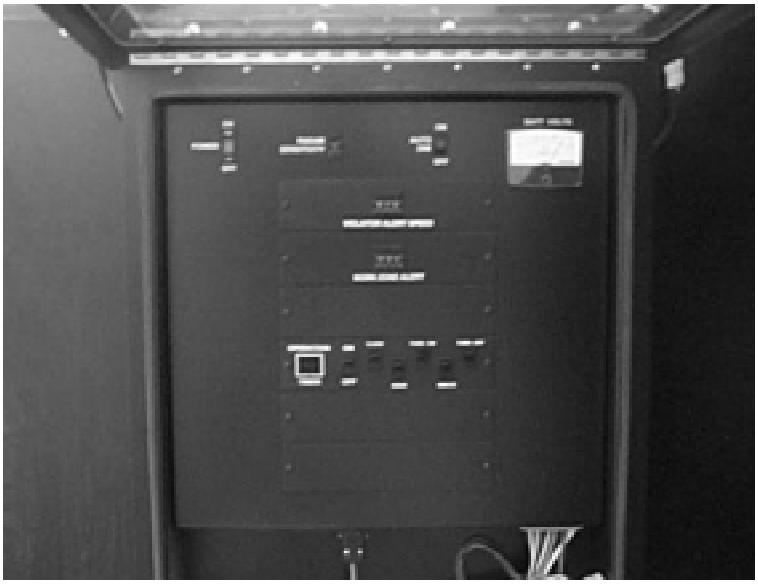

Figure 19. Controls for Speed Display.

CHAPTER 3
RESEARCH METHODOLOGY

This chapter describes the data collection process that was utilized during second year activities. Site selection was based on the type of device being evaluated. While speed and volume data were collected for each device, additional measures of effectiveness were sometimes used if they were more appropriate for describing the effectiveness of the device. The data collection section describes the equipment and procedures used to collect these data. This chapter also describes the data analysis and reduction.

SITE SELECTION AND LAYOUT

Data were collected at high-speed rural maintenance work zones. Maintenance activities typically lasted a single day at these sites, with traffic control being installed in the morning and removed by dusk. Second year data collection activities took place in the Childress District, since these locations offered rural work zones.

Several factors influenced the selection of test sites. Preliminary requirements for sites were developed based on the devices to be evaluated. Site requirements were then communicated to the project director. The project director coordinated with the district maintenance sections to ensure that appropriate data collection sites were available. Once the study sites had been confirmed, a data collection trip was scheduled.

Depending on the devices to be evaluated, the study sites were either two-lane or four-lane roads. All sites were located in rural areas at short-term maintenance work zones. Appendix A provides a description of each work zone site along with a sketch of the site layout. Table 4 summarizes some of the key characteristics of the sites. The designation listed in the Site ID column will be used to refer to the individual sites throughout this report.

Table 4. Site Descriptions.

Site ID	Road	Date	Number of Lanes	Average Daily Traffic (1997)	Device(s) Tested
RS1	SH 6	3/21/00	2	1250	Rumble strips
RS2	US 83	5/3/00	2	1850	Rumble strips
RS3	US 83	5/4/00	2	1850	Rumble strips
VMS1	I-40	6/6/00	4	12,000	Variable message sign
VMS2	I-40	6/7/00	4	12,000	Variable message sign
RD1	SH 6	6/8/00	2	750	Radar drone, fluorescent signs, fluorescent yellow-green vests, high visibility magnetic strips
SD1	US 62	6/20/00	2	1000	Speed display
SD2	US 62	6/22/00	2	1000	Speed display

DATA COLLECTION

Data collection at each site was separated into two periods. First, data were collected with standard work zone traffic control in place (the "before" period). Approximately halfway through the day, the test treatments would be installed. Data were then collected until work zone activities came to an end (the "after" period). The effects of the treatments on the various measures of effectiveness were evaluated to determine if the treatment resulted in a positive safety impact at the work zone.

A number of measures of effectiveness were evaluated to determine the impact of the various test treatments on traffic through the work zone. This section provides a detailed description of the methods used to collect and reduce the data collected at the sites. Table 5 summarizes the data that were collected at each site.

Table 5. Summary of Data Collected.

Site	Speed Data		Video Data		Worker Comments
	LIDAR	Counter	Conflicts	Percent of Vehicles in Closed Lane	
RS1	✔	✔	✔		✔
RS2	✔	✔	✔		✔
RS3	✔	✔	✔		✔
VMS1	✔	✔	✔	✔	✔
VMS2	✔	✔	✔	✔	✔
RD1	✔	✔	✔		✔
SD1	✔	✔	✔		✔
SD2	✔	✔	✔		✔

Speed Data

Two different methods were used to collect speed data. LIDAR guns were used to collect the speeds of free flowing vehicles. Traffic counters were used to collect speed and vehicle class information for all vehicles in the traffic stream. The collection of speed data with these two devices is summarized below.

LIDAR Speed Data

The speed data collected by the LIDAR guns provided an indication of free-flow speeds throughout the work zone. Free-flow vehicles are driving at their desired speed and are not being impeded in any way by other vehicles. The LIDAR guns were used to track vehicles as they traveled through the work zone. The LIDAR measures the speed and distance to a vehicle by emitting hundreds of infrared light pulses every second. These light pulses are reflected off a vehicle and back to the gun. A distance to the vehicle is determined by the LIDAR based on the elapsed time for the light pulse to return to the gun. An algorithm then computes the velocity of the vehicle based upon successive range measurements. Since the LIDAR transmits a narrow beam of light, it is possible to track individual vehicles through the work zone.

The LIDAR guns used in this project are linked to laptop computers throughout the data collection. A software program records the speed, time, and distance generated by the LIDAR gun onto the laptop. For each vehicle where speed data are collected, the operator inputs the type of vehicle for later reference. These data are recorded at the end of the speed data for each individual vehicle.

Counter Data

Researchers used traffic counters to collect speed and vehicle class data for all vehicles in the traffic stream. Unlike the LIDAR data, these speeds do not represent free-flow speed. The traffic counters were used to ensure that data were available at certain key locations within the work zone. Class II piezoelectric sensors were used to collect vehicle speeds and classifications. The piezoelectric sensors are attached to the pavement using bitumen road tape. These sensors are highly portable and provide accurate measurements of speeds and volumes. The traffic counters collected individual vehicle data at all sites.

Video Data

The research team also collected video data at a number of sites. The videotape data provided information for the traffic conflict analysis and lane distribution examination. Two separate systems were used for the video data collection. A mobile video recording system was used at several sites. This system consists of an enclosed trailer and a 30 ft tall telescoping pole with a camera in an environmental housing unit. This unit allowed researchers to gain a better perspective on traffic maneuvers downstream of the camera. On several occasions, a handheld camcorder was used to provide video data. The camcorder was used when video data were not needed a great distance away.

Conflicts

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, traffic 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" (*24*). A FHWA study analyzed the relationship between traffic conflicts and crashes using the traffic conflicts technique methodology (*25*). 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 being 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.

Researchers examined the videotapes obtained during data collection 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.

Percent of Vehicles in Closed Lane

When the VMS was tested, the percent of vehicles occupying the closed lane was examined. The video data was used in conjunction with the counter data to determine the number of vehicles that occupied the closed lane in advance of the work zone. The researchers used these data to determine if the VMS caused vehicles to move out of the closed lane farther away from the taper.

Worker Comments

Following data collection, the research team asked maintenance crew workers about their opinions of the devices tested. The worker comments provided valuable insights into the practical issues that the workers would need to address in order to use a device. These comments were the primary factor in determining the usability of a device.

SPEED DATA REDUCTION

Table 6 summarizes some of the key characteristics of the study sites. This table shows the total amount of time that data were collected, as well as the number of vehicles that traversed the work zone while data were being collected. The volume of traffic varied quite a bit between sites.

More vehicles were detected using the traffic counters than the LIDAR. The counters would collect data on every vehicle that traveled over their sensors. The LIDAR guns were used to collect data on free-flowing vehicles. Thus, vehicles that were not traveling at free-flow speeds are not included with the LIDAR data.

Table 6. Summary of Study Sites.

Site	Date	Measures Tested	Elapsed Time		No. of Counter Vehicles		No. of LIDAR Vehicles	
			Before	After	Before	After	Before	After
SH 6 NB	3/21/00	Portable rumble strips	2:45	0:50	53	23	50	20
US 83 NB	5/3/00	Portable rumble strips	2:15	4:09	103	678[a]	57	210
US 83 NB	5/4/00	Portable rumble strips	2:57	3:06	184	176	98	105
I-40 WB	6/6/00	Portable VMS	2:00	3:00	683	1043	128	209
I-40 EB	6/7/00	Portable VMS	3:00	3:00	1099	1232	199	166
SH 6 NB	6/8/00	Fluorescent signs, fluorescent vests, radar drone, retroreflective strips	2:00	3:05	79	77	11	23
US 62 EB	6/20/00	Speed trailer	1:25	3:30	43	94	28	66
US 62 EB	6/22/00	Speed trailer	3:20	2:40	92	71	61	71

[a] Vehicles were unexpectedly detoured onto US 83 following a train derailment on a nearby road. This detour resulted in an increase in traffic on US 83 during the after period on May 4.

LIDAR Data

Prior to leaving each study site, a sketch of the work zone would be constructed. Distances between features in the work zone were measured using a laser range finder. Locations of traffic control devices, data collection equipment, and other important features were noted. This detailed sketch allowed the researchers to tie the speed and distance information collected with the LIDAR gun to specific locations within the work zone.

By matching the LIDAR data to features within the work zone, a speed profile showing the average speed of vehicles at various points throughout the work zone could be created. In order to create the speed profile, locations of traffic control devices or other features within the work zone that could influence vehicle speeds were identified. Since there can be very large distances between these points, additional intermediate reference points were defined so that a smooth speed profile could be created. The reference points used for the sites are shown in Tables 7 and 8. These tables note locations where a traffic control device was placed.

Table 7. Reference Points for LIDAR Data[a].

Ref. Point	RS1		RS2		RS3		RD1	
	Dist. (ft)	Notes	Dist. (ft)	Notes	Dist. (ft)	Notes	Dist. (ft)	Notes
A	0	LIDAR station	0	LIDAR station	0	LIDAR station	0	LIDAR station, "Road Work Ahead" (CW20-1D)
B	600		350		350		250	
C	1199	"Work Zone – Traffic Fines Double" (R20-5)	600	"Road Work Ahead" (CW20-1D)	600	"Road Work Ahead" (CW20-1D)	500	
D	1377		850		850		750	
E	1727		1115	Rumble strips	1115	Rumble strips	1023	"One Lane Road Ahead" (CW20-4D)
F	2128	"Road Work Ahead" (CW20-1D)	1365		1365		1250	
G	2453	Rumble strips	1630	"Left Lane Closed Ahead" (CW20-5L)	1630	"Left Lane Closed Ahead" (CW20-5L)	1500	
H	2803	"One Lane Road Ahead" (CW20-4D)	1880		1880		1750	
I	3170	Rumble strips	2130		2130		2081	"Flagger Ahead" (CW20-7D)
J	3520	"Flagger Ahead" (CW20-7D)	2720	Arrow Panel	2720	Arrow Panel	2250	
K	4020		3200		3200		2500	
L			3478	Counter #5	3478	Counter #5	2750	
M			3700		3700		3000	
N			4200		4200			

[a] = (MUTCD designations for signs are shown in parentheses)

Table 8. Reference Points for LIDAR Data[a].

Ref. Point	VMS1		VMS2		SD1		SD2	
	Dist. (ft)	Notes	Dist. (ft)	Notes	Dist. (ft)	Notes	Dist. (ft)	Notes
A	0	LIDAR station	0	LIDAR station	0	LIDAR Station	0	LIDAR station
B	250		250		300		300	
C	500		500		644	"Work Zone – Traffic Fines Double" (R20-5)	711	"Work Zone – Traffic Fines Double" (R20-5)
D	788	"Right Lane Closed Ahead" (CW20-5R)	785	"Right Lane Closed Ahead" (CW20-5R)	965	Speed Display	1000	
E	1000		1000		1300		1300	
F	1250		1250		1543	"Road Work Ahead" (CW20-1D)	1605	"Road Work Ahead" (CW20-1D)
G	1500		1500		1750		1800	
H	1750		1750		2000		2021	Speed Display
I	1918	Arrow Panel	1908	Arrow Panel	2250		2200	
J	2250		2250		2447	Reverse Curve (CW1-4R)	2458	Reverse Curve (CW1-4R)
K	2500		2500		2750		2750	
L	2750		2750		3000		3000	
M	3000		2846	Counter #4	3256		3250	
N	3191	Counter #4	3000		3500		3500	
O	3500		3250				3750	
P	3750		3421	End Work Zone			4000	
Q	4000		3750				4341	Flagger
R	4250		4000					
S	4393	End Work Zone	4250					

[a] = (MUTCD designations for signs are shown in parentheses)

Speeds at the reference points were determined using the LIDAR data. The LIDAR guns collected a data point three times per second. Since a vehicle traveling 70 mph moves about 100 feet per second, a speed measurement is usually recorded every 33 feet. As a result, data may not be available precisely at each reference point. Therefore, when the descriptive speed statistics for the LIDAR data were being calculated, all speeds within ±25 feet of the actual reference point were examined. For example, if a reference point was located 500 feet from the LIDAR gun, all speeds from 475 to 525 feet would be examined. If researchers located more than one speed observation within this range, only the speed collected at the distance closest to the actual reference points would be retained. This regimen resulted in only one speed being reported for each vehicle at each reference point.

Counter Data

Traffic counters were also used extensively to collect data on vehicle speeds, class, and volume. The traffic counters were used to capture speeds prior to work zone traffic control becoming visible, near test treatments, and within the work zone. Table 9 shows the location of the traffic counters relative to the start of the work zone taper.

Table 9. Location of Traffic Counters.

Site	Position	Counter 1	Counter 2	Counter 3	Counter 4	Counter 5
RS1	Location	Upstream	One Lane Road Ahead	Flagger Ahead	Work Zone	
	Dist. from taper (ft)	12,426	1703	986	-1584	
RS2	Location	Upstream	Road Work – Traffic Fines Double	Road Work Ahead	Left Lane Closed Ahead	Work Zone
	Dist. from taper (ft)	10,818	3270	2220	1090	-758
RS3	Location	Upstream	Road Work – Traffic Fines Double	Road Work Ahead	Left Lane Closed Ahead	Work Zone
	Dist. from taper (ft)	10,818	3270	2220	1090	-758
VMS1	Location	Upstream	Road Work Ahead	Lane Closure Symbol	Work Zone	
	Dist. from taper (ft)	8423	5313	1130	-1273	
VMS2	Location	Upstream	Road Work Ahead	Right Lane Closed Ahead	Work Zone	
	Dist. from taper (ft)	9329	5139	2551	-938	
RD1	Location	Upstream	Road Work Ahead	Flagger Ahead		
	Dist. from taper (ft)	9491	3221	1140		
SD1	Location	Upstream	Road Work – Traffic Fines Double	Road Work Ahead	Reverse Curve	
	Dist. from taper (ft)	6177	4065	3166	2262	
SD2	Location	Road Work – Traffic Fines Double	Road Work Ahead	Reverse Curve	Work Zone	
	Dist. from taper (ft)	3630	2736	1883	-300	

CHAPTER 4
FIELD EVALUATION RESULTS

The research team examined the data obtained during the second year of data collection to determine which devices were most effective. Speed and video data were collected at all eight sites. The TxDOT maintenance crews were interviewed to learn their opinions on the devices being tested. Researches also examined conflict and traffic volume data at several sites.

ANALYSIS RESULTS

The analysis results for all of the devices tested are discussed in the following sections. Detailed descriptions of each test site are presented in Appendix A. The devices under evaluation are summarized in Table 10.

Table 10. Devices Tested.

Site	Date	Location	Treatment
RS1	3/21/00	SH 6	Portable rumble strips
RS2	5/3/00	US 83	Portable rumble strips
RS3	5/4/00	US 83	Portable rumble strips
VMS1	6/6/00	I-40	Variable message sign
VMS2	6/7/00	I-40	Variable message sign
RD1	6/8/00	SH 6	Radar drone, fluorescent orange signs, fluorescent yellow-green vests and hard hat covers, retroreflective magnetic strips attached to flagger vehicle
SD1	6/20/00	US 62	Speed display
SD2	6/22/00	US 62	Speed display

Summaries of the LIDAR speed data collected at each site and their reference points are included in Appendix B, and summaries of the counter data are included in Appendix C. Graphs of the counter speed profiles of all eight sites are included in Appendix D. The cells in these tables that are shown in bold with a shaded background indicate a statistically significant speed difference between the test treatment and normal work zone traffic control. Since the devices were tested at low-volume sites, it is possible that large differences in speeds may not be statistically significant due to relatively small amounts of data. These results may not be statistically significant, but they may represent an important trend in the data. Likewise at some of the high-volume sites, small changes in speed can be statistically significant but may not represent a practical difference.

Portable Rumble Strips

Portable rumble strips were tested at three sites, RS1, RS2, and RS3. The impact of the rumble strips on speeds and vehicle conflicts was examined. The usability of these devices for maintenance work zones was also examined.

Speed Data

Speeds were collected at the three sites using both traffic counters and LIDAR guns. The traffic counters show the impact of the devices on the entire traffic stream while the LIDAR guns show the impact of the devices on free-flowing vehicles.

Counter Speeds. Figures D-1 to D-3 in Appendix D show the speeds obtained by the counters at each site. The counter data are also summarized in Tables C-1 to C-3 in Appendix C. Figure 20 shows the speed reductions achieved with the rumble strips at sites RS2 and RS3. Counter data were limited at RS1 due to equipment malfunction and is not shown. Positive numbers represent increases in speed when the rumble strips were installed while negative numbers represent reductions in speed.

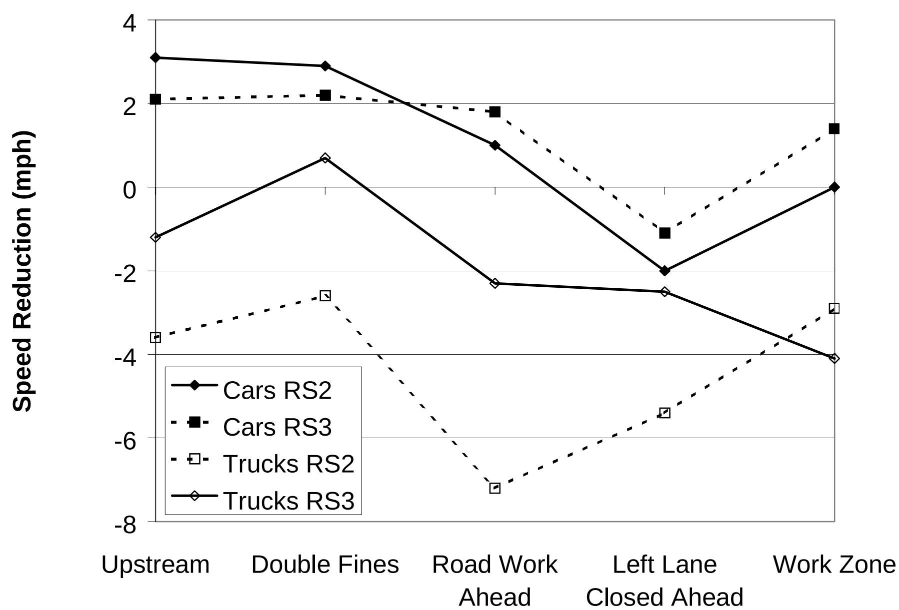

Figure 20. Reduction in Average Speed at RS2 and RS3.

First, the mean speeds of passenger cars were examined. The only location within the work zone where passenger car speed reductions were observed was at the "Flagger Ahead" sign at RS1 and the "Left Lane Closed Ahead" signs at RS2 and RS3. Speed reductions at these points were 6 mph at RS1 and 2 mph at RS2 and RS3. All of these locations were approximately 1000 feet before the work zone taper. However, RS2 was the only site where the passenger car speed reductions were statistically significant.

Next, researchers analyzed the percentage of cars exceeding the speed limit. RS2 was the only site where the percentage of cars exceeding the speed limit consistently declined after passing over the rumble strips. RS2 was also the only site where the differences in the percentage of speeding vehicles was found to be statistically significant.

The research team also examined the average truck speeds collected when the rumble strips were in place. Limited data existed at RS1, so no conclusions could be drawn from that site. At RS2, mean truck speeds were consistently lower when the rumble strips were installed, and speeds were lower at RS3 at all data collection points after the rumble strip installations. Mean speeds were lower at a statistically significant level at the data collection stations immediately following the rumble strips at RS2 and within the work zone at RS3. Speed reductions at these locations were generally about 5 mph.

The percentage of trucks exceeding the speed limit was also examined. RS2 was the only site that showed a consistent reduction in the percentage of speeding trucks approaching the work zone. The reduction in the percentage of speeders was statistically significant at all locations except within the work zone at RS2.

LIDAR speeds. Figures E-1 to E-3 of Appendix E show the average speeds collected by the LIDAR guns approaching the work zone. These data are summarized in a more detailed form in Tables B-1 to B-3 in Appendix B.

The LIDAR data generally show a reduction in the mean speed of passenger cars following the rumble strip installations. Limited data at RS1 make these LIDAR data inconclusive. At RS2, LIDAR speeds drop below the average speed with normal traffic control after the second rumble strip installation. At RS3, passenger car speeds are consistently lower with the rumble in place. Speeds approaching the flagger were about 1 to 3 mph slower at RS2 and RS3. Speeds within the work zone were up to 15 mph lower when the rumble strips were in place.

The impact of the rumble strips on truck speeds produced mixed results. The data collected at RS1 are limited, and no conclusions can be drawn. At RS2, truck speeds were consistently lower when the rumble strips were in place. At RS3, the truck speeds when the rumble strips were installed were very close to the speeds with normal traffic control on the approaches to the work zone. The speeds were lower within the work zone, however.

Conflicts

Observation of vehicle maneuvers at the rumble strip installations revealed that motorists will occasionally drive around the rumble strips to avoid hitting them. This was observed twice at RS2 and once at RS3, yielding an average occurrence rate of approximately 2.9 maneuvers per 1000 vehicles at RS2 and 5.7 maneuvers per 1000 vehicles at RS3. These vehicles moved into an oncoming traffic lane in order to go around the rumble strips. The rumble strips were installed in a passing zone, and no oncoming traffic was observed when these maneuvers were made. It is possible that these maneuvers could be hazardous in locations with high volumes or limited site distance.

Usability

The usability of the rumble strips for rural maintenance activities was also evaluated. Installation of the rumble strips involved a series of activities to prepare the strips for use and then place them in the field. A double thickness strip was created by peeling off the adhesive backing of one strip and placing it onto the top surface of another strip. This part of the process was performed prior to arriving in the field and took approximately 30 minutes for four workers to complete. The backing on some of the rumble strips was very fragile, and frequently tore as it was peeled off, lengthening this part of the process.

Once in the field, workers used a tape measure to mark where the rumble strips should be placed. The rumble strips were placed at 18 inch intervals perpendicular to traffic. The adhesive backing of each strip was peeled off, and the strip was placed onto the asphalt. The strips were trimmed so as to ensure that they did not cover any pavement markings. Once the strips were placed on the asphalt, a tamping car or vehicle was used to apply additional pressure to the strips. Installation time for all twelve strips was approximately 40 minutes.

Once in place, the strips did not move under traffic. Removal of the strips was accomplished by peeling them off the road surface. The strips were easily removed. If the road surface was loose, some gravel or debris would be found on the back of the rumble strips. If the road surface was clean, there may be a possibility that the strips could be re-used.

Workers had mixed opinions on the rumble strips. Many expressed concerns about the time required to install and remove the strips. Other felt that the strips would reduce speeds and increase driver awareness of the upcoming work zone.

Portable Variable Message Signs

A portable VMS was examined at two interstate sites. The impact of the VMS on speeds, lane occupancy, and traffic conflicts was examined. The usability of the device for rural maintenance operations was also assessed.

Speed Data

Vehicle speeds were collected at VMS1 and VMS2 using both traffic counters and LIDAR guns. Tables B-4, B-5, C-4, and C-5 in the appendices summarize these data.

Counter Data. Figures D-4 and D-5 show the speeds collected at VMS1 and VMS2. Figure 21 shows the speed reductions achieved with the VMS. Very small speed changes were observed at the sites.

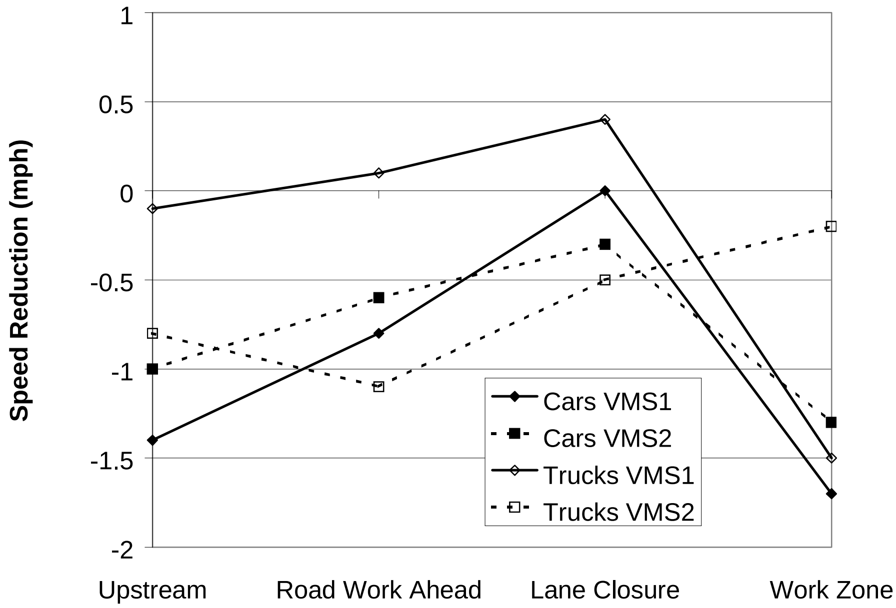

Figure 21. Speed Reductions at VMS1 and VMS2.

Passenger car speeds were usually lower at all of the data collection stations at both sites, with speed reductions of no more than 2 mph. These speed reductions were found to be significant for cars upstream of the work zone and within the work zone at both sites. The percentage of cars speeding was also significantly reduced within the work zone at both sites.

The VMS also appeared to have an impact on truck speeds. The average speed and the percent of vehicles exceeding the speed limit were significantly reduced within the work zone at VMS1, and speeds upstream of the work zone were reduced at VMS2.

LIDAR Data. The two test sites produced inconsistent LIDAR speed results. Passenger car speeds were usually lower at VMS1 when the VMS was operational. The VMS appeared to have less of an impact at VMS2. At VMS1, speeds were reduced by about 3 mph on approaching the taper, and the percentage of vehicles exceeding the speed limit was also significantly reduced. No statistically significant changes in passenger car behavior were observed at VMS2.

Truck speeds were usually lower when the VMS was operation at VMS1 and were often higher at VMS2 when the VMS was operational. Speed reductions observed at VMS 1 were approximately 2 mph.

Percent of Vehicles in Closed Lane

The percentage of vehicles occupying the closed lane was also examined to determine if the VMS caused drivers to move into the proper lane earlier than when no VMS was present. Figures 22 and 23 show the percentage of traffic in the closed lane at VMS1 and VMS2. The VMS appeared to have less of an impact at VMS1 than at VMS2. At VMS2, the percent of vehicles in the closed lane was consistently lower when the VMS was operational. Typically, 20 to 30 percent fewer vehicles were in the closed lane at VMS2 at each of the data collection points. The impact of the VMS on the lane distribution of traffic was less consistent at VMS1, with the percent of traffic in the closed lane sometimes increasing when the VMS was operational.

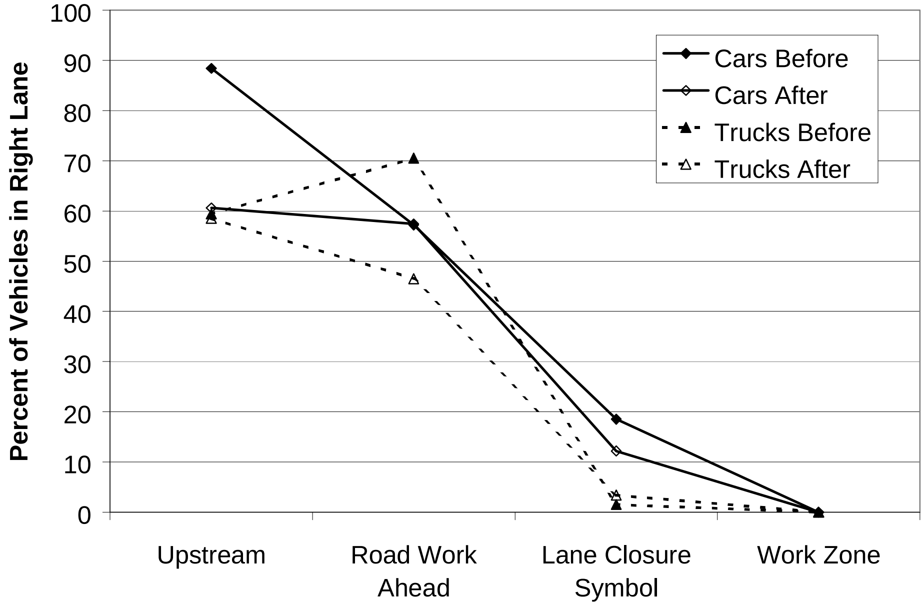

Figure 22. Percentage of Vehicles in Closed Lane at VMS1.

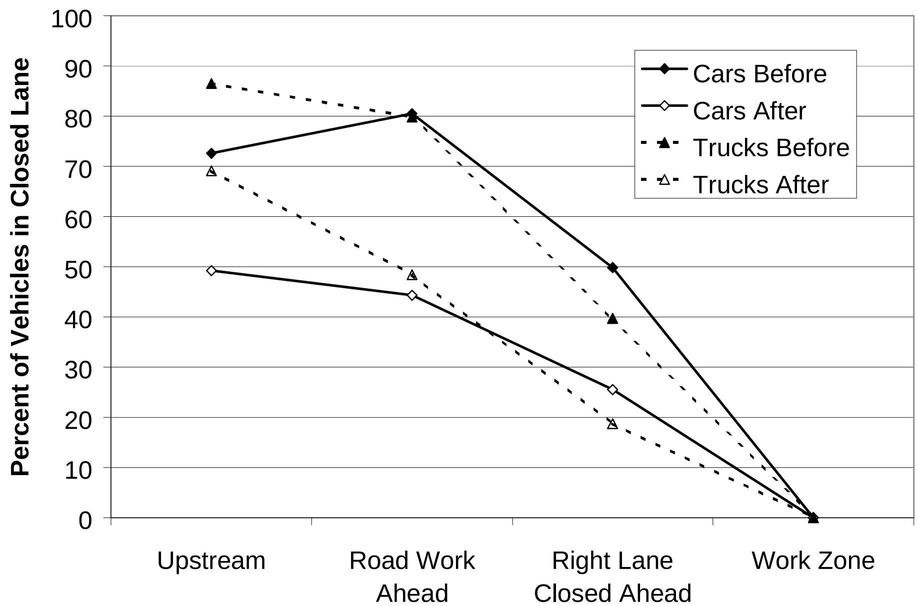

Figure 23. Percentage of Vehicles in Closed Lane at VMS2.

Conflicts

The research team also examined the impact of the VMS on conflicts. Table 11 summarizes the conflict data:

Table 11. Conflicts at VMS1 and VMS2.

Site	Conflicts per 1000 Vehicles		
	Normal Traffic Control	VMS	Difference
VMS1	13.5	10.2	-3.3
VMS2	15.0	9.4	-5.6

The VMS appeared to reduce the number of conflicts observed at the work zone. This reduction means that there were fewer late merges or braking maneuvers when the VMS was operational, which might be an indication that the VMS could provide a safety benefit.

Usability

TxDOT personnel were used to set up the VMS. The VMS was set up by two proficient users within 10 minutes. A variety of pre-programmed messages were available on the VMS, making the selection of messages very easy. The VMS was solar-powered, so no additional trips were necessary to ensure that the VMS was operational.

Worker comments on the VMS were uniformly positive. They indicated that the VMS was very easy to set up and required very little maintenance. The workers felt the VMS commanded more driver attention than normal signs and had a number of potential applications in work zones.

Radar Drone and Improvements to Traffic Control and Worker Visibility

The radar drone, fluorescent orange signs, fluorescent yellow-green vests, and vehicle visibility improvements were tested at one site. The research team evaluated the impact of these devices on speeds and the usability of the various devices.

Speed Data

LIDAR and counter data were collected at RD1. Tables B-6 and C-6 summarize the speed data for this site.

Counter Data. Figure 24 shows the average speed reductions observed at the three data collection stations. Passenger car speeds were consistently lower when the devices were in place, and truck speeds were lower within the work zone when the devices were operational. These speed reductions were significant at the “Flagger Ahead” sign for both cars and trucks. The devices also reduced the number of passenger cars speeding at all three data collection stations. These results are based on a limited number of data points, however. Thus, the magnitudes of the speed reductions observed may not be representative of what could be expected with these devices.

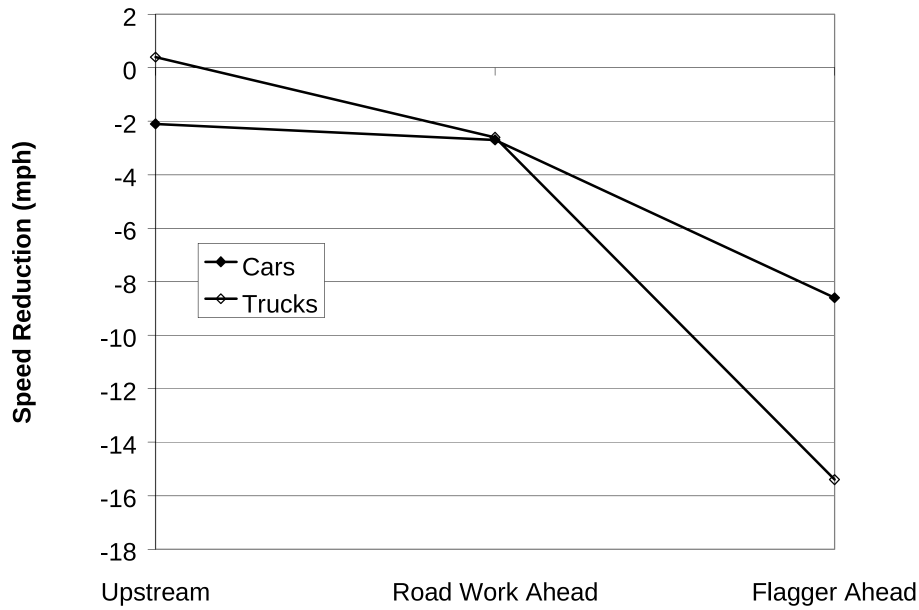

Figure 24. Speed Reduction at RD1.

LIDAR Data. Figure E-6 shows the LIDAR data collected at RD1. The passenger car speeds at RD1 were consistently lower when the devices were set up, while the truck speeds were consistently higher during the after period. While these devices showed a general trend in speed reduction during the after period, the reductions were not found to be statistically significant.

Usability

Four separate devices were used in this evaluation: a radar drone, fluorescent orange signs, fluorescent yellow-green flagger vests, and high visibility magnetic strips.

The devices tested were easily set up and used. The drone was simply plugged into a cigarette lighter in a vehicle and operated continuously throughout testing. The fluorescent orange signs were placed in the sign stands used for the normal traffic control signs.

The fluorescent flagger vest and magnetic strips were both placed at the flagger station. The flagger stated that he felt both devices significantly improved visibility. He felt that the vests should be implemented immediately. He also stated that the magnetic strips should be made a permanent part of the worker truck and should not be temporary.

Speed Display

The speed display was evaluated at two sites. Speed data and usability data were collected at the sites.

Speed Data

Counter and LIDAR data were collected at both sites. Tables B-7, B-8, C-7, and C-8 in the appendices summarize the data collected.

Counter Data. Figures D-7 and D-8 show the speed data collected with the counters at SD1 and SD2. Figure 25 shows the speed reductions observed when the speed display was set up at SD1 and SD2. At all data collection locations, the speeds were reduced when the display was operating. Speeds at SD2 tended to be reduced less than the speeds at SD1.

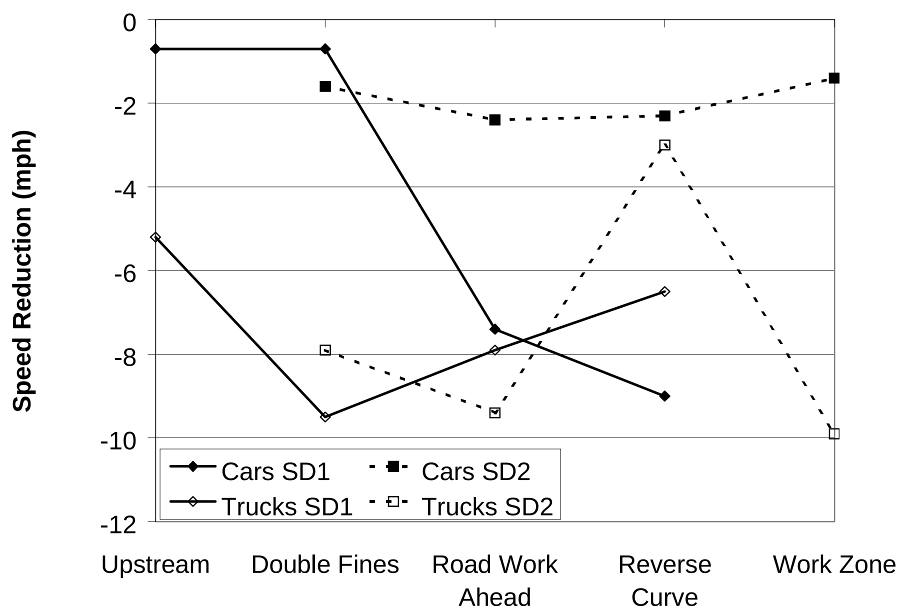

Figure 25. Speed Reductions at SD1 and SD2.

Average speeds for both cars and trucks were consistently lower when the speed display was active. Passenger car speeds were reduced by 7 to 9 mph approaching the work zone at SD1 and by about 2 mph at SD2. SD1 also showed a significant reduction in the percent of cars exceeding the speed limit at SD1. Trucks generally experienced larger speed reductions than cars at both sites. Trucks at SD1 slowed 7-8 mph, and trucks at SD2 slowed by as much as 10 mph.

LIDAR data. Figures E-7 and E-8 show the LIDAR data collected at SD1 and SD2. SD1 shows larger speed reductions than SD2 for both cars and trucks. Passenger car speeds were reduced up to 10 mph within the work zone at SD1, and truck speeds were reduced by up to 15 mph. The percent of passenger cars exceeding the speed limit was also reduced at SD1. At SD2, passenger car speeds were between 1 and 5 mph lower, and the trucks speeds were slightly lower after the speed display.

Usability

The speed display was very quick to set up. Workers detached the display from a towing vehicle. The face of the display was opened, the power was turned on, and the speed threshold for the strobe light was set. The trailer was leveled using its adjustable legs and a bubble level. The speeds produced by the display were checked with a LIDAR gun, and they agreed to within ±1 mph. When data collection was finished, the power was turned off, and the display was re-attached to the towing vehicle.

On one occasion, a vehicle was observed speeding up as it approached the display. This vehicle appeared to be attempting to see how high the speed display would read. This may be a potential problem with the speed display since certain drivers may choose to accelerate upon seeing the display.

Worker comments on the speed display were very positive. The maintenance crew felt that the display was very effective at reducing vehicle speeds. The display that was tested was borrowed from San Angelo, where TxDOT personnel had extensive experience with the display. The San Angelo maintenance crews had used the displays for about six months and reported very favorable results. They felt that the display effectively slowed speeds in work zones, especially for short-term applications.

SITE SUMMARY

Table 12 summarizes the performance of the various alternatives at each site. The changes in speed observed for cars and trucks at the work zone taper and within the work zone are listed.

Table 12. Summary of Speed Impacts at Each Site.

Site	Vehicle Type	Change in Mean Speed (mph)		Change in Percent Speeding	
		Before Taper	In Work Zone	Before Taper	In Work Zone
RS1	Car	-6.1[a]	+3.6[a]	No Change[a]	No Change[a]
	Truck	No Data[a]	No Data[a]	No Data[a]	No Data[a]
RS2	Car	-2.0	No Change	-3.8%	-4.7%
	Truck	-5.4	-2.9	-5.4%	+0.4%
RS3	Car	-1.1	+1.4	-1.8%	-0.3%
	Truck	-2.5	-4.1	+2.2%	No Change
VMS1	Car	No Change	-1.7	+6.3%	-9.1%
	Truck	+0.4	-1.5	No Change	-3.9%
VMS2	Car	-0.3	-1.3	+4.9%	-4.8%
	Truck	-0.5	-0.2	+3.6%	+0.7%
RD1	Car	-4.7	No Data[b]	-5.9%	No Data[b]
	Truck	-11.4	No Data[b]	No Change	No Data[b]
SD1	Car	-9.0	No Data[a]	-20.0%	No Data[a]
	Truck	-6.5	No Data[a]	No Change	No Data[a]
SD2	Car	-2.3	-1.4	+5.8%	No Change
	Truck	-3.0	-9.9	No Change	No Change

[a] Data were limited or unavailable at this location due to counter malfunctions.
[b] Due to site constraints, no data could be collected within the work zone.

CHAPTER 5
WORKER GARMENT EVALUATION RESULTS

INTRODUCTION

In the first year of this research, the research team asked maintenance crews to replace their standard fluorescent orange mesh-vests with various designs of a fluorescent yellow-green vest. They were also asked to wear fluorescent yellow-green pull-over hard hat covers. After each work day, maintenance crews were asked to comment about the different vests and hard hat covers. The maintenance crews indicated that they preferred the fluorescent yellow-green color and thought that they were probably more visible to approaching motorists, especially considering the amount of orange traffic control behind them acting as camouflage. The research team and project director agreed that the fluorescent yellow-green vests and hard hat covers appeared more conspicuous than the standard fluorescent orange vests that TxDOT personnel normally wear.

Because of the promising first-year findings related to the fluorescent yellow-green vests and hard hat covers, the Advisory Panel decided to continue to evaluate these options in year two of this research project. Related year two activities included additional field use of the fluorescent yellow-green vests and hard hat covers and photometric measurements of various vest and hard hat designs. The photometric measurements were performed in order to quantify the benefits observed in the first year of this research project.

THE VISION SYSTEM

Visual performance is dependent on the two types of receptor cells that differ significantly in the way they allow us to see objects. These receptor cells are called rods and cones. Table 13 provides the principal differences between rods and cones.

Table 13. Difference Between Rods and Cones.

Cones	Rods
Provide color vision	Do not provide color vision
Function under high levels of light (daytime)	Functional at low light levels
Only receptor in fovea	Distributed throughout retina, including periphery

Visibility of objects on the road is dependent on rods and cones and their distribution in the retina. Under photopic and mesopic conditions (i.e., daytime, including dawn and dusk), cones are dominant, and objects are seen most clearly when they are located on the fovea. Objects imaged in the periphery are not seen as clearly, with clarity falling off very rapidly in proportion to the object's angular separation from the fovea. Figure 26 demonstrates this relationship.

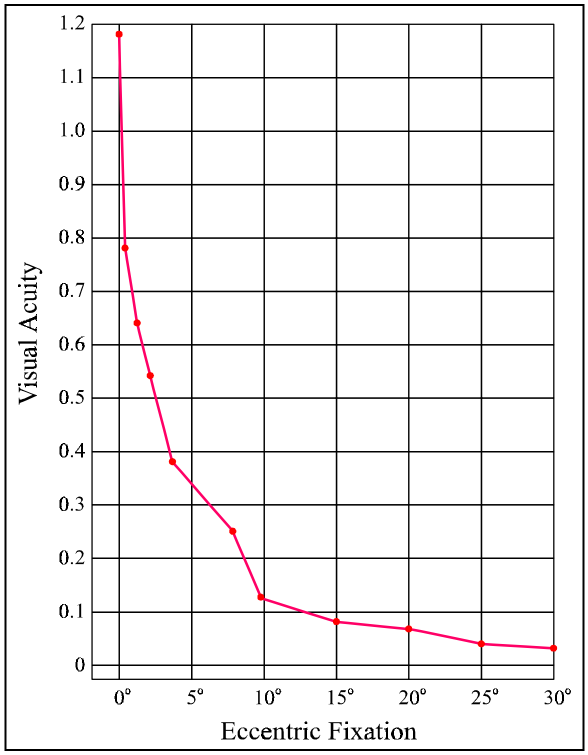

Figure 26. Conspicuity vs. Periphery Angle (*26*).

The fovea area is limited to approximately a 2 degree visual arc. This rather narrow field of vision, combined with the relatively poor visibility performance characteristics of the peripheral area, is critical when assessing the conspicuity of highway workers under photopic and mesopic conditions. Figure 27 shows a picture taken of a typical rural high-speed maintenance work zone with flagger operations. The circle in the middle of Figure 27 represents the approximate area covered by foveal vision. Mostly because of the limited size of the foveal area, object detection usually occurs in the periphery. As such, the foveal area is shifted to the area of interest in order to determine recognition of the object. However, in order for an object to be detected in the periphery, it must have certain characteristics that make its attention-getting ability substantial enough for peripheral detection. Furthermore, as demonstrated in Figure 26, the farther an object is from the foveal area, the less likely it is to be detected. In this case, which is perhaps the best-case scenario, the flagger is on the edge of the foveal vision area and is in a good spot for detection. However, not all real-world situations can be set up as nicely as shown in Figure 27, and the flagger often ends up being in an area of the visual field where detection is less likely.

Figure 27. Area Covered by Foveal Vision.

The characteristics of objects that contribute to their visibility define visual contrast, the differences between the object and the background against which it is viewed. In general terms, these differences can be in motion, size, color, or brightness. Assuming motorists are concentrating their attention straight ahead, objects first enter the field of view outside of the foveal range, in the periphery. In this range, as explained above, there is low color sensitivity but high brightness sensitivity (because of the diminished concentration of cones and increased concentration of rods). Therefore, initial detection of objects in the periphery is determined primarily by their luminance contrast (*27*).

Previous research on driver eye-tracking behavior has shown that motorists tend to concentrate their focus ahead of the vehicle and slightly down and to the right (i.e., in the general vicinity of the right-side pavement marking) (*28-31*). However, the majority of this type of research has been carried out during the night. Furthermore, the research has been conducted on roadways without work zones. Consequently, it has been assumed herein that motorists tend to focus their attention straight ahead while approaching a work zone during daylight conditions.

Perception

The perception of objects along the road truly defines how visible and conspicuous they appear to each individual driver. However, perception cannot be directly measured and varies with each driver and within each driver depending on an array of factors such as attentiveness, sleep deprivation, and age. On the other hand, researchers can measure photometric properties of objects and use them to help predict the perceived visibility of such objects. Table 14 presents some common measured photometric parameters and their corresponding precepts.

Table 14. Photometric Properties.

Photometric Properties	Perceived Property
Luminance (cd/m^2)	Brightness
Luminance Factor (%)	Lightness
Chromaticity (unitless)	Color

Using these photometric properties, worker vests and hard hats were evaluated in typical rural high-speed maintenance work zone set-ups during cloudless midday conditions.

Photometric Measurements

The field measurements were made using a PR-650 telespectroradiometer and a LMT-1009 telephotometer. The PR-650 was used to measure the chromaticity of the vests, hard hats, and background, and the LMT-1009, which has a variable viewing aperture, was used to measure the luminance of the targets. Measurements were also made of a white poster board next to the targets. The poster board was used as a crude substitute for a diffuse reflector which is the common tool of choice. The poster board was measured in the lab to have a luminance factor of 89 percent (illuminant D65 measured 2 degrees with a polychromatic spectrophotometer). This measurement provided a way to estimate the field luminance factor of the worker garments.

Experimental Design

The goal of this task was to determine the relative visibility (i.e., conspicuity) of the various colors and color configurations of highway worker safety vests and hard hats. However, visibility is a factor of the surroundings (i.e., amount and type of traffic control and machinery behind the highway worker) and the environmental conditions (i.e., daytime, nighttime, and dusk/dawn). For example, certain colors or color configurations may differ substantially depending on the type of work zone or under different lighting conditions.

Researchers wanted to conduct the experiment under conditions that most closely represent what can be expected in a typical high-speed rural maintenance work zone on Texas roadways. Therefore, the following criteria and methods were established.

Because the focus of the research was maintenance work zones, only daytime measurements were made of the worker garments. As summarized earlier, several researchers have already conducted dusk and overcast research related to fluorescent colors. Furthermore, maintenance work zone activities are generally performed during normal business hours of 8:00 AM to 5:00 PM, and therefore, nighttime data were not measured. Furthermore, the color of the worker garments would not appreciably affect nighttime detection. Retroreflectivity is the critical element of worker garments that provides nighttime detection.

A typical rural high-speed maintenance work zone was set up on a closed-course facility near Bryan, Texas. The traffic control was in accordance with the Texas MUTCD (*2*). The work zone was meant to simulate a closed lane on a two-lane highway with flagger operations. The work zone was on a tangent section with almost no vertical alignment change and a grade of zero. Using minimum stopping sight distances from American Association of State Highway and Transportation Official's (AASHTO) *Green Book* (*32*) and assuming an approach speed of 55 mph, an evaluation distances of 500 feet was chosen. This distance also coincides with average detection distances of work clothing found in other earlier research (*7, 8*).

The researchers evaluated both worker garments and hard hats. Five different garments and three different hard hat designs were evaluated. Table 15 provides a summary of these targets and Figures 28 and 29 show pictures of the worker garments and hard hats used.

Table 15. Description of Vests and Hard Hats.

Worker Garments	
TxDOT Fluor. Orange	mesh vest
TxDOT Fluor. Yellow-Green	mesh vest
Alternative Fluor. Yellow-Green	mesh vest
Fluor. Yellow-Green	solid vest with mesh sides
Fluor. Yellow-Green	solid jacket
Hard Hats	
TxDOT White	TxDOT hard hat
Silver and Fluor. Yellow-Green	alternative
Solid Fluor. Yellow-Green	alternative (pull-over cap)

Figure 28. Worker Garments Evaluated.

Figure 29. Hard Hats Evaluated.

Luminance values were taken through the windshield at 500 feet for all garments and hard hats, as shown in Figure 30. Chromaticity data were recorded through the windshield at approximately 40 feet because of the restrictive viewing aperture of the PR-650.

Figure 30. Background Luminance Measurement Locations.

Another set of photometric measurements was also taken. This time, each garment and hard hat was measured against more uniform work zone backgrounds. The backgrounds included an open concrete road, an open asphalt road, a mix of fluorescent and standard orange work zone traffic control, a white pick-up truck (typical of the TxDOT issued work vehicles), foliage typical of a Texas summer, and a used construction-yellow front-end loader. When the researchers made background luminance measurements all locations shown in Figure 30 were measured. For example, Figure 31 is a magnified picture of the measurements made in an open concrete environment. Obviously, not all of the background is concrete. Under scenarios such as this one, measurements of the background luminance were made only where the entire aperture of the LMT was completely filled with the appropriate background, concrete for the example provided here.

Figure 31. Photometric Measurement Locations

The research team took a final set of chromaticity measurements in order to compare the color differences of the mesh vests when a white T-shirt and a navy blue T-shirt were worn as the undergarments. It was thought that the resulting color may shift with these different types of undergarments, especially for vests with larger mesh openings. These measurements were made at a distance of approximately 20 feet in order to fill the aperture with the mesh material exclusively, in other words, measurements with the trim material or retroreflective material would not have given a true reading of the color of the mesh with the two types of undergarments.

All measurements were made under ambient daylight illumination (no daytime running lights). These midday measurements were made between 11:00 AM and 4:00 PM on a clear day in August.

RESULTS

Luminance and Luminance Factors

Table 16 summarizes the photometric data taken of all worker garments and hard hats. The chromaticity measurements were taken with as much of the vest in the view of the aperture as possible. Chromaticity measurements were specified using the coordinate system established by the International Committee on Illumination (CIE). Consequently, the recorded values represent overall values for the vest, including the background material and trim material (which is typically a different color than the background material).

Table 16. Photometric Measurements.

Photometric Properties	Chromaticity ①		Field Lum. (cd/m^2)	Field Lum. Factor (%) ②
	x	y		
Worker Garments				
TxDOT FO mesh vest ③	0.452	0.408	3570	35.5
TxDOT FYG mesh vest ③	0.362	0.473	5926	58.9
Alternative FYG mesh vest ③	0.380	0.436	3431	34.1
FYG solid vest	0.435	0.464	7998	78.4
FYG solid jacket	0.398	0.482	7197	71.5
Hard Hats				
TxDOT White	0.321	0.356	10963	108.9
Silver & FYG	0.363	0.453	7502	75.5
FYG pull-over cap	0.336	0.521	8825	87.7

① Chromaticity coordinates are dimensionless
② Adjusted white reference luminance = 10068.32 cd/m^2
③ Measured with dark T-shirt worn as undergarment

For the worker garments, the resulting chromaticity data include measurements of the background material and trim material. Consequently, the data cannot be directly compared to required color boxes provided by ANSI and American Society for Testing and Materials (ASTM) (this issue is addressed in a subsequent discussion). Rather, the chromaticity data here can be used for relative purposes.

The field luminance values of the worker garments also include the background material of garments along with the trim material. These values, when combined with the adjusted white reference, can be used to determine the field luminance factor. The field luminance factor is the ratio of the luminance of the target to that of a perfect diffuse reflector and provides a way to measure the relative brightness of color. For this evaluation, the perfect diffuse reflector was replaced with a white reference measured after each set of measurements were taken, which provided a way to standardize the measurements. Theoretically, the luminance factor is a value between zero and 100. A low value near zero represents a very dark color, near black. A value near 100 represents a very bright color, mostly white. When fluorescent materials are measured, luminance factors can exceed 100 since the material has the capability of emitting more visible light than it receives. Luminance factors can also exceed 100 when the measurement geometry with respect to the illuminating source is not held constant among the targets (i.e., the reference target and the evaluation target). A review of the hard hat data shows that the standard TxDOT hard hat had a luminance factor over 100. Two reasons may account for this finding. First, the shape of the hard hat makes is difficult to measure because there is essentially no flat area. However, the white reference target was a flat target. Therefore, the illumination and measurement geometry of the two targets (the sun in this case) were different. Also, the TxDOT hard hat, like all other hard hats and worker garments, was unused and in pristine condition. When these hard hats are in such condition, they have a relatively high sheen level or gloss level. This effect can exaggerate the luminance readings. Because of these two issues, the luminance values associated with the hard hats are not realistic and will not be evaluated. However, the chromaticity measurements of the hard hats should not be affected.

Luminance Contrast Ratio

Luminance values were also recorded for various backgrounds. These values were used to determine luminance contrast ratios (shown in Table 17) of the worker garments compared to the various backgrounds. As discussed in the literature review, higher luminance ratio values are associated with greater conspicuity values.

Table 17. Luminance Contrast Values.

Background	Lane Closure	Sky	Asphalt	Concrete	Foliage	Work Zone Traffic Control Devices	White Pick-Up	Yellow Front End Loader
Worker Garments								
TxDOT FO mesh vest	2.00	0.88	1.54	0.90	1.99	1.14	0.67	2.24
TxDOT FYG mesh vest	3.21	1.42	2.33	1.68	3.56	1.61	1.28	3.64
Alternative FYG mesh vest	1.89	0.83	1.32	0.84	2.16	1.19	0.71	1.94
FYG solid vest	4.30	1.90	3.06	2.46	4.76	2.19	1.51	4.75
FYG solid jacket	4.61	2.04	2.64	1.97	4.07	1.97	1.41	4.70
Hard Hats								
TxDOT White	7.03	3.11	3.46	2.46	5.54	2.43	2.76	5.90
Silver & FYG	5.80	2.57	3.67	1.89	2.11	1.57	2.19	4.24
FYG pull-over cap	6.08	2.69	3.73	2.47	4.44	2.51	1.67	4.96

Color

Outdoor color measurements of worker vests and hard hats are shown in Figures 32 through 37. Each figure contains recommended color limits from the ANSI and ASTM (*18*, *33*). The recommended color limits are to be evaluated in a laboratory setting with controlled lighting and geometry. The field results shown here are based on practical criteria. The color boxes are shown for reference and later comparison. Researchers in the profession are increasingly recognizing that test methods do not always simulate practical field conditions and that test methods may need to be modified to better correlate them to field observations (*34*).

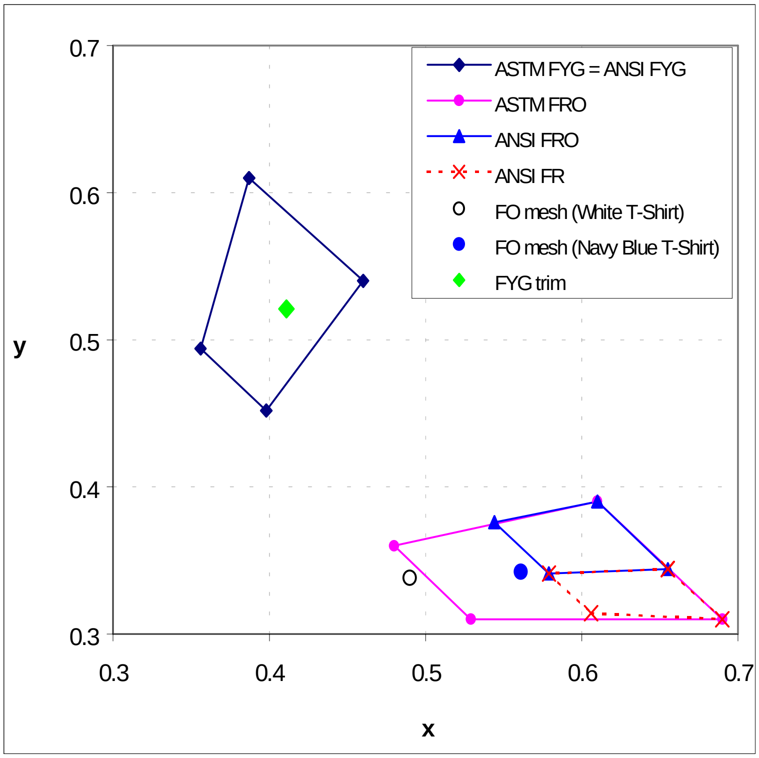

Figure 32. TxDOT Fluorescent Orange Mesh Vest.

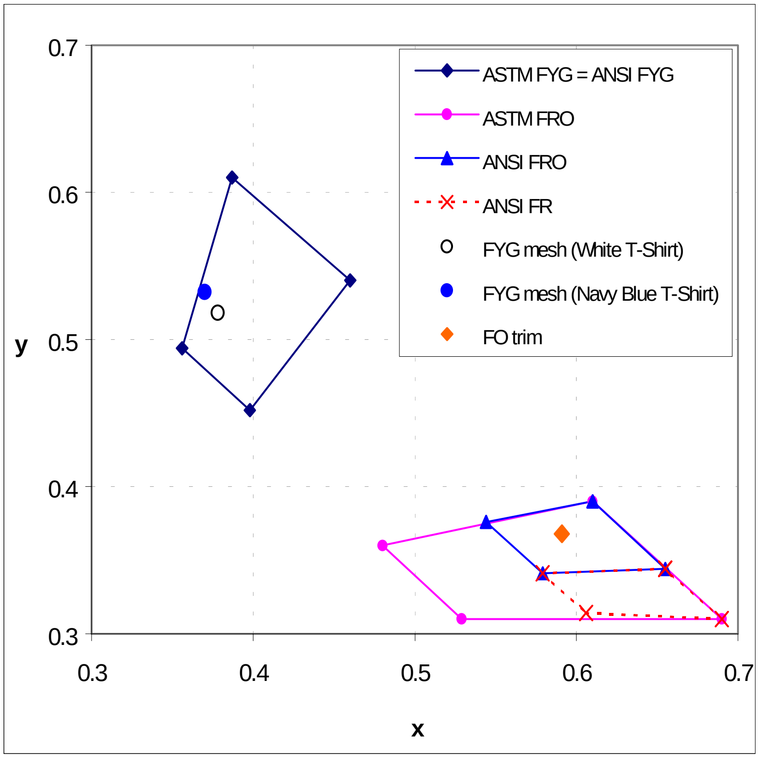

Figure 33. TxDOT Fluorescent Yellow-Green Mesh Vest.

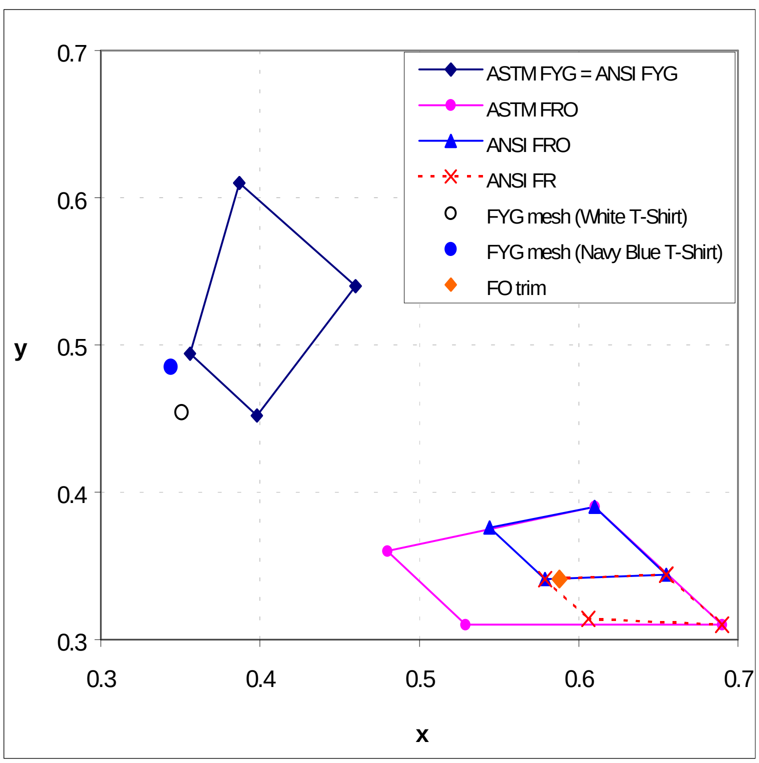

Figure 34. Alternative Fluorescent Yellow-Green Mesh Vest.

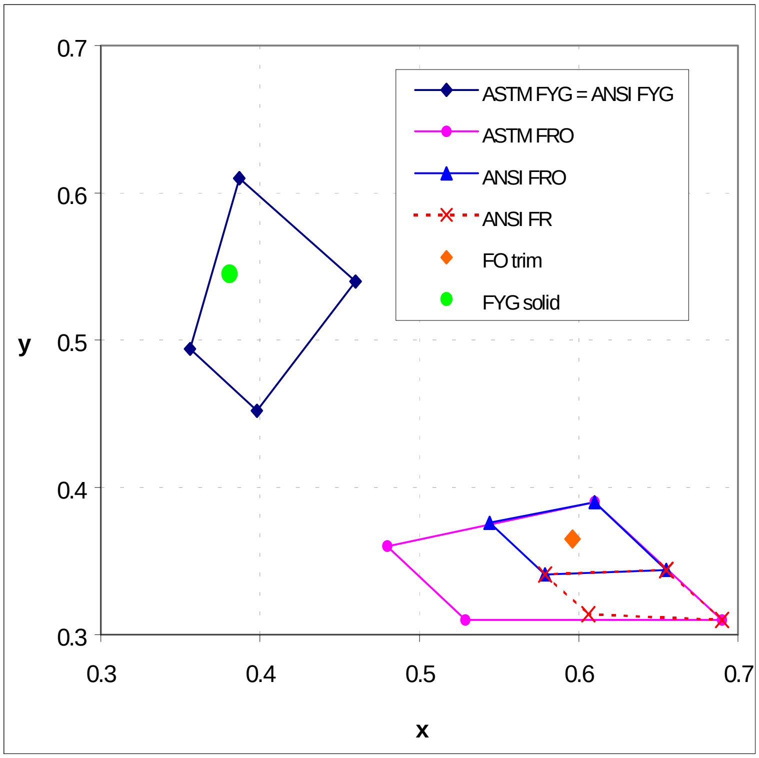

Figure 35. Fluorescent Yellow-Green Solid Vest.

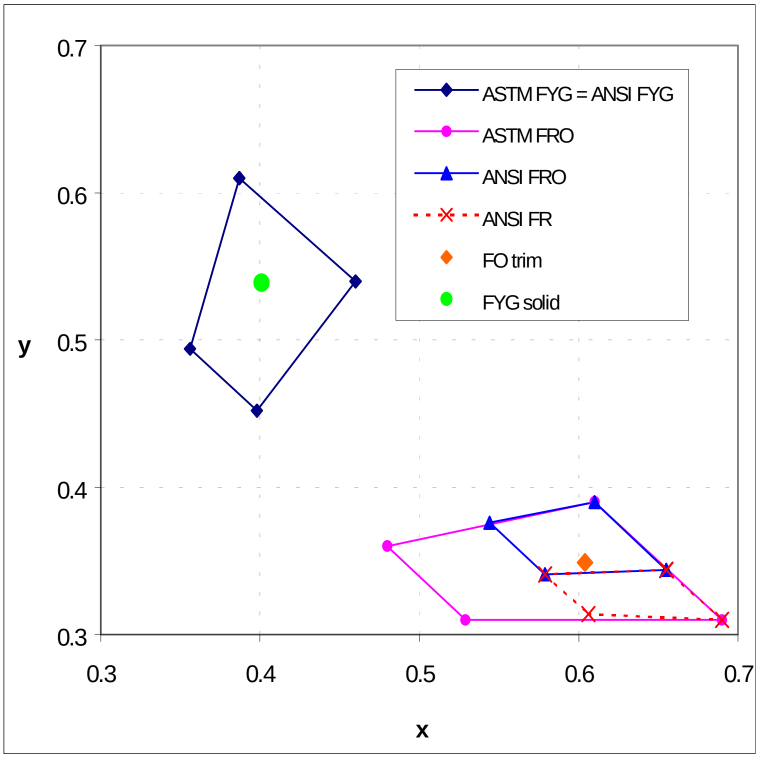

Figure 36. Fluorescent Yellow-Green Solid Jacket.

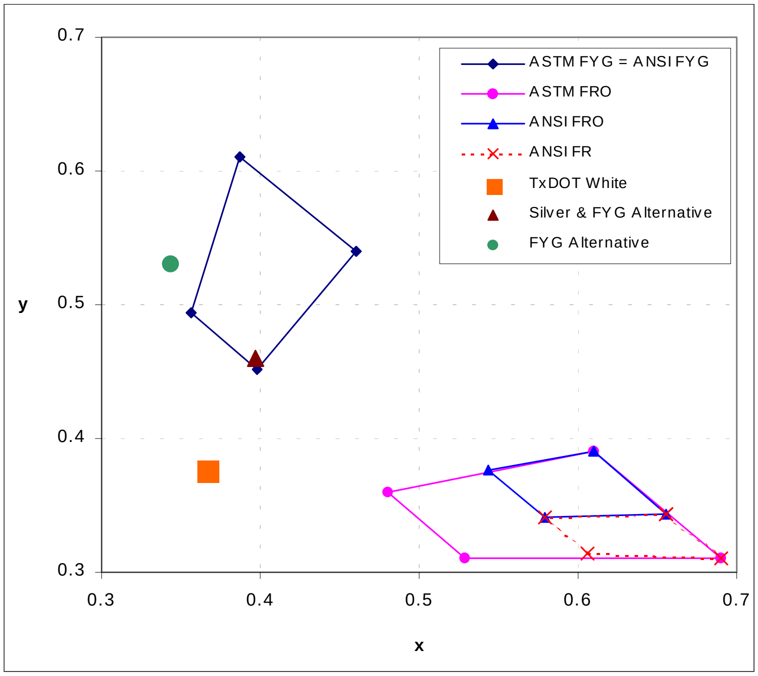

Figure 37. Color of Tested Hard Hats.

CHAPTER 6
SECOND YEAR FINDINGS

The research performed during the second year of the project provided further insight into some of the devices evaluated during the first year of the project, as well as some new information about devices that were not previously evaluated. The effectiveness of specific devices is 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 SIGNS

- Maintenance crew opinions were 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 are made of prismatic retroreflective sheeting. Consequently, if workers used the signs during nighttime conditions, they would appear brighter than the beaded retroreflective material normally used.

FLUORESCENT YELLOW-GREEN WORKER VESTS

- The maintenance crews responded favorably to the fluorescent yellow-green vests.
- Of all the mesh vests, the TxDOT fluorescent yellow-green vest provides the greatest field luminance and luminance factor results. Both non-mesh garments tested had larger luminance and luminance factor values than the three mesh garments.
- For all eight difference background types, the TxDOT fluorescent yellow-green mesh vest provided the highest luminance ratio values of all three mesh vests tested. Once again, the non-mesh garments consistently provided higher luminance contrast ratios.
- The color of the mesh vests depends on the color of the garment worn underneath. For this evaluation, two types of undergarments were used: a white T-shirt and a navy blue T-shirt. For the mesh vests, the TxDOT fluorescent yellow-green vest maintains the best conformance with the ANSI and ASTM color specifications. Both non-mesh alternatives also conform well with the color recommendations of ANSI and ASTM.

HARD HATS

- The luminance measurements of the hard hats did not result in realistic results. The measurements were skewed because of the inconsistent illumination and measurement geometry caused by the unique shape of the hard hats.

PORTABLE RUMBLE STRIPS

- The portable rumble strips had little impact on passenger car speeds but reduced truck speeds by 3-5 mph.
- The percentage of vehicles exceeding the speed limit tends to be reduced following the rumble strip installations.
- Occasionally, vehicles would swerve around the rumble strip installation into the oncoming traffic lane. While researchers did not observe this maneuver when oncoming traffic was present, these observations could indicate that these devices should be used with care when there are high volumes of opposing traffic.
- Installation time for the rumble strips was probably too lengthy to justify their use at rural maintenance work zones.
- The maintenance crews had mixed opinions on the rumble strips due to the time required to install the devices.

PORTABLE VARIABLE MESSAGE SIGN

- The VMS produced speed reductions of about 1.5 mph within the work zone.
- The VMS also reduced the percentage of vehicles exceeding the speed limit inside the work zone.
- The VMS caused vehicles to move out of the closed lane earlier than when the VMS was not operational, which resulted in fewer observed conflicts when the VMS was operational.
- Portable VMSs have a number of applications beyond work zone traffic control and can be used for other purposes when needed.

RADAR-ACTIVATED FLAGGER PADDLE

- No field testing was performed with this device. The device could reduce speeds approaching the flagger while simultaneously improving the visibility of the flagger. Some field testing should be performed to determine if the device is effective. If the device does improve worker safety, a more rugged version of the paddle should be developed.

RADAR DRONE

- The use of the radar drone generally reduced speeds. Speeds approaching the work zones were about 2 mph less with the radar drone compared to when the radar drone was not present.

RETROREFLECTIVE MAGNETIC STRIPS ON WORK VEHICLES

- 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.
- Being retroreflective, the strips' main benefit would occur at night.
- Workers seemed receptive to permanently attaching the retroreflective strips to vehicles.

SPEED DISPLAY

- The speed display reduced passenger car speeds by 7-9 mph at the first test site and 2-3 mph at the second test site.
- The speed display reduced truck speeds by 3-10 mph at both sites.
- The speed display had a positive impact on the percent of vehicles speeding.
- Set up and removal of the display was easily accomplished.
- Workers commented that the display seemed to be very effective at reducing speeds.

DEVICE SUMMARY

Table 18 summarizes the performance of the various devices tested in the field during the second year activities. The average impact of the device on speeds and the percent of vehicles exceeding the speed limit is noted. A subjective rating is also provided based on a researcher assessment of the usability of the device for rural maintenance work zones. Table 18 also provides a subjective rating based on comments received from the workers.

Table 18. Device Summary.

Device	Average Speed Reduction		Average Reduction in % Speeders		Usability		Worker Comments
	Before Taper	Work Zone	Before Taper	Work Zone	Installation	Removal	
Rumble strips	-2 mph	-1 mph	-3	-2	✖	—	—
VMS	-0.5 mph	-1 mph	0	-3	✔	✔	✔
Radar drone, fluorescent signs, fluorescent yellow-green vests, vehicle visibility improvements	-4 mph[a]	n.d.	-5[a]	n.d.	✔	✔	✔
Speed display	-5 mph	-3 mph	-5	0[b]	✔	✔	✔

✔ = Acceptable
✖ = Unacceptable
— = Inconclusive/Marginal
n.d. = no data
[a] = Limited baseline data was available at this site due to an unexpected change in the layout of the work zone. These speed reductions may not accurately reflect the impact of this device.
[b] = All vehicles traveling through this work zone when normal traffic control was in place were traveling under the speed limit.

CHAPTER 7
FINAL ASSESSMENT OF DEVICES

The research team tested a total of nine devices during the first and second years of this project. The devices evaluated were:

- fluorescent orange signs,
- fluorescent yellow-green worker vests and hard hat covers,
- portable rumble strips,
- portable variable message signs,
- radar-activated flagger paddle,
- radar drone,
- retroreflective magnetic strips for work vehicles,
- Safe-T-Spins,
- speed display trailers, and
- worker strobe lights.

The following devices were found to be effective at improving safety in temporary maintenance work zones:

- fluorescent yellow-green worker vests and hard hat covers,
- portable variable message signs, and
- speed display trailers.

Several devices were found to show some promise, but they either need to be further refined, studied in greater detail, or evaluated on a more quantitative basis. In the case of the radar drone, it produces a positive benefit, but the speed reductions observed do not appear to result in a significant decrease in speed. These devices include:

- fluorescent orange signs,
- radar-activated flagger paddle,
- radar drone, and
- retroreflective magnetic strips for work vehicles.

Some of the devices evaluated were not found to be appropriate and/or effective for use in maintenance work zone. While these devices may not have been useful in high-speed, temporary work zones, they may have some application at other types of work zones. These countermeasures included:

- portable rumble strips,
- Safe-T-Spins, and
- worker strobe lights.

These devices were evaluated based on their impact on traffic speeds, conflicts, and a variety of other measures. This chapter provides a one page summary of the effectiveness of each device, and a recommendation as to whether the device should be used in rural maintenance work zones. The data included in this chapter are based on the results of testing from both the first and second years of this project.

Each device summary has several key components. They are:

- **Description:** A brief description of the device.
- **Application:** The type of work zone where the device was evaluated.
- **Usability:** An assessment of how quickly and easily the device can be installed and removed.
- **Evaluation:** The effectiveness of the device based on relevant measures of effectiveness. The measures of effectiveness vary from device to device. The impact of the device on these measures of effectiveness is rated as either positive, negative, marginal, or inconclusive.
- **Recommendation:** A final evaluation as to whether the device should be used for rural maintenance activities, and a description of the conditions under which the device should be used.

FLUORESCENT ORANGE SIGNS

Description: This project evaluated fluorescent orange signs with a variety of common work zone legends. All of the roll-up signs evaluated were composed of microprismatic sheeting.

Application: Fluorescent orange signs were tested at both two-lane and four-lane rural work zones.

Usability: Maintenance crews can install fluorescent orange signs in the same amount of time as standard high intensity signs. Fluorescent orange signs do cost more than high intensity signs, however.

Figure 38. Fluorescent Orange Signs.

Evaluation:

Table 19. Fluorescent Orange Signs Evaluation.

Speeds		% Speeding		Conflicts	Worker Comments	Driver Comments	Traffic Control Visibility
Before Taper	Work Zone	Before Taper	Work Zone				
?	?	?	?	?	✔	✔	✔

✔ = Positive Impact/Comments
? = Inconclusive Impact

Recommendations: Fluorescent orange signs offer two potential benefits over the standard TxDOT high intensity work zone signs. 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 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. This device was very well received by the workers and motorists surveyed. These signs are ready for implementation and could be used in rural maintenance operations without increasing the time for workers to set up traffic control. Although a number of positive comments were received on the signs, limited data exists to determine if they actually improve safety at work zones. Additional data should be collected before fluorescent signs are used on a widespread basis.

FLUORESCENT YELLOW-GREEN WORKER VESTS AND HARD HAT COVERS

Description: Five separate worker garments and three hard hat styles were evaluated. Most of the styles evaluated involved using fluorescent yellow-green fabric or mesh in order to improve the contrast between the worker and work zone traffic control.

Application: The fluorescent yellow-green worker clothing was field tested at both two-lane and four-lane work zones. A closed course test was also performed to quantify if there was any difference in the vests.

Usability: The yellow-green vests and hard hat covers can be easily implemented and require no additional effort on the part of the worker.

Evaluation: The evaluation was based on both the closed course testing and the field testing of the garments.

Figure 39. Fluorescent Yellow-Green Vests and Hard Hat Covers.

Table 20. Fluorescent Yellow-Green Worker Vests and Hard Hat Covers Evaluation.

Speeds		% Speeding		Conflicts	Worker Comments	Driver Comments	Worker Visibility
Before Taper	Work Zone	Before Taper	Work Zone				
?	?	?	?	?	✔	✔	✔

✔ = Positive Impact/Comments
? = Inconclusive Impact

Recommendations:

Worker Vests: The best options appear to be either non-mesh yellow-green vest or the TxDOT fluorescent yellow-green vest. However, based on the warm summer months typically associated with Texas, a non-mesh garment does not seem appropriate. Consequently, the best photometrically performing and comfortable worker garment option is the fluorescent yellow-green mesh vest.

Hard Hats: The photometric data do not support a conclusive recommendation for a hard hat color. However, with the considerable amount of visibility research demonstrating that fluorescent colors are more visible in terms of detection and color recognition, it would seem appropriate to consider further research and consideration of the move from a white hard hat to a fluorescent yellow-green hard hat.

In addition, the hard hat donated for evaluation purposes included retroreflective elements. Although nighttime evaluations were not performed as part of this research, the research team feels that TxDOT should adopt a statewide policy requiring retroreflective elements on all hard hats.

PORTABLE RUMBLE STRIPS

Description: The portable rumble strips used were manufactured by Advance Traffic Markings. The rumble strips were shipped as individual 12 feet long strips that are 4 inches wide and 0.125 inch thick. The strip thickness was doubled to 0.25 inches for this study. The strips were colored bright orange and had an adhesive backing. When these strips are placed perpendicular to the direction of traffic, they create an auditory and vibratory warning to drivers

Figure 40. Portable Rumble Strips.

Application: Portable rumble strips were tested only on two-lane roads. If they are to be used on four-lane roads, the strips may be more difficult to install.

Usability: It took approximately 20 minutes to install each set of six rumble strips on a low-volume road. Removal took about 5 minutes for each set of six strips. Installation times could be significantly larger on high-volume roads. Rumble strips were not reusable after they were applied to the road surface.

Evaluation:

Table 21. Portable Rumble Strips Evaluation.

Speeds		% Speeding		Conflicts/ Erratic Maneuvers	Worker Comments	Noise
Before Taper	Work Zone	Before Taper	Work Zone			
-2 mph	-1 mph	-3	-2	✖	—	✖

✖ = Negative Impact/Comments
— = Marginal Impact/Comments

Recommendations: Portable rumble strips should not be used at rural maintenance work zones. While the rumble strips do reduce average speeds by about 1 to 2 mph, the time to install the rumble strips is too lengthy for a short duration work site where maintenance crews must install and remove traffic control each day. The rumble strips may be more appropriate for work zones where the rumble strips could be left in place for an extended period of time. Rumble strips should not be used near residential areas due to noise concerns. Vehicles may attempt to swerve around the rumble strips, so they should be used with caution on high-volume roads.

PORTABLE VARIABLE MESSAGE SIGNS

Description: This project utilized a trailer-mounted solar variable message sign. The VMS could display up to three lines of text with eight characters on each line. LEDs were used to display the characters. The message board met the TxDOT specification that requires the sign to meet the MUTCD visibility and legibility requirements

Figure 41. Portable Variable Message Sign.

Application: The portable variable message sign was evaluated on a four-lane divided highway.

Usability: The device was set up in under 10 minutes. The VMS was solar assisted, so the unit required little day-to day maintenance.

Evaluation:

Table 22. Portable Variable Message Sign Evaluation.

Speeds		% Speeding		Percent in Closed Lane	Conflicts	Worker Comments
Before Taper	Work Zone	Before Taper	Work Zone			
-0.5 mph	-1 mph	No Change	-3	-20	✔	✔

✔ = Positive Impact/Comments

Recommendation: The portable VMS is a versatile device that can be used for a variety of applications. The VMS results in minimal speed reductions within the work zone. The primary benefit of the VMS was in reducing the number of vehicles in the closed lane approaching the work zone taper. On average, there were 20 percent fewer vehicles in the closed lane when the VMS was operational, which resulted in fewer conflicts created by later merges at the work zone taper. A supplemental VMS appears to have positive benefits in creating earlier lane changes at work zones, and the use of the VMS should be considered when a lane closure exists.

RADAR-ACTIVATED FLAGGER PADDLE

Description: The radar-activated flagger paddle is a prototype device that was developed by the Texas Transportation Institute during this project. It consists of a flashing flagger paddle that has been modified so that the LEDs in the sign face are activated when the radar detects vehicles traveling over a preset speed threshold.

Figure 42. Radar-Activated Flagger Paddle.

Application: The Texas Transportation Institute developed this device at the end of the project, and no suitable data collection sites were identified to test the device prior to project termination.

Usability: The device is a prototype and has several obvious usability issues. First, the battery for the unit is located within the face of the sign, making the unit rather top-heavy. Also, the wiring for the radar is exposed to the elements and is very fragile. Users of the prototype must be very careful in order to ensure that the radar is not damaged. Should a commercial version of this device be made available, it is quite likely that these issues could be resolved.

Evaluation: The evaluation of this device is based solely on subjective observations of the device. Some field testing should be performed to determine if the device holds promise in the field.

Table 23. Radar-Activated Flagger Paddle Evaluation.

Speeds		% Speeding		Conflicts	Worker Comments	Worker Visibility
Before Taper	Work Zone	Before Taper	Work Zone			
?	?	?	?	?	?	✔

✔= Positive Impact/Comments
? = Inconclusive/unknown impacts

Recommendations: This device would seem to hold promise for flagger-controlled work zones. More detailed testing is needed to determine the effectiveness of the device. The unit would also need to be made substantially more rugged in order to withstand extended use in the field.

RADAR DRONE

Description: This evaluation utilized a commercially available radar drone. The radar drone emits a K-band radar signal that can be detected up to a mile away. The radar signal will activate radar detectors, potentially decreasing vehicles speeds as they approach the drone site.

Figure 43. Radar Drone.

Application: The radar drone was tested at both two-lane and four-lane work zones.

Usability: The drone is simply plugged into the cigarette lighter. It then continuously emits a radar signal until turned off.

Evaluation:

Table 24. Radar Drone Evaluation.

Speeds		% Speeding		Conflicts	Worker Comments	Driver Comments
Before Taper	Work Zone	Before Taper	Work Zone			
-2 mph	-1 mph	-1	+0.5	—	—	✔

✔ = Positive Impact/Comments
— = Marginal Impact/Comments

Recommendations: The radar drone provides small reductions in average speeds approaching and traveling through the work zone. It has a marginal impact on the percent of vehicles exceeding the speed limit. Limited data indicates that it may have a positive impact in reducing conflicts at the work zone taper, but there is insufficient data to make a conclusion. The radar drone may be an appropriate device for use in rural work zones. It provides limited benefits in terms of speed reductions but use of the drone requires little effort.

RETROREFLECTIVE MAGNETIC STRIPS ON WORK VEHICLES

Description: The vehicle visibility treatment tested consisted of an 8-inch wide strip of sheeting on a magnetic backing. The strips were produced in lengths of 3 feet. Square blocks with 4-inch sides were alternated along the strip to produce a checkerboard pattern. The blocks were composed of microprismatic sheeting in orange and fluorescent orange colors. The magnetic strips were manufactured specifically for this project

Figure 44. Vehicle Visibility Improvements.

Application: The strips were evaluated on both two-lane and four-lane roads.

Usability: The magnetic strips were simply placed around the perimeter of the flagger vehicle. These strips could easily be made a permanent part of the vehicle.

Evaluation:

Table 25. Retroreflective Magnetic Strips on Work Vehicles Evaluation.

Speeds		% Speeding		Conflicts	Worker Comments	Driver Comments	Vehicle Visibility
Before Taper	Work Zone	Before Taper	Work Zone				
?	?	?	?	?	✔	?	✔

✔ = Positive Impact/Comments
? = Inconclusive Impact

Recommendations: Since the focus of this project was on daytime work zones, the retroreflective strips did not have much of an impact. However, the strips could significantly improve the visibility of the vehicle during nighttime operations. TxDOT should consider adding the retroreflective strips to their flagger vehicles. The strips improved vehicle visibility and could be made a permanent part of maintenance vehicles. One potential drawback from adding the retroreflective strips is that it may lower any potential resale value of TxDOT vehicles once the department has finished using them.

SAFE-T-SPINS

Figure 45. Safe-T-Spins.

Description: Safe-T-Spins are reflective three-sided warning devices that can be placed on top of a traffic cone. The three sides of the Safe-T-Spin are covered with 4 inch by 6 inch strips of either orange or white prismatic sheeting. The Safe-T-Spin rotates when hit by wind. The purpose of the Safe-T-Spin is to draw further attention to traffic control devices.

Application: The Safe-T-Spins were tested on both two-lane and four-lane roads.

Usability: There were several problems with the Safe-T-Spins. When they were used on high-speed roads, passing trucks would generate so much wind that the cones would be knocked over. This problem forced the maintenance crew to assign a worker to reset the cones throughout the work activities. The Safe-T-Spins also increased the time required to set up work zone traffic control.

Evaluation:

Table 26. Safe-T-Spins Evaluation.

Speeds		% Speeding		Conflicts	Worker Comments	Driver Comments	Traffic Control Visibility
Before Taper	Work Zone	Before Taper	Work Zone				
?	?	?	?	?	✖	—	✔

✔ = Positive Impact/Comments
✖ = Negative Impact/Comments
— = Marginal Impact/Comments
? = Inconclusive Impact

Recommendations: Safe-T-Spins are not recommended for use on high-speed roads. At these locations, maintenance crews must devote too much time to maintaining traffic control since passing vehicles will blow over the cones with the Safe-T-Spins. Safe-T-Spins may be appropriate on low-speed facilities where the cones would be less likely to blow over.

SPEED DISPLAY

Description: This evaluation utilized a trailer-mounted speed display provided by TxDOT. The features a 24-inch LED display and uses Ka-band radar to detect oncoming vehicles. The display has a strobe lamp that flashes when a vehicle is detected traveling over a preset speed threshold. This feature is intended to simulate the operation of photo radar, possibly decreasing speeds through the threat of automated enforcement. During this evaluation, the speed threshold for the strobe light was set at 75 mph. The display also has a 130 dB siren that can be activated by vehicles traveling over a preset speed. This option is intended to warn workers when an extremely high-speed vehicle is approaching.

Figure 46. Speed Display Trailer.

Application: The speed display was tested at both two-lane and four-lane roads.

Usability: The display could be set up in under 10 minutes. The controls were easy to operate, and TxDOT crews that have used the device have reported no maintenance problems.

Evaluation:

Table 27. Speed Display Evaluation.

Speeds		% Speeding		Conflicts	Worker Comments
Before Taper	Work Zone	Before Taper	Work Zone		
-5 mph	-3.5 mph	-13	-6	?	✔

✔ = Positive Impact/Comments
? = Inconclusive Impact

Recommendations: The speed display trailer was the device evaluated that had the largest impact on traffic speeds. The display can be quickly set up and removed from the site. The speed display appears to be an appropriate device for improving work zone safety in rural maintenance work zones.

WORKER STROBE LIGHTS

Description: The worker strobe lights are small, self-contained battery operated strobe lights that can be attached to worker vests. Lenses can be added to the strobes so that they emit either a white or yellow flash.

Application: The strobe light was tested at two-lane flagger-controlled work zones.

Usability: The strobe light tested was pinned to a worker vest. Workers indicated that the size and weight of the strobe were a concern.

Evaluation:

Table 28. Worker Strobe Lights Evaluation.

Speeds		% Speeding		Conflicts	Worker Comments	Worker Visibility
Before Taper	Work Zone	Before Taper	Work Zone			
?	?	?	?	?	✖	—

✖ = Negative Impact/Comments
— = Marginal Impact/Comments
? = Inconclusive Impact

Recommendations: The strobe lights evaluated were not very visible during the day. These devices may improve nighttime visibility but could also create confusion among motorists if a larger number of individual strobe lights are going off within the work zone. Strobe lights are not recommended for application to short-term work zones.

CHAPTER 8
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APPENDIX A
WORK ZONE SITE LAYOUTS

RS1 – SH 6: March 21, 2000

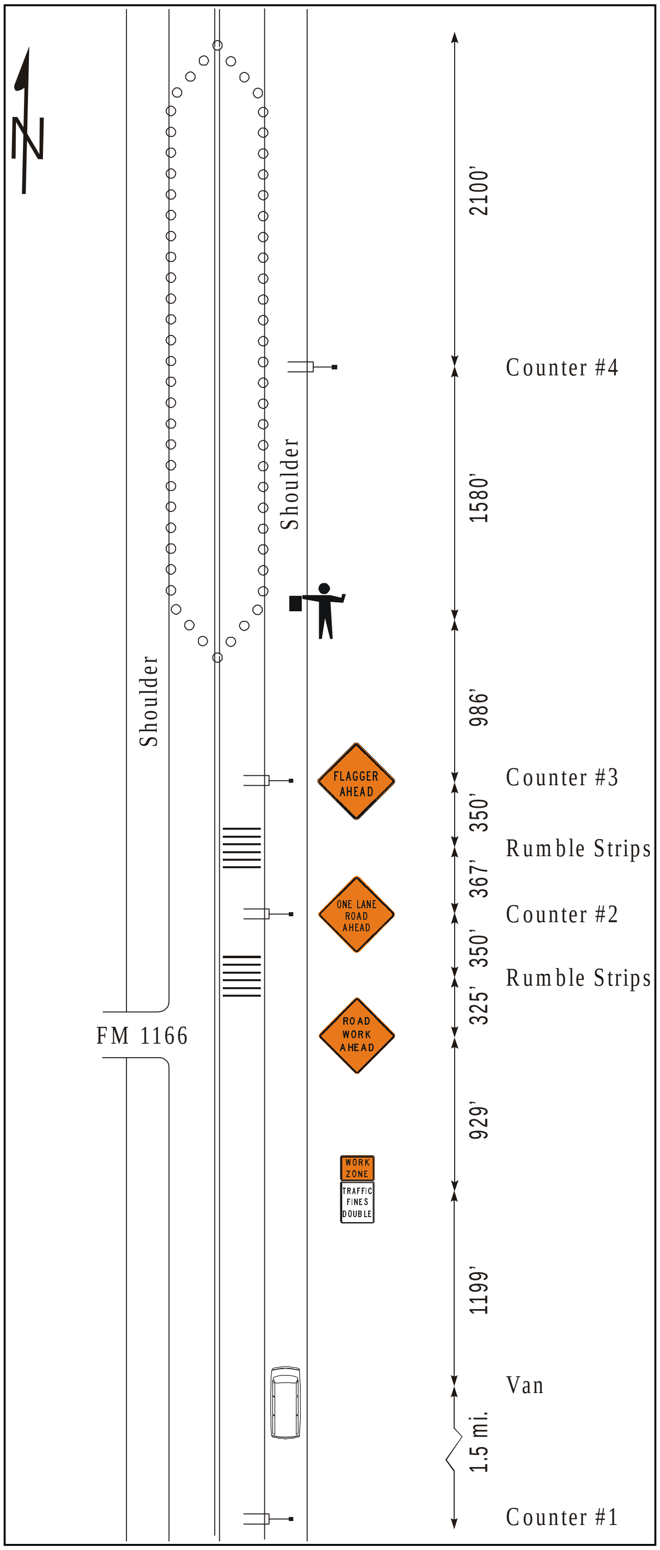


Figure A- 1. RS1 Site Layout (Not to Scale).

Location: SH 6, approximately 5 miles north of Quanah, TX.

Average Daily Traffic (ADT): 1250 (1998)

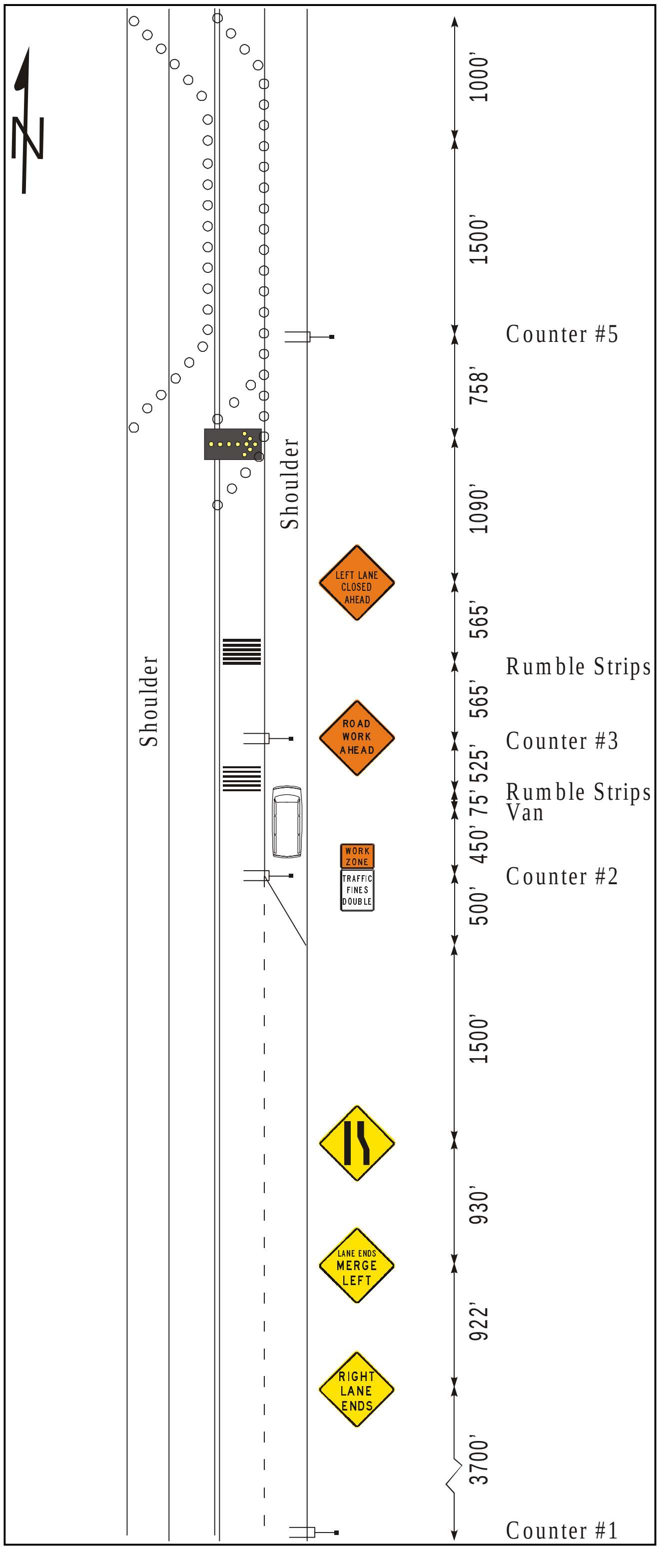
Description of Work: Repair and resurface approximately 0.7 mile stretch of travel lanes.

Device Tested: Portable rumble strips

Site Description: SH 6 is a north-south, two-lane rural highway. The posted speed limit was 70 mph for both cars and trucks.

Data Collection Comments: The traffic counters used during data collection produced a number of erroneous readings. Temperatures were around 60 °F during data collection, forcing the traffic counter sensors to be nailed to the pavement rather than adhered using bitumen tape, which resulted in lengthy set-up times and may have impacted the data accuracy of the traffic counters. Two LIDAR data collection stations were used. One was located at the flagger station, and the second was located 4186 feet in advance of the flagger.

RS2 and RS3 – US 83: May 3-4, 2000



Location: US 83, approximately 5 miles north of Childress, TX.

ADT: 1850 (1998)

Description of Work: Repair and resurface approximately 0.6 mile stretch of southbound lane.

Device Tested: Portable rumble strips

Site Description: US 83 is a north-south, three-lane rural highway. The posted speed limit was 70 mph for both cars and trucks. The work zone was located where US 83 transitioned from two lanes northbound and one lane southbound to one lane northbound and two lanes southbound. The work zone was at the same location on May 3 and May 4.

Data Collection Comments: At noon on May 3, a train derailed on US 287. The train derailment forced US 287 to be closed to through traffic. Through traffic was detoured onto US 83, resulting in a significant increase in volume during the afternoon on May 3. US 287 was open to traffic on May 4, and traffic volumes returned to their normal levels on US 83.

Figure A- 2. RS2 and RS3 Site Layout (Not to Scale).

VMS1 – I-40: June 6, 2000

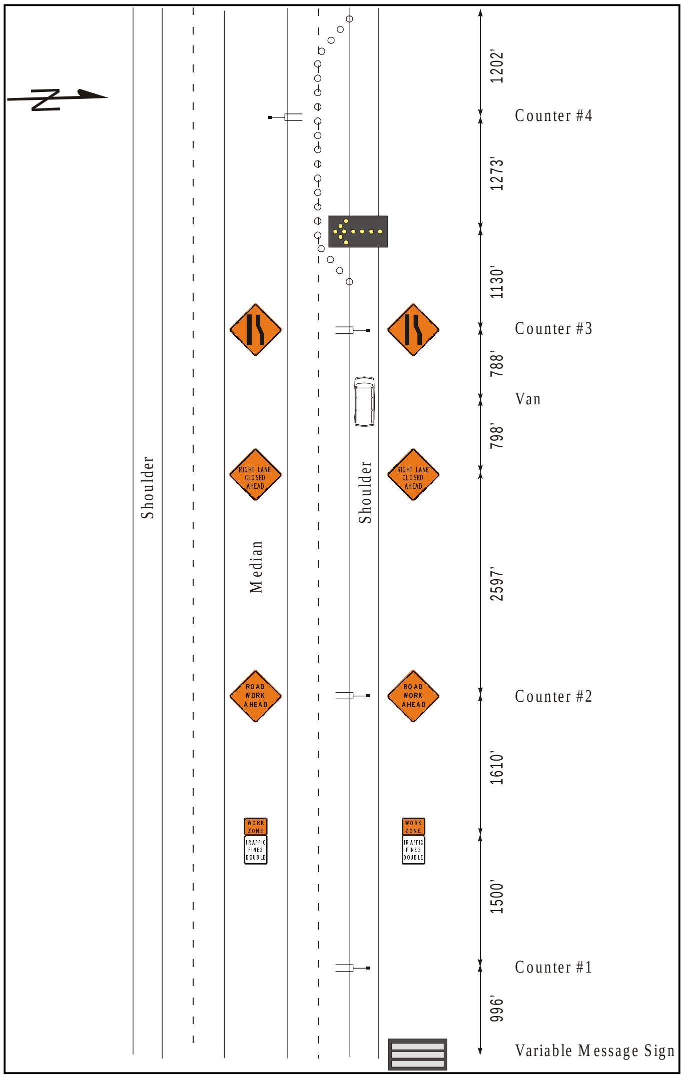


Figure A- 3. VMS1 Site Layout (Not to Scale).

Location: I-40 westbound, approximately 0.2 miles from the Texas-Oklahoma border

ADT: 12,000 (1998)

Description of Work: Repair isolated pavement damage in right lane in the westbound direction. The righthand lane was closed to allow concrete to cure.

Device Tested: Variable message sign

Site Description: I-40 is a four-lane access-controlled freeway. I-40 runs east-west. The posted speed limit was 70 mph for both cars and trucks. No maintenance crew workers were present at the site during the after period.

Data Collection Comments: None

VMS1 – I-40: June 7, 2000

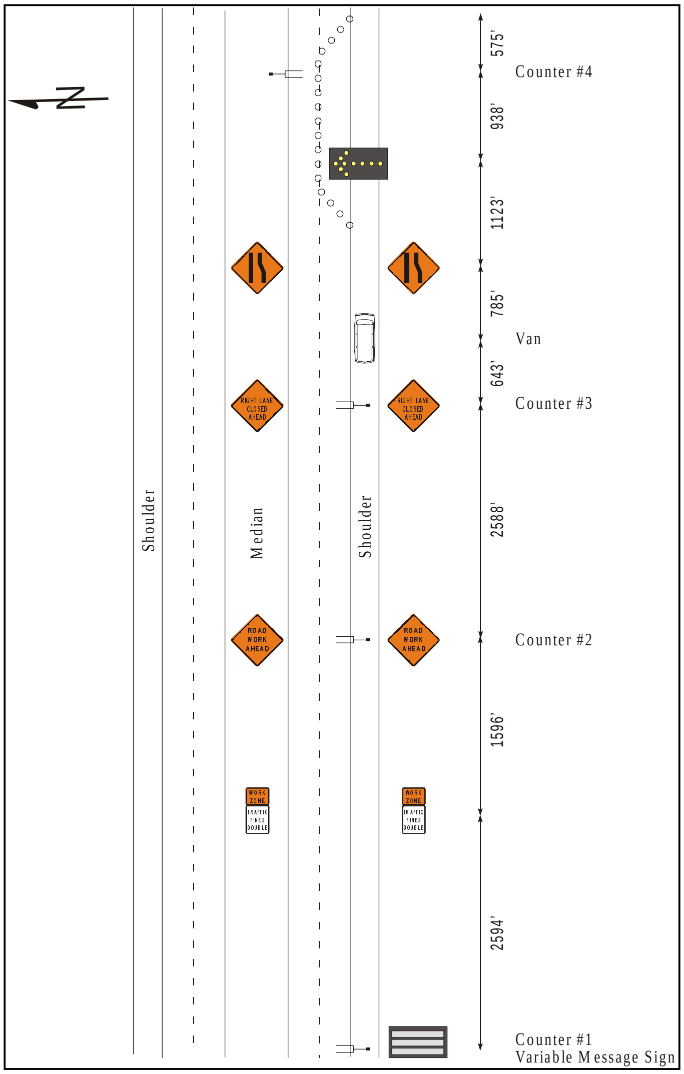


Figure A- 4. VMS2 Site Layout (Not to Scale).

Location: I-40 eastbound, approximately 2 miles east of Shamrock, TX.

ADT: 12,000 (1998)

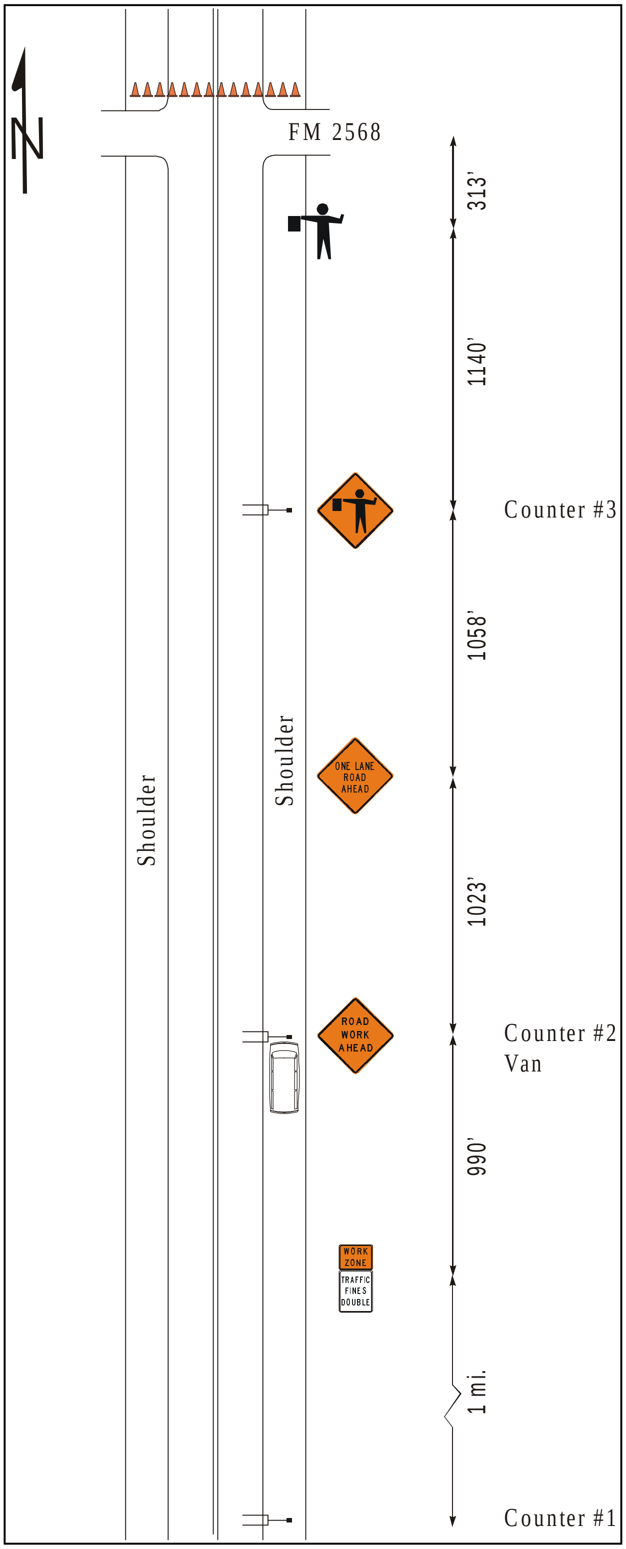
Description of Work: Repair isolated damage in the right lane in the eastbound direction. The right lane was closed to allow concrete to cure.

Device Tested: Variable message sign

Site Description: I-40 is a four-lane divided access-controlled freeway. I-40 runs east-west. The posted speed limit was 70 mph for both cars and trucks. No workers were present during the after period.

Data Collection Comments: None

RD1 – SH 6: June 8, 2000



Location: SH 6, approximately 2 miles south of Quanah, TX.

ADT: 750 (1998)

Description of Work: Repair and resurface approximately 2 mile stretch of SH 6 going towards Quanah.

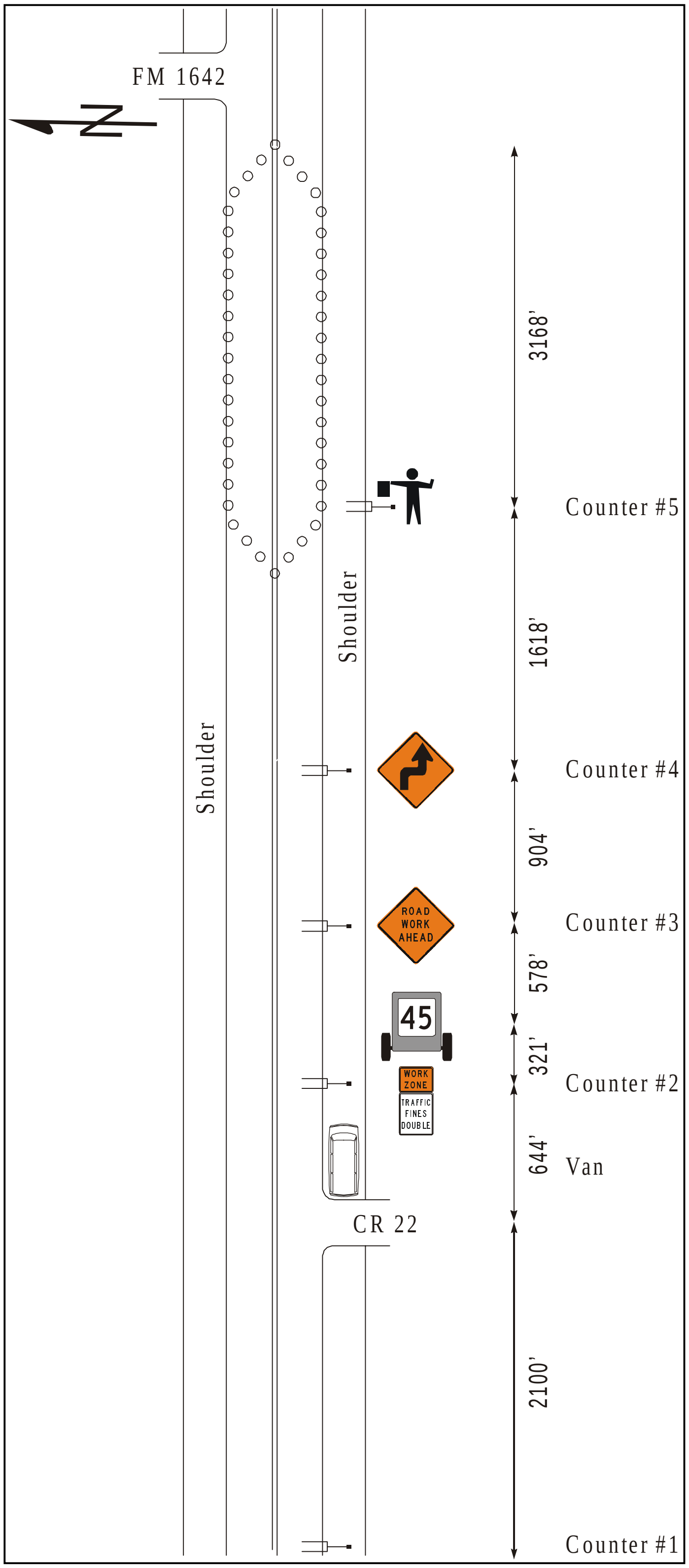
Device Tested: Radar drone, fluorescent orange signs, fluorescent yellow-green flagger vest, vehicle visibility improvements

Site Description: SH 6 is a two lane road with 10 feet wide shoulders that runs north-south. The posted speed limit was 70 mph for both cars and trucks

Data Collection Comments: After researchers had collected baseline data for several hours, the location of the work zone channelizing devices was moved south by about 1 mile. The advance signs were not moved, but work activities became visible to oncoming drivers at an earlier point. Researchers discarded the data collected prior to the movement of the work zone and only used the before data that were collected following the shifting of the work zone location.

Figure A- 5. RD1 Site Layout (Not to Scale).

SD1 – US 62: June 20, 2000



Location: US 62 eastbound, approximately 6 miles from the Texas-Oklahoma border.

ADT: 1000 (1998)

Description of Work: Repair and resurface approximately 0.6 mile stretch of travel lanes.

Device Tested: Speed display

Site Description: US 62 is a two-lane road with 10 foot wide shoulders that runs east-west. The posted speed limit was 70 mph for both cars and trucks.

Data Collection Comments: The traffic counter within the work zone malfunctioned during data collection, and all information on the counter was lost.

Figure A- 6. SD1 Site Layout (Not to Scale).

SD2 – US 62: June 22, 2000

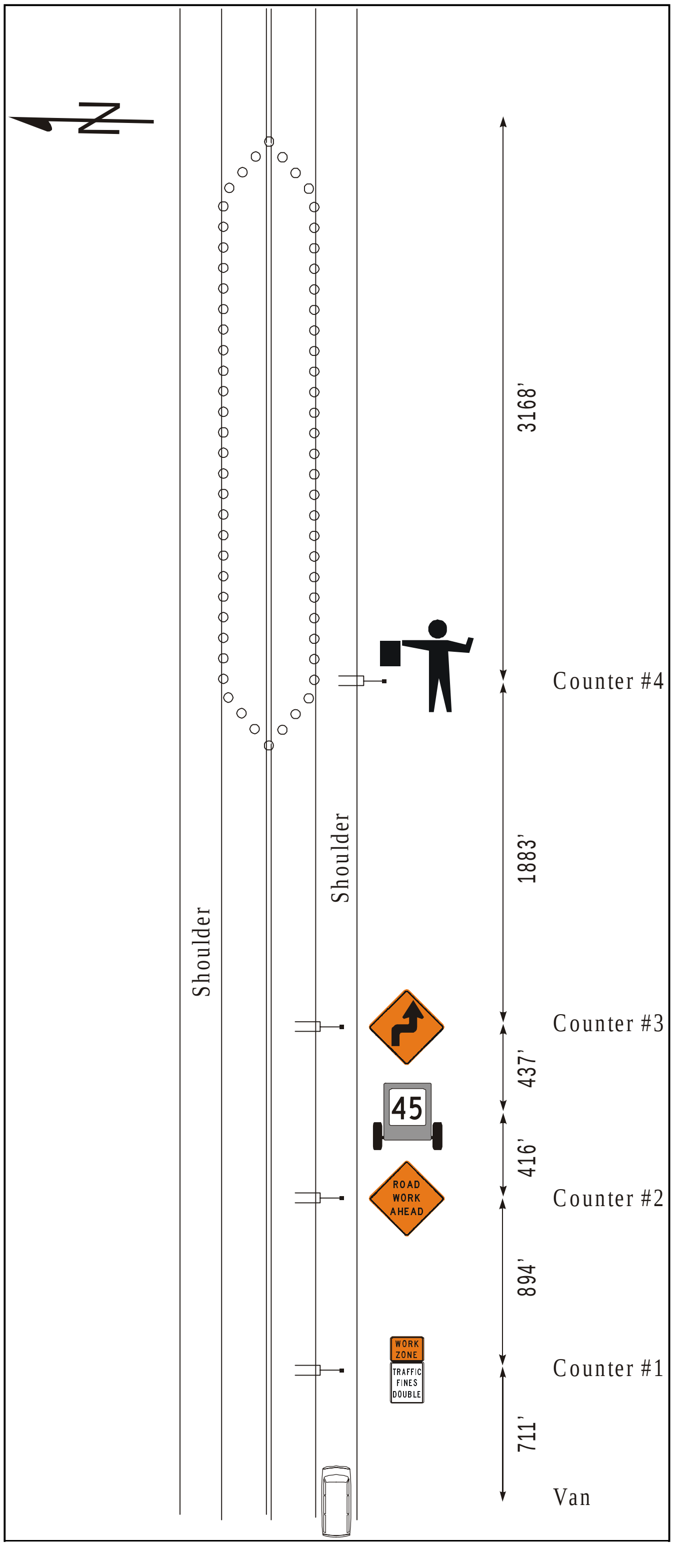


Figure A- 7. SD2 Site Layout (Not to Scale).

Location: US 62 eastbound, approximately 5 miles from the Texas-Oklahoma border.

ADT: 1000 (1998)

Description of Work: Repair and resurface approximately 0.6 mile stretch of travel lanes.

Device Tested: Speed display

Site Description: US 62 is a two-lane road with 10 foot wide shoulders that runs east-west. The posted speed limit was 70 mph for both cars and trucks. This site was located approximately 1 mile west of SD1.

APPENDIX B
LIDAR SPEED DATA

Table B-1. LIDAR Data Collection Summary for RS1.

Reference Point	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
B	Before	5	57.6	6.7	50	66	0.0	10	66.3	11.1	52	89	30.0
	After	6	67.2	8.9	50	76	33.3	10	63.5	7.2	48	73	10.0
C	Before	5	58.2	8.1	49	66	0.0	12	64.3	10.9	52	89	33.3
	After	6	66.8	9.0	49	74	33.3	8	61.0	9.3	42	73	12.5
D	Before	4	59.5	7.6	49	66	0.0	10	61.4	8.0	50	75	20.0
	After	4	68.5	2.1	66	71	25.0	10	59.4	10.8	40	74	10.0
E	Before	①	①	①	①	①	①	1	61	②	61	61	0.0
	After	1	69.0	②	69	69	0.0	1	66	②	66	66	0.0
F	Before	1	38.0	②	38	38	0.0	2	59.0	1.4	58	60	0.0
	After	①	①	①	①	①	①	①	①	①	①	①	①
G	Before	①	①	①	①	①	①	3	55.0	0	55	55	0.0
	After	①	①	①	①	①	①	1	41.0	②	41	41	0.0
H	Before	1	64.0	②	64	64	0.0	3	50.0	2.0	48	52	0.0
	After	①	①	①	①	①	①	①	①	①	①	①	①
I	Before	11	48.9	10.1	31	63	0.0	3	45.7	2.9	44	49	0.0
	After	1	47.0	②	47	47	0.0	①	①	①	①	①	①
J	Before	17	45.3	8.5	30	61	0.0	2	44.0	4.2	41	47	0.0
	After	①	①	①	①	①	①	1	42.0	②	42	42	0.0
K	Before	20	41.4	10.1	24	65	0.0	2	37.0	8.5	31	43	0.0
	After	1	40	②	40	40	0.0	①	①	①	①	①	①

Shaded cells with bold text indicate statistically significant at α=0.05
① = No data
② = No standard deviation could be computed since there was only one data point

Table B-2. LIDAR Data Collection Summary for RS2.

Reference Points	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
B	Before	19	62.4	7.3	45	73	10.5	3	69.0	3.5	67	73	**33.3**
	After	79	64.6	6.3	50	76	12.7	60	63.5	6.3	47	76	**10.0**
C	Before	29	62.3	7.2	45	73	**6.9**	7	65.4	4.2	60	73	14.3
	After	97	64.1	6.3	48	75	**12.4**	71	62.7	6.2	46	80	8.5
D	Before	36	62.4	7.2	45	73	11.1	12	65.1	4.5	56	72	8.3
	After	94	62.9	6.5	48	77	10.6	76	61.6	6.3	44	79	5.3
E	Before	39	62.9	7.6	45	73	12.8	11	64.1	5.4	53	72	9.1
	After	72	61.5	6.8	46	76	6.9	76	60.6	6.4	42	78	5.3
F	Before	42	62.7	8.1	44	73	14.3	10	62.3	5.1	52	70	0.0
	After	57	61.3	7.3	44	76	8.8	77	59.7	6.3	40	77	3.9
G	Before	35	62.2	8.2	44	73	8.6	12	**62.5**	5.7	50	70	0.0
	After	63	60.8	7.9	43	77	9.5	73	**58.5**	6.1	44	74	4.1
H	Before	33	61.4	8.1	44	74	12.1	12	60.4	5.3	48	68	0.0
	After	70	59.9	7.7	43	75	10.0	69	57.8	6.6	39	73	4.3
I	Before	27	**62.4**	7.8	43	73	**18.5**	10	58.8	6.5	46	71	**10.0**
	After	69	**58.9**	6.9	45	73	**2.9**	65	56.2	6.3	42	73	**1.5**
J	Before	23	59.7	8.9	41	73	8.7	7	57.7	5.7	52	67	0.0
	After	44	58.3	8.3	43	72	9.1	57	53.7	6.9	36	73	1.8
K	Before	20	58.7	9.1	38	72	10.0	7	55.6	5.6	50	63	0.0
	After	19	53.3	8.7	37	70	0.0	39	51.7	6.4	43	73	2.6
L	Before	14	58.1	9.2	43	72	14.3	6	54.5	6.7	48	63	0.0
	After	9	50.7	10.7	34	70	0.0	25	52.2	7.4	41	73	4.0
M	Before	10	**60.0**	7.8	51	72	20.0	4	52.5	7.3	47	63	0.0
	After	10	**50.7**	9.0	32	61	0.0	19	51.0	8.6	35	73	5.3
N	Before	10	**61.2**	7.7	50	73	20.0	4	51.8	7.0	46	62	0.0
	After	2	**44.5**	12.0	36	53	0.0	7	53.7	11.3	40	73	14.3

Shaded cells with bold text indicate statistically significant at α=0.05

Table B-3. LIDAR Data Collection Summary for RS3.

Reference Points	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
B	Before	25	63.8	6.8	52	74	**28.0**	20	63.4	6.5	44	73	10.0
	After	39	60.9	7.2	48	72	**12.8**	7	64.3	5.2	55	69	0.0
C	Before	48	63.5	6.9	49	74	20.8	28	62.8	6.1	45	73	7.1
	After	66	63.2	7.4	48	76	21.2	16	63.8	9.7	48	87	18.8
D	Before	51	63.1	6.6	50	73	13.7	29	62.0	6.8	44	73	**3.4**
	After	76	62.3	7.6	46	79	14.5	19	62.8	9.8	41	86	**15.8**
E	Before	59	63.0	6.2	49	73	11.9	31	61.3	7.4	44	73	9.7
	After	79	61.4	8.0	43	79	12.7	16	60.4	12.6	24	84	12.5
F	Before	57	62.8	6.2	50	73	12.3	30	61.3	8.2	41	74	10.0
	After	74	60.9	7.3	46	73	9.5	19	61.8	6.9	51	82	5.3
G	Before	57	61.8	6.5	45	73	10.5	34	60.3	7.7	40	73	8.8
	After	70	60.1	7.5	46	80	8.6	19	60.7	6.8	52	81	5.3
H	Before	55	**61.7**	6.2	42	72	5.5	32	59.1	8.0	37	72	6.3
	After	67	**58.9**	7.5	46	73	6.0	19	59.5	6.5	51	79	5.3
I	Before	53	**61.7**	5.9	49	73	9.4	30	57.6	8.2	35	72	3.3
	After	64	**58.9**	7.5	44	73	6.3	19	57.6	5.3	51	72	5.3
J	Before	43	59.7	6.8	48	73	11.6	29	54.2	7.8	33	70	0.0
	After	52	57.1	8.1	42	73	7.7	20	55.3	7.1	45	71	5.0
K	Before	44	57.0	8.1	39	73	9.1	26	51.9	7.5	30	62	0.0
	After	50	54.7	9.1	38	73	6.0	15	49.7	5.9	42	63	0.0
L	Before	32	56.3	9.6	32	73	9.4	24	51.1	7.2	33	61	0.0
	After	34	52.5	9.8	36	73	5.9	14	49.4	7.4	40	64	0.0
M	Before	23	56.7	11.3	30	73	13.0	20	50.9	7.0	33	61	0.0
	After	24	52.5	9.4	36	73	4.2	9	47.7	6.7	40	60	0.0
N	Before	17	55.4	11.7	28	73	17.6	12	52.8	5.8	43	62	0.0
	After	14	52.7	7.7	44	69	0.0	8	48.1	6.4	42	59	0.0

Shaded cells with bold text indicate statistically significant at α=0.05

Table B-4. LIDAR Data Collection Summary for VMS1.

Reference Points	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
B	Before	8	62.1	6.8	52	71	12.5	15	63.9	6.5	49	73	13.3
	After	8	65.1	5.8	58	75	25.0	20	62.0	6.1	45	72	5.0
C	Before	48	69.9	6.1	53	81	54.2	54	65.3	4.4	51	72	11.1
	After	71	69.6	5.9	56	86	47.9	73	64.1	6.0	45	78	16.4
D	Before	57	70.8	6.1	56	83	**59.6**	59	65.6	4.8	51	76	18.6
	After	87	69.0	5.9	55	86	**43.7**	93	64.7	5.9	45	79	18.3
E	Before	56	70.5	6.2	56	87	**57.1**	57	65.5	5.0	52	76	22.8
	After	92	69.0	5.9	55	86	**41.3**	98	64.4	5.8	46	78	20.4
F	Before	56	**71.0**	6.4	56	87	**58.9**	59	65.7	5.0	53	75	20.3
	After	92	**68.5**	6.1	54	87	**41.3**	94	64.0	5.7	46	78	17.0
G	Before	49	**70.4**	6.3	55	82	**53.7**	56	64.8	5.1	53	76	10.7
	After	84	**67.8**	6.4	55	86	**35.7**	97	63.7	5.8	46	78	14.4
H	Before	48	**69.4**	6.3	53	82	**39.1**	55	64.3	5.1	53	75	10.9
	After	87	**66.6**	6.3	53	87	**25.3**	92	62.7	5.9	45	77	9.8
I	Before	46	**69.0**	6.9	53	82	**39.1**	51	64.0	5.1	52	74	9.8
	After	77	**66.1**	6.7	51	87	**23.3**	88	62.5	6.3	45	78	11.4
J	Before	35	**68.7**	6.7	52	81	**42.9**	47	**63.1**	5.3	52	73	6.4
	After	68	**65.1**	6.6	47	78	**23.5**	76	**60.9**	6.3	47	78	7.9
K	Before	31	670	7.9	52	82	**41.9**	37	62.3	5.1	50	73	5.4
	After	57	64.2	8.2	44	89	**22.8**	79	61.0	6.9	44	78	10.1
L	Before	26	67.8	8.5	54	82	**53.8**	37	62.2	5.2	48	73	5.4
	After	35	64.3	7.4	51	76	**22.9**	68	60.4	6.8	43	75	7.4
M	Before	10	64.9	8.5	54	80	30.0	30	61.1	5.4	46	70	0
	After	26	64.3	9.5	47	79	30.8	55	60.0	7.3	43	75	9.1
N	Before	8	65.4	7.4	53	76	25.0	23	61.1	6.5	45	72	4.3
	After	17	61.9	9.6	46	75	29.4	51	60.3	7.5	42	76	9.8
O	Before	4	60.0	6.1	51	64	0.0	9	61.6	7.3	51	71	11.1
	After	11	61.1	10.0	51	75	27.3	42	60.0	7.3	41	75	4.8
P	Before	①	①	①	①	①	①	3	62.3	10.3	51	71	**33.3**
	After	6	67.5	9.3	50	75	50.0	22	62.0	6.4	50	75	**9.1**
Q	Before	1	58.0	②	58	58	0.0	3	61.7	8.5	52	68	0.0
	After	2	68.5	3.5	66	71	50.0	14	62.4	7.1	48	75	14.3
R	Before	①	①	①	①	①	①	2	59.0	8.5	53	65	0.0
	After	2	69.0	4.2	66	72	50.0	6	62.7	5.5	53	69	0.0
S	Before	①	①	①	①	①	①	①	①	①	①	①	①
	After	1	71.0		71	71	100	5	63.4	5.4	55	69	0

Shaded cells with bold text indicate statistically significant at α=0.05

① = No data

② = No standard deviation could be computed since there was only one data point

Table B-5. LIDAR Data Collection Summary for VMS2.

Reference Points	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
B	Before	25	64.3	6.3	47	72	**12.0**	39	63.2	4.5	54	71	5.1
	After	9	66.0	5.8	56	73	**33.3**	28	62.7	5.4	52	77	10.7
C	Before	64	66.7	5.1	56	75	28.1	88	64.3	4.8	55	74	11.4
	After	43	66.6	5.6	52	77	27.9	79	64.2	5.5	50	78	13.9
D	Before	75	67.6	5.3	56	79	32.0	100	64.3	4.9	55	76	11.0
	After	62	66.8	5.6	54	78	29.0	89	64.1	5.6	50	79	13.5
E	Before	82	67.4	5.7	47	79	31.7	100	63.9	4.7	55	75	8.0
	After	58	67.3	6.0	53	81	31.0	86	63.6	5.4	51	79	9.3
F	Before	78	67.4	5.9	47	79	33.3	93	63.6	4.8	54	75	6.5
	After	63	67.0	5.8	53	81	27.0	84	64.0	5.4	50	80	8.3
G	Before	78	67.5	5.8	48	79	32.1	94	63.6	5.0	54	76	8.5
	After	61	66.9	5.7	53	78	29.5	76	63.7	5.3	51	80	7.9
H	Before	72	67.7	5.7	54	79	37.5	83	63.6	5.1	54	77	10.8
	After	56	67.8	5.4	54	78	37.5	73	63.6	5.5	51	80	8.2
I	Before	71	68.3	5.4	56	79	40.8	74	63.	5.2	54	77	9.5
	After	49	67.6	5.5	55	83	32.7	68	64.2	5.4	52	81	11.8
J	Before	58	67.9	5.5	55	78	39.7	70	63.4	5.3	54	77	11.4
	After	39	67.5	5.5	56	75	38.5	60	64.2	5.4	52	81	10.0
K	Before	44	66.7	5.5	53	74	34.1	64	63.7	5.5	53	77	14.1
	After	31	68.4	4.7	60	75	35.5	46	63.6	5.1	51	81	8.7
L	Before	24	67.2	5.1	56	74	41.7	56	63.6	5.6	53	78	10.7
	After	15	69.1	3.6	63	74	40.0	40	63.7	6.3	50	81	15.0
M	Before	26	68.2	5.2	56	75	50.0	48	63.5	5.4	53	78	10.4
	After	11	67.6	4.5	59	74	27.3	36	63.9	6.1	50	81	16.7
N	Before	20	67.6	5.6	56	75	40.0	39	62.4	4.7	52	74	5.1
	After	11	67.9	4.3	59	72	45.5	27	63.0	6.0	50	80	11.1
O	Before	7	64.6	6.4	56	73	14.3	24	62.1	5.0	52	73	**4.2**
	After	1	64.0	②	64	64	0.0	17	65.4	5.9	58	80	**23.5**
P	Before	1	70.0	②	70	70	0.0	20	62.5	4.9	52	73	**5.0**
	After	①	①	①	①	①	①	10	65.4	6.9	58	80	**30.0**
Q	Before	1	70.0	②	70	70	0.0	10	62.0	4.6	54	67	0.0
	After	①	①	①	①	①	①	7	67.0	8.9	57	80	42.9
R	Before	①	①	①	①	①	①	8	62.9	3.7	56	67	0.0
	After	①	①	①	①	①	①	6	68.8	8.8	57	80	50.0
S	Before	①	①	①	①	①	①	1	67.0	②	57	67	0.0
	After	①	①	①	①	①	①	3	72.3	7.5	65	80	66.7

Shaded cells with bold text indicate statistically significant at α=0.05
① = No data
② = No standard deviation could be computed since there was only one data point

Table B-6. LIDAR Data Collection Summary at RD1.

Reference Points	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
B	Before	6	61.3	6.9	53	73	16.7	5	52.2	5.9	44	57	0.0
	After	1	35.0	②	35	35	0.0	4	59.5	6.4	56	69	0.0
C	Before	5	62.2	7.9	53	74	20.0	5	53.0	5.3	46	59	0.0
	After	8	55.6	9.6	38	69	0.0	11	60.7	7.3	48	72	9.1
D	Before	6	62.2	7.1	53	74	16.7	5	53.6	5.8	46	61	0.0
	After	8	56.0	9.4	41	70	0.0	12	59.6	7.1	47	72	8.3
E	Before	6	62.7	7.3	54	75	16.7	5	54.6	5.9	47	63	0.0
	After	10	57.3	8.3	44	70	0.0	13	59.7	6.6	49	72	7.7
F	Before	6	62.7	7.3	54	75	16.7	4	55.5	7.0	47	64	0.0
	After	9	58.9	7.1	46	70	0.0	12	59.4	6.9	49	72	8.3
G	Before	5	63.6	8.5	54	76	20.0	5	56.0	6.4	47	65	0.0
	After	9	58.3	7.0	48	70	0.0	12	59.3	7.0	50	72	8.3
H	Before	6	63.0	7.8	54	76	16.7	4	55.5	8.3	47	67	0.0
	After	8	56.9	7.1	47	69	0.0	8	57.3	5.6	48	65	0.0
I	Before	3	57.3	3.1	54	60	0.0	1	47.0	②	47	47	0.0
	After	4	52.5	3.9	48	57	0.0	6	53.7	7.2	46	65	0.0
J	Before	2	56.5	2.1	55	58	0.0	1	49.0	②	49	49	0.0
	After	4	50.8	5.7	43	56	0.0	6	53.5	8.3	44	64	0.0
K	Before	①	①	①	①	①	①	①	①	①	①	①	①
	After	1	51.0	②	51	51	0.0	1	41.0	②	41	41	0.0
L	Before	1	48.0	②	48	48	0.0	①	①	①	①	①	①
	After	1	48.0	②	48	48	0.0	3	43.7	7.6	35	49	0.0
M	Before	①	①	①	①	①	①	①	①	①	①	①	①
	After	①	①	①	①	①	①	3	36.7	6.8	29	42	0.0

Shaded cells with bold text indicate statistically significant at α=0.05
① = No data
② = No standard deviation could be computed since there was only one data point

Table B-7. LIDAR Data Collection Summary for SD1.

Reference Points	Study Period	Passenger Cars						Trucks					
		Number	**Mean**	**Std. Dev.**	**Min**	**Max**	**% > 70**	**Number**	**Mean**	**Std. Dev.**	**Min**	**Max**	**% > 70**
B	Before	15	66.7	5.7	51	74	20.0	6	66.8	2.2	65	70	**0**
	After	26	66.5	6.0	51	76	15.4	22	63.0	7.5	46	72	**4.5**
C	Before	14	**68.1**	6.2	50	76	**35.7**	8	**67.5**	3.4	62	72	25.0
	After	29	**63.1**	7.5	42	75	**10.3**	24	**61.3**	6.9	45	70	0.0
D	Before	13	**67.8**	6.4	49	74	**38.5**	8	**64.5**	5.8	53	71	12.5
	After	22	**57.8**	8.7	40	74	**9.1**	19	**57.0**	8.2	42	69	0.0
E	Before	9	**67.6**	4.6	59	73	**33.3**	8	**64.1**	6.4	50	70	0.0
	After	26	**57.0**	8.7	39	71	**3.8**	16	**56.9**	8.7	40	69	0.0
F	Before	11	**65.0**	7.0	48	73	**18.2**	7	**63.4**	4.6	57	69	0.0
	After	25	**57.2**	8.4	37	69	**0.0**	14	**56.6**	7.0	43	66	0.0
G	Before	6	62.7	9.0	47	70	0.0	8	**61.9**	5.4	54	70	0.0
	After	17	55.3	9.0	39	66	0.0	15	**54.1**	6.6	43	64	0.0
H	Before	1	56.0	②	56	56	0.0	7	**61.4**	5.7	53	70	0.0
	After	4	54.5	5.9	46	59	0.0	9	**51.9**	7.6	42	62	0.0
I	Before	5	47.2	8.4	45	68	0.0	4	61.5	7.6	51	69	0.0
	After	10	52.1	6.8	42	61	0.0	10	51.8	8.2	41	68	0.0
J	Before	2	57.5	3.5	55	60	0.0	5	**61.4**	8.0	49	71	20.0
	After	5	55.2	8.1	41	60	0.0	6	**48.5**	7.2	40	60	0.0
K	Before	1	53.0	②	53	53	0.0	3	**56.7**	8.7	47	64	0.0
	After	①	①	①	①	①	①	4	**41.5**	4.4	38	47	0.0
L	Before	①	①	①	①	①	①	3	54.7	9.1	45	63	0.0
	After	①	①	①	①	①	①	2	41.0	1.4	40	42	0.0
M	Before	①	①	①	①	①	①	1	42.0	②	42	42	0.0
	After	①	①	①	①	①	①	2	42.0	9.9	35	49	0.0
N	Before	①	①	①	①	①	①	1	40.0	②	40	40	0.0
	After	①	①	①	①	①	①	1	29.0	②	29	29	0.0

Shaded cells with bold text indicate statistically significant at $\alpha=0.05$

① = No data

② = No standard deviation could be computed since there was only one data point

Table B-8. LIDAR Data Collection Summary for SD2.

Reference Points	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
B	Before	3	68.7	5.1	63	73	33.3	4	61.3	4.9	55	67	0.0
	After	28	63.7	7.8	49	75	25.0	21	59.6	9.4	46	82	9.5
C	Before	2	66.0	8.5	60	72	**50.0**	5	58.0	6.0	48	63	0.0
	After	31	63.7	6.5	50	74	**19.4**	29	59.8	9.0	47	82	10.3
D	Before	3	65.3	5.5	59	69	0.0	3	58.3	2.5	56	61	0.0
	After	38	61.6	7.4	43	73	7.9	25	58.0	10.0	45	84	12.0
E	Before	4	63.5	4.2	58	68	0.0	3	57.0	1.0	56	58	0.0
	After	36	59.8	7.9	44	73	8.3	25	58.2	10.5	42	86	12.0
F	Before	3	59.0	3.5	55	61	0.0	2	56.5	2.1	55	58	0.0
	After	35	58.3	8.6	42	72	11.4	23	57.6	11.6	40	88	13.0
G	Before	3	58.7	8.3	52	68	0.0	3	51.3	4.7	46	55	0.0
	After	29	57.3	8.3	41	73	6.9	16	54.8	8.0	41	71	6.3
H	Before	18	59.3	7.7	48	75	5.6	23	56.3	8.5	42	72	4.3
	After	25	54.6	8.9	36	73	4.0	15	56.1	10.1	46	88	6.7
I	Before	23	58.0	9.1	32	73	4.3	18	56.5	9.3	42	72	5.6
	After	26	53.0	8.9	35	73	3.8	14	56.6	10.6	43	87	7.1
J	Before	20	60.4	9.9	35	75	10.0	22	55.3	7.8	42	70	0.0
	After	20	55.7	9.4	40	73	10.0	11	53.1	6.1	45	65	0.0
K	Before	21	60.9	8.3	40	75	9.5	20	53.2	7.6	43	70	0.0
	After	16	55.7	8.2	42	71	6.3	8	52.0	5.9	44	62	0.0
L	Before	19	56.9	9.4	38	75	5.3	21	51.1	6.9	41	69	0.0
	After	8	57.1	8.0	45	67	0.0	6	48.7	8.4	37	62	0.0
M	Before	17	54.4	10.0	34	74	5.9	17	47.9	7.6	39	70	0.0
	After	3	59.7	5.1	54	64	0.0	5	44.8	9.1	34	58	0.0
N	Before	15	46.3	11.0	26	60	0.0	14	41.6	5.1	33	50	0.0
	After	1	55.0	②	55	55	0.0	5	43.0	5.8	35	50	0.0
O	Before	14	43.7	9.3	25	62	0.0	11	37.9	6.0	28	48	0.0
	After	①	①	①	①	①	①	4	35.5	6.8	28	43	0.0
P	Before	4	32.3	7.3	22	38	0.0	9	31.1	8.0	19	42	0.0
	After	①	①	①	①	①	①	2	30.0	5.7	26	34	0.0
Q	Before	①	①	①	①	①	①	4	23.8	5.4	16	28	0.0
	After	①	①	①	①	①	①	①	①	①	①	①	①

Shaded cells with bold text indicate statistically significant at α=0.05
① = No data
② = No standard deviation could be computed since there was only one data point

APPENDIX C
COUNTER SPEED DATA

Table C-1. Counter Data Collection Summary for RS1.

Counter Number	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
1	Before	28	68.3	9.7	53	89	39.3	6	63	13.6	38	78	16.7
	After	18	66.6	8.2	43	78	27.8	1	68	②	68	68	0.0
2	Before	49	51.6	11.2	28	84	4.1	4	50.3	14.8	33	64	0.0
	After	18	52.3	10.2	39	73	5.6	3	32.3	15.9	14	43	0.0
3	Before	11	51.5	13.3	28	69	0.0	1	49	②	49	49	0.0
	After	5	45.4	9.6	35	61	0.0	①	①	①	①	①	①
4	Before	25	29.9	5.8	18	40	0.0	2	30	3.0	29	31	0.0
	After	2	33.5	3.5	31	36	0.0	①	①	①	①	①	①

Shaded cells with bold text indicate statistically significant at α=0.05
① = No data
② = No standard deviation could be computed since there was only one data point

Table C-2. Counter Data Collection Summary for RS2.

Counter Number	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
1	Before	47	**65.9**	6.8	49	76	**25.5**	5	70.6	4.0	66	77	**40.0**
	After	209	**69.0**	6.3	53	86	**45.5**	133	67.0	4.6	44	80	**21.1**
2	Before	80	**64.3**	9.6	13	82	22.5	13	68.5	2.5	64	72	**23.1**
	After	373	**67.2**	6.2	47	84	26.3	174	65.9	5.6	44	83	**14.4**
3	Before	87	62.8	10.2	35	81	**25.3**	15	**69.6**	5.4	61	79	**40.0**
	After	443	63.8	7.6	22	89	**18.1**	235	**62.4**	6.6	33	77	**6.0**
4	Before	86	**60.9**	8.4	44	77	**10.5**	15	**62.7**	5.7	50	74	**6.7**
	After	432	**58.9**	7.9	30	77	**6.7**	236	**57.3**	7.0	37	77	**1.3**
5	Before	87	51.6	11.5	17	72	**5.7**	16	51.9	8.2	36	63	0.0
	After	393	51.6	8.4	27	76	**1.0**	242	49.0	7.5	27	71	0.4

Shaded cells with bold text indicate statistically significant at α=0.05

Table C-3. Counter Data Collection Summary for RS3.

Counter Number	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
1	Before	76	**67.5**	5.9	52	83	**34.2**	27	69.4	4.0	60	78	29.6
	After	90	**69.6**	6.8	44	86	**45.6**	15	68.2	2.9	63	73	20.0
2	Before	131	**65.5**	7.7	35	89	29.0	42	66.1	5.4	47	72	11.9
	After	142	**67.7**	6.5	45	85	29.6	23	66.8	6.3	45	73	21.7
3	Before	142	62.2	9.8	29	86	19.0	42	65.7	7.1	46	83	19.0
	After	148	64.0	8.5	31	89	24.3	28	63.4	8.2	38	74	14.3
4	Before	134	60.7	7.2	32	77	7.5	47	61.0	7.7	38	80	4.3
	After	141	59.6	8.1	26	80	5.7	31	58.5	8.2	37	80	6.5
5	Before	126	51.8	9.4	24	75	3.2	46	**53.8**	7.7	37	69	0.0
	After	138	53.2	8.9	34	74	2.9	35	**49.7**	7.4	35	69	0.0

Shaded cells with bold text indicate statistically significant at α=0.05

Table C-4. Counter Data Collection Summary for VMS1.

Counter Number	Study Period	Passenger Cars							Trucks						
		Number	% in Right Lane	Mean	Std. Dev.	Min	Max	% > 70	Number	% in Right Lane	Mean	Std. Dev.	Min	Max	% > 70
1	Before	373	88.4	**71.3**	5.3	52	90	**56.3**	155	59.4	67.1	4.7	39	74	18.7
	After	401	60.6	**69.9**	6.6	38	92	**50.6**	223	58.5	67.0	4.3	50	77	17.9
2	Before	368	87.2	71.0	5.0	54	89	**54.9**	184	70.5	67.1	3.8	55	74	17.9
	After	380	57.4	70.2	5.8	54	91	**47.9**	177	46.5	67.2	4.2	53	76	22.6
3	Before	78	18.5	67.7	6.7	43	90	29.5	4	1.5	60.8	4.3	55	65	0.0
	After	81	12.2	67.7	8.0	46	90	35.8	13	3.4	61.2	3.8	55	68	0.0
4	Before	422	0.0	**65.2**	8.8	37	86	**29.9**	261	0.0	**62.1**	6.7	43	79	**12.3**
	After	662	0.0	**63.5**	8.6	32	86	**20.8**	381	0.0	**60.6**	7.4	37	76	**8.4**

Shaded cells with bold text indicate statistically significant at α=0.05

Table C-5. Counter Data Collection Summary for VMS2.

Counter Number	Study Period	Passenger Cars							Trucks						
		Number	% in Right Lane	Mean	Std. Dev.	Min	Max	% > 70	Number	% in Right Lane	Mean	Std. Dev.	Min	Max	% > 70
1	Before	443	72.6	**66.1**	6.8	45	86	**26.2**	423	86.5	**62.3**	4.0	44	74	0.2
	After	348	49.2	**65.1**	6.9	36	84	**19.8**	363	69.1	**61.5**	5.1	32	72	0.3
2	Before	491	80.5	68.5	5.7	48	95	38.5	390	79.8	**66.3**	4.1	47	77	12.1
	After	313	44.3	67.9	6.2	49	89	37.1	254	48.4	**65.2**	5.2	25	75	10.2
3	Before	304	49.8	65.2	5.7	48	77	16.8	194	39.7	63.4	4.2	49	73	**0.5**
	After	180	25.5	64.9	7.0	44	91	21.7	98	18.7	62.9	5.4	41	73	**4.1**
4	Before	610	0.0	**63.9**	6.5	39	80	**14.6**	489	0.0	60.5	5.5	35	77	**0.6**
	After	707	0.0	**62.6**	6.2	44	79	**9.8**	525	0.0	60.3	5.0	45	77	**1.3**

Shaded cells with bold text indicate statistically significant at α=0.05

Table C-6. Counter Data Collection Summary for RD1.

Counter Number	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
1	Before	14	63.4	9.1	51	77	**28.6**	1	61	①	61	61	0.0
	After	64	61.4	8.9	25	73	**12.5**	11	63.7	4.5	56	69	0.0
2	Before	14	57.9	8.9	37	72	7.1	2	57.5	3.5	55	60	0.0
	After	66	58.8	9.8	20	74	7.6	11	60.9	11.2	43	73	18.2
3	Before	17	53.9	14.2	22	77	**5.9**	2	53.5	0.7	53	54	0.0
	After	65	49.2	11.5	11	70	**0.0**	12	42.1	7.9	23	52	0.0

Shaded cells with bold text indicate statistically significant at α=0.05
① = No standard deviation could be computed since there was only one data point

Table C-7. Counter Data Collection Summary for SD1.

Counter Number	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
1	Before	30	70.3	3.9	63	77	40.0	12	**70.3**	4.4	66	79	25.0
	After	63	69.6	5.6	49	83	36.5	18	**65.1**	7.6	51	76	27.8
2	Before	28	64.6	10.7	34	77	**25.0**	10	65.6	6.1	54	73	**20.0**
	After	43	59.4	10.9	23	73	**7.0**	25	56.1	15.1	21	72	**4.0**
3	Before	31	**63.4**	7.8	42	74	**16.1**	12	**62.1**	6.6	49	68	0.0
	After	65	**56.0**	8.3	30	68	**0.0**	29	**54.2**	9.3	36	66	0.0
4	Before	30	**61.2**	8.6	43	74	**20.0**	11	**56.1**	8.1	44	69	0.0
	After	63	**52.2**	7.5	29	67	**0.0**	30	**49.6**	8.6	34	64	0.0

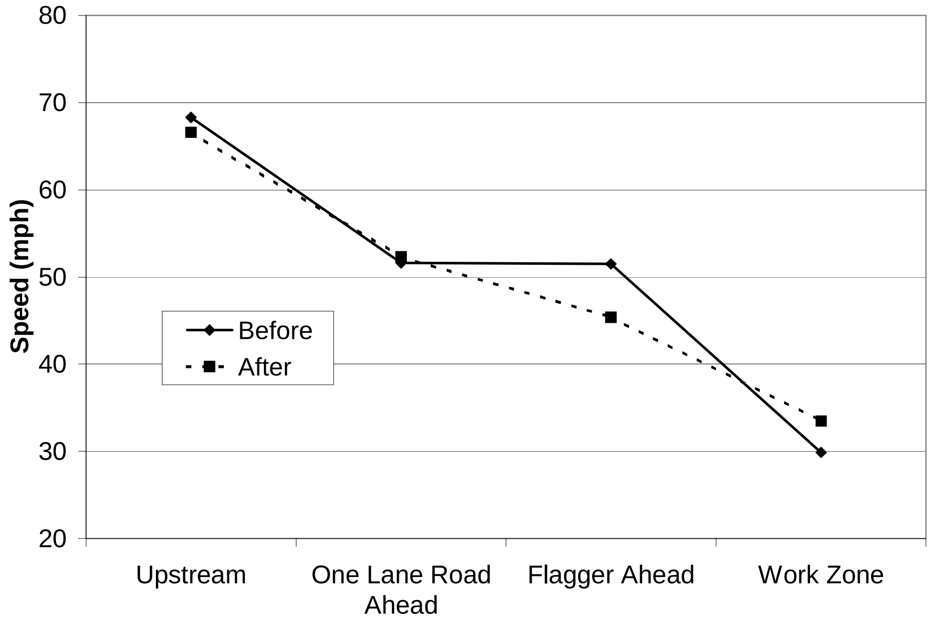
Shaded cells with bold text indicate statistically significant at α=0.05

Table C-8. Counter Data Collection Summary for SD2.

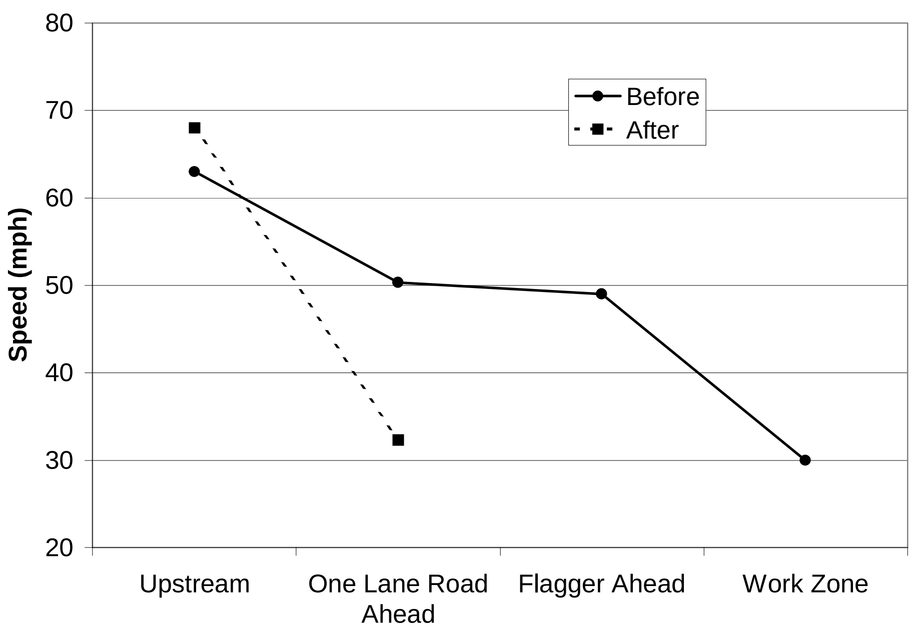
Counter Number	Study Period	Passenger Cars						Trucks					
		Number	Mean	Std. Dev.	Min	Max	% > 70	Number	Mean	Std. Dev.	Min	Max	% > 70
2	Before	66	63.9	8.6	41	77	18.2	19	**60.5**	10.6	35	73	15.8
	After	52	62.3	8.7	40	82	11.5	15	**52.6**	11.4	21	66	0.0
3	Before	61	60.2	9.4	40	77	18.0	19	**59.0**	8.8	337	68	0.0
	After	51	57.8	10.7	36	90	11.8	17	**49.6**	8.3	31	61	0.0
4	Before	68	55.6	9.7	31	75	**1.5**	24	49.5	11.7	12	66	0.0
	After	55	53.3	10.2	35	85	**7.3**	16	46.5	7.5	36	61	0.0
5	Before	50	27.2	9.3	14	52	0.0	11	**29.2**	8.0	15	48	0.0
	After	51	25.8	6.2	14	45	0.0	6	**19.3**	7.5	9	27	0.0

Shaded cells with bold text indicate statistically significant at α=0.05

APPENDIX D
COUNTER SPEED PROFILES

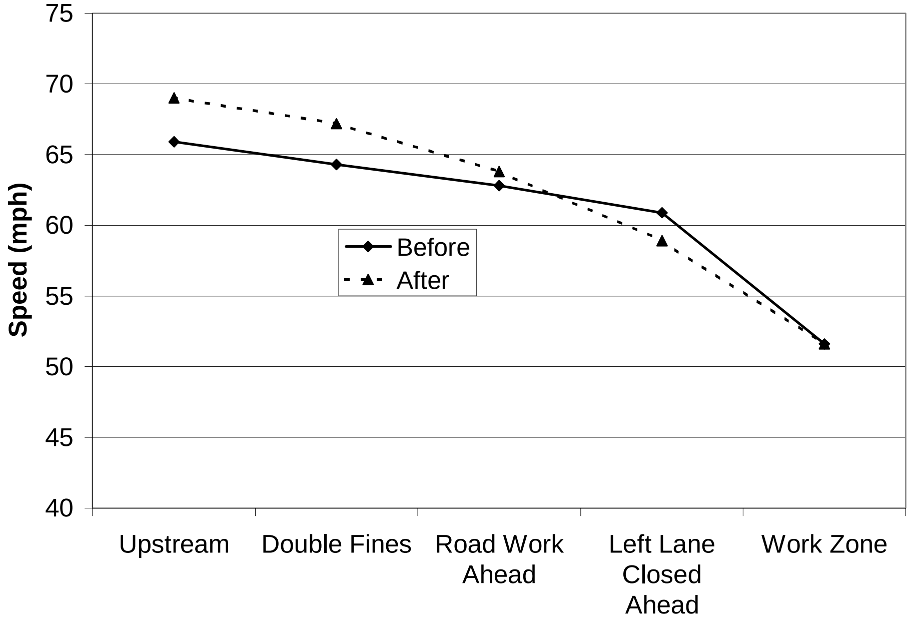


(a)

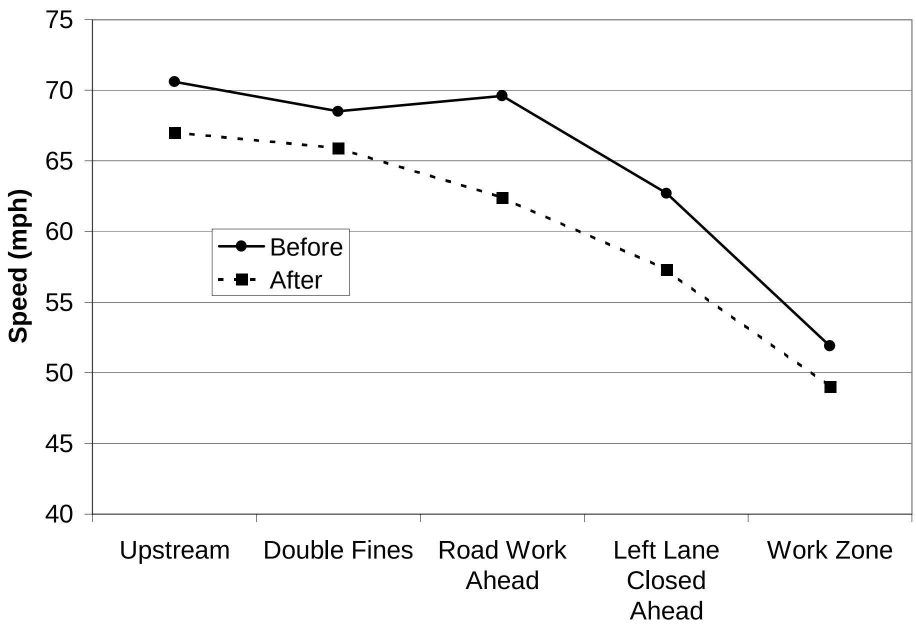


(b)

Figure D-1. RS1 Counter Speeds for (a) Cars (b) Trucks.

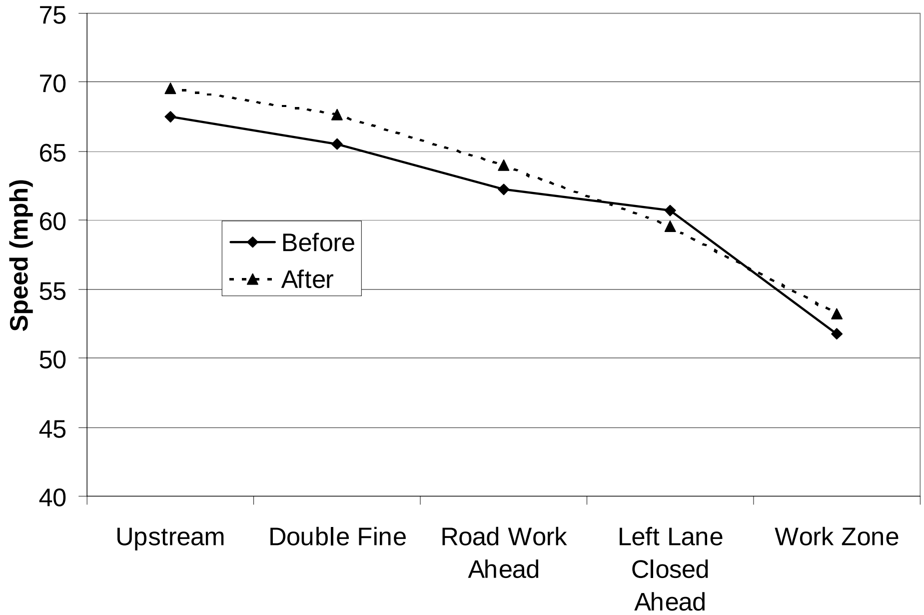


(a)



(b)

Figure D-2. RS2 Counter Speeds for (a) Cars (b) Trucks.



(a)

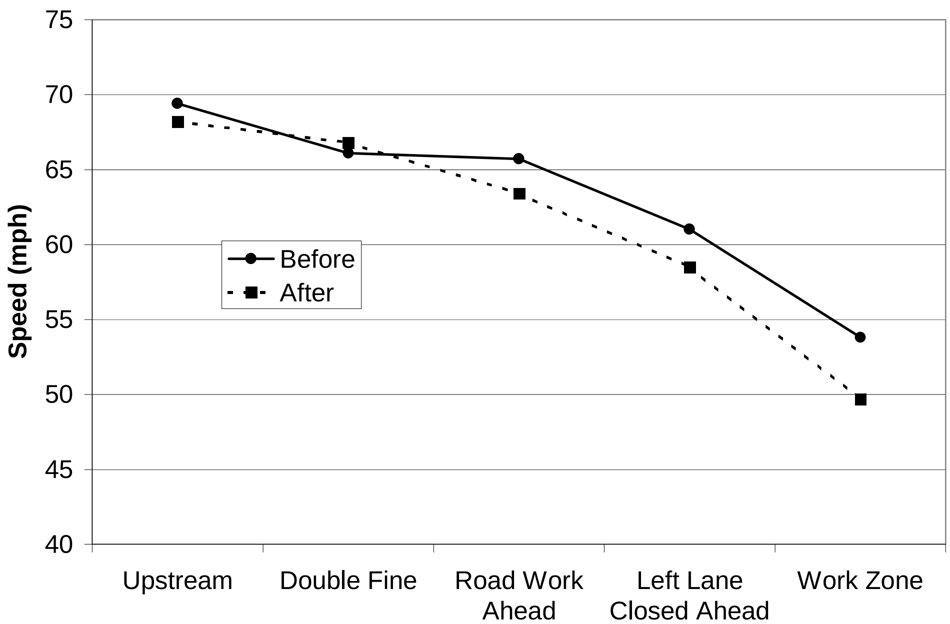
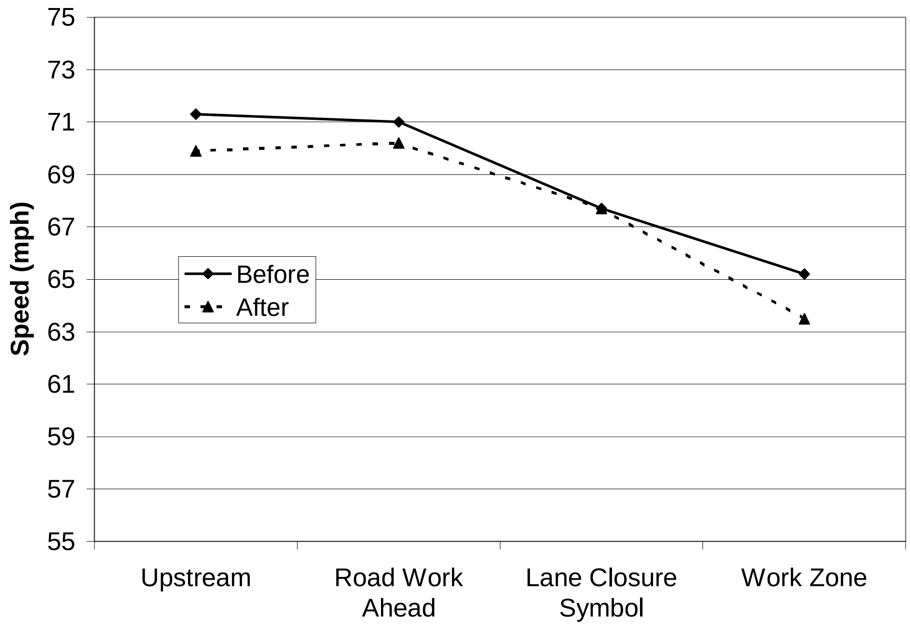
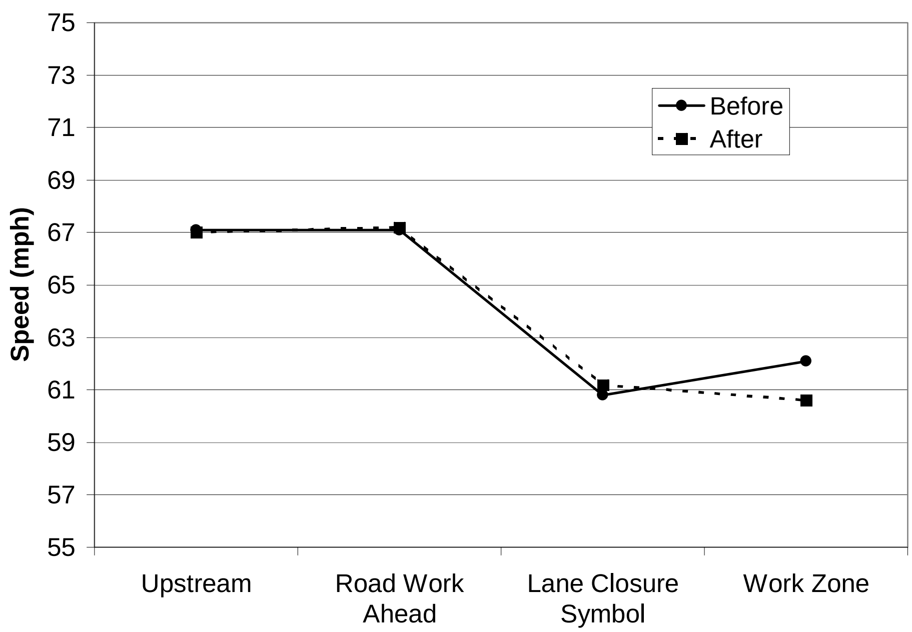


Figure D-3. RS3 Counter Speeds for (a) Cars (b) Trucks.

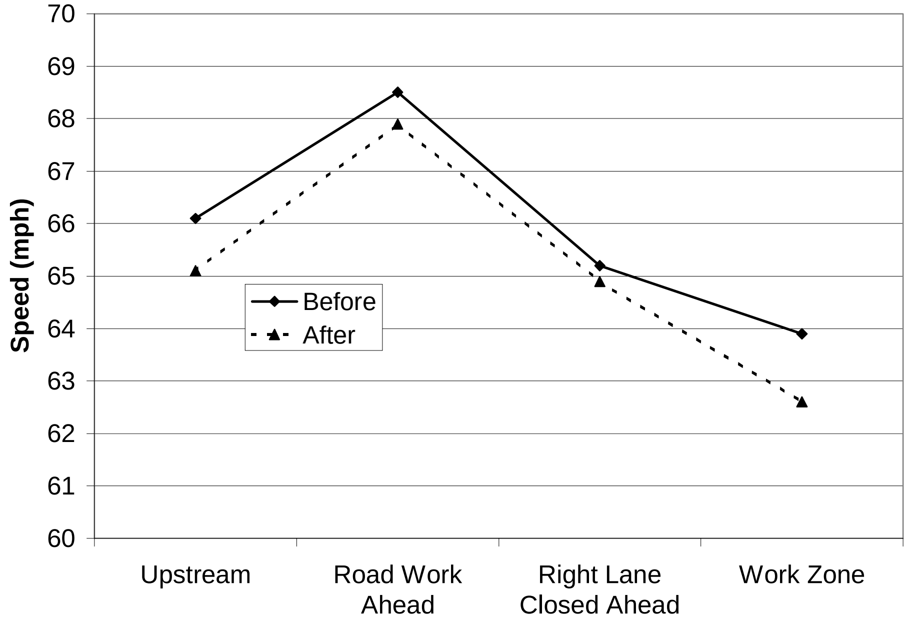


(a)

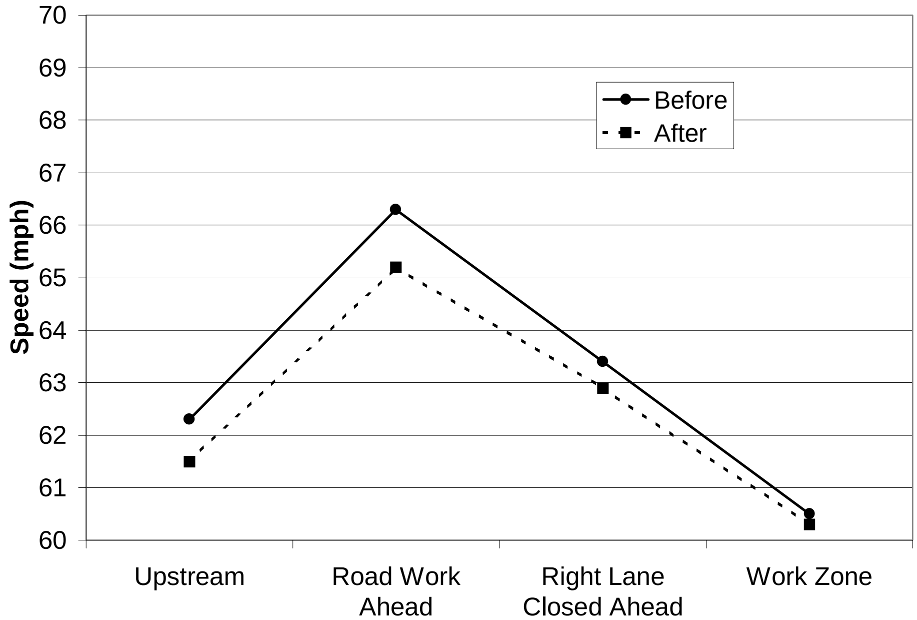


(b)

Figure D-4. VMS1 Counter Speeds for (a) Cars (b) Trucks.

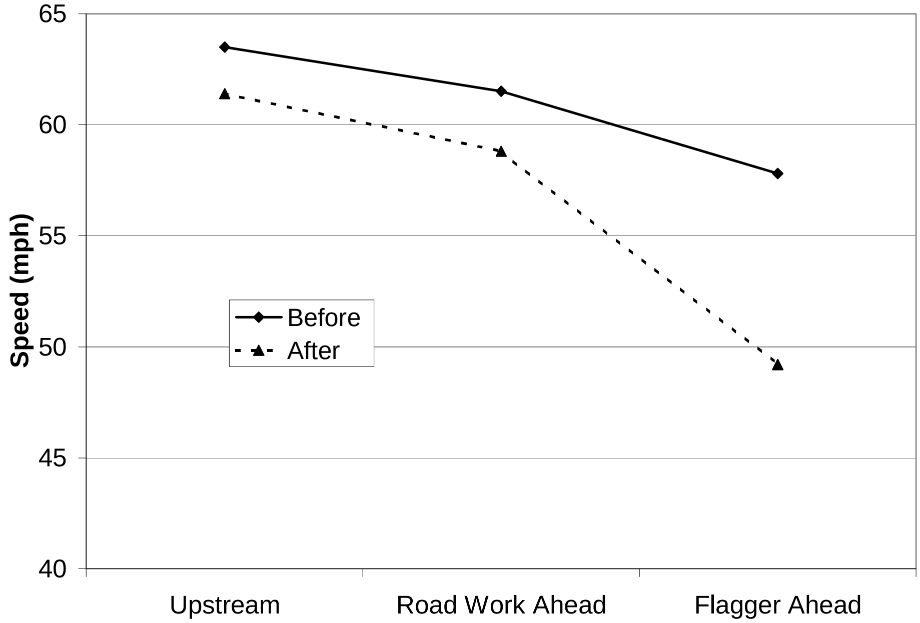


(a)

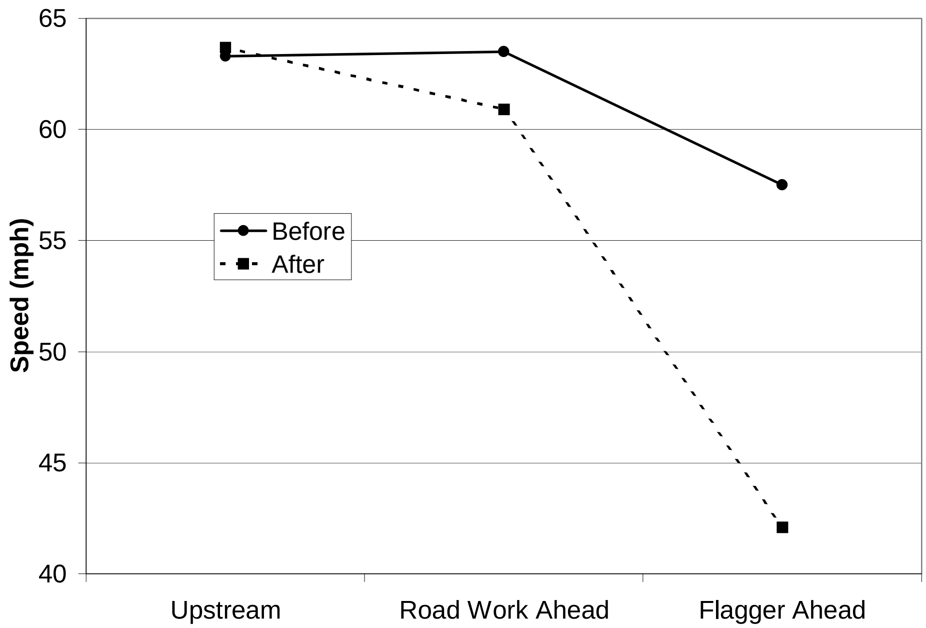


(b)

Figure D-5. VMS2 Counter Speeds for (a) Cars (b) Trucks.

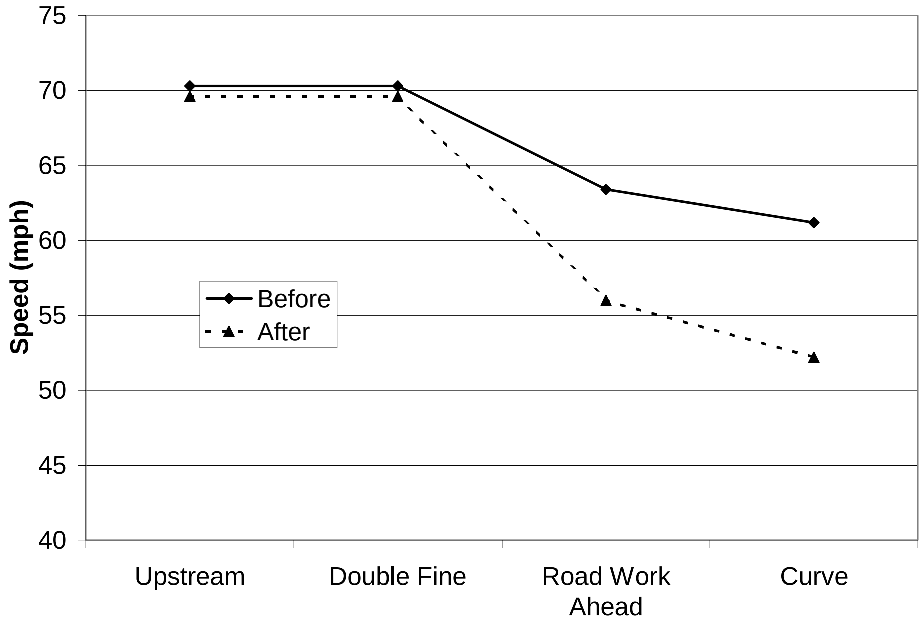


(a)

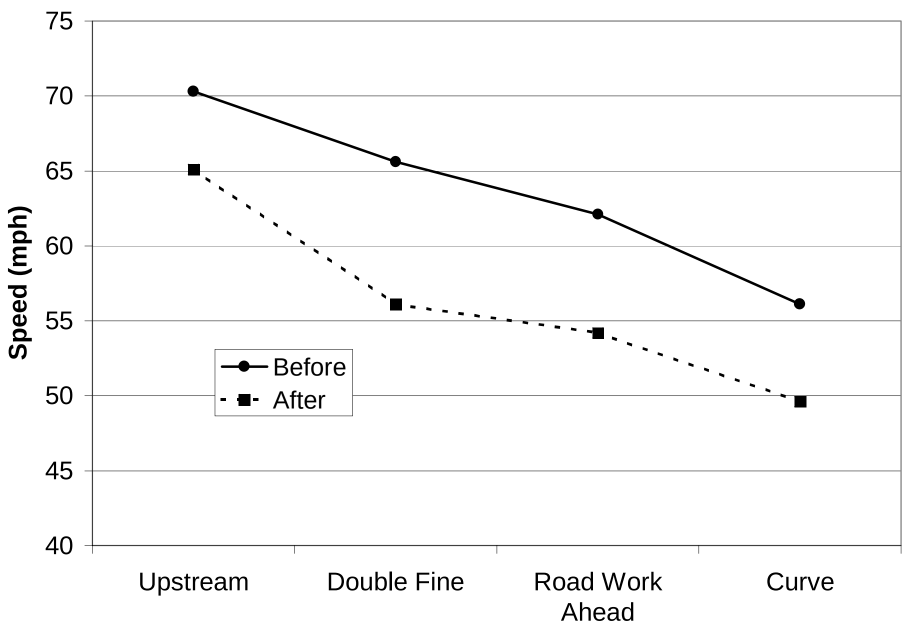


(b)

Figure D-6. RD1 Counter Speeds for (a) Cars (b) Trucks.

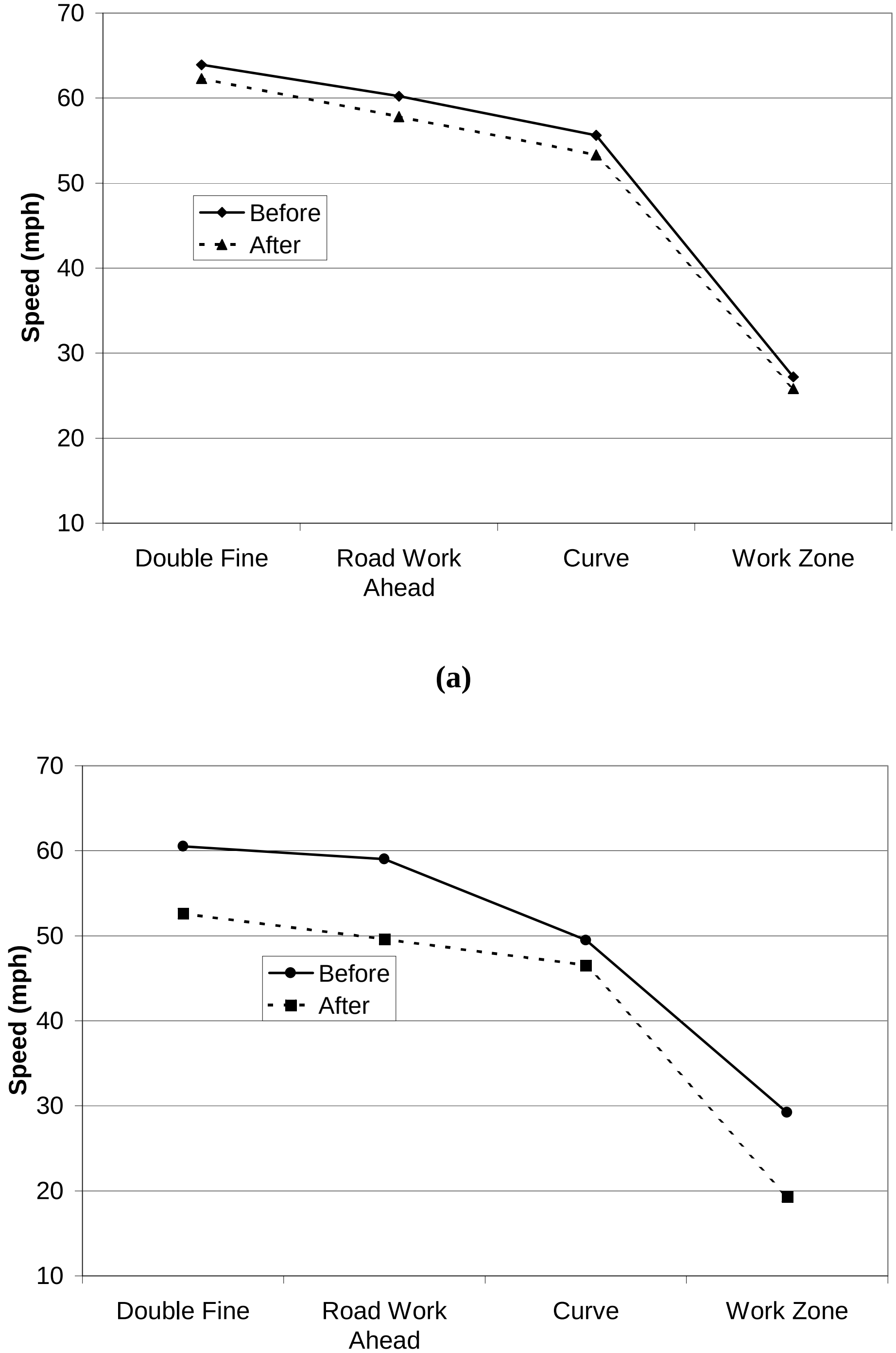


(a)



(b)

Figure D-7. SD1 Counter Speeds for (a) Cars (b) Trucks.

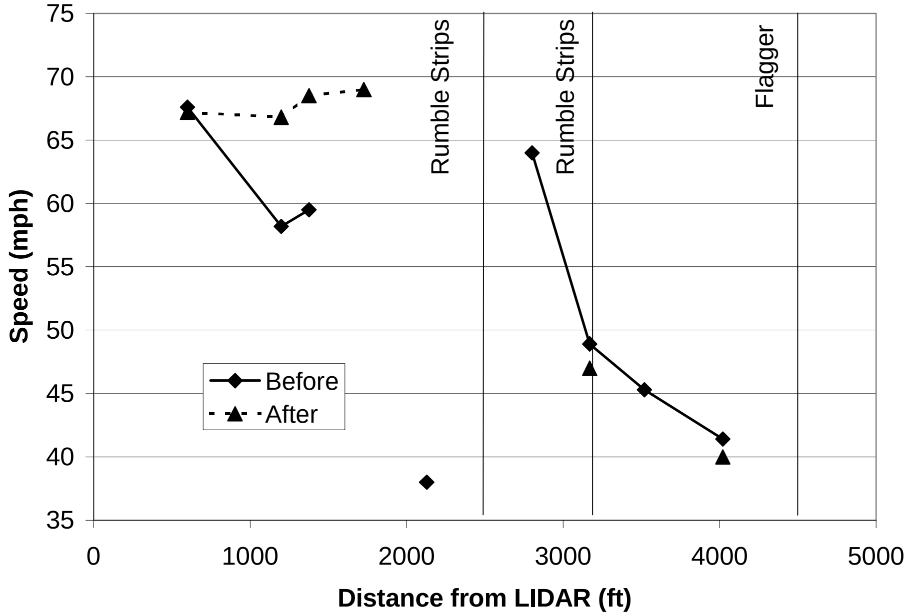


(a)

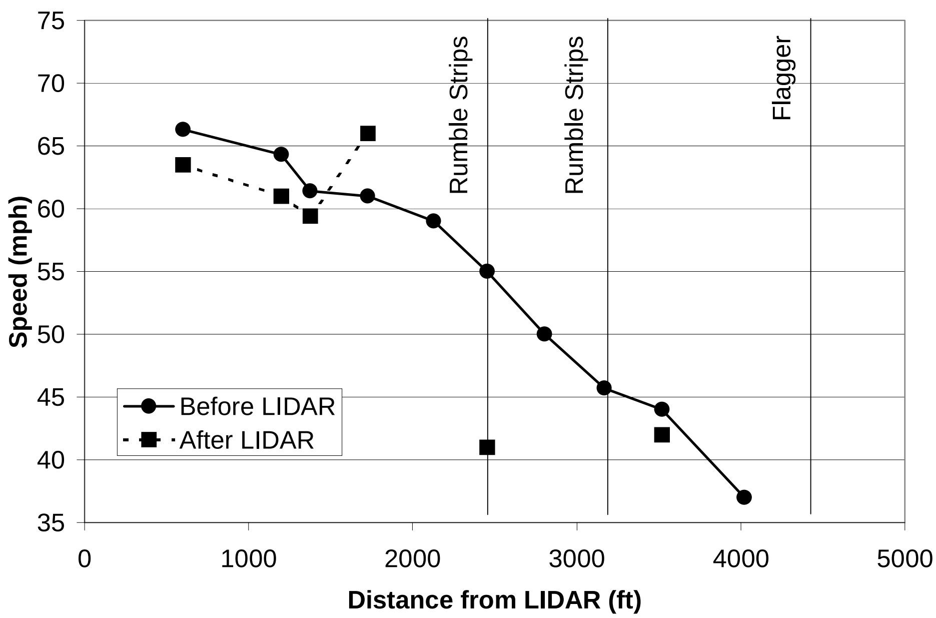
(b)

Figure D-8. SD2 Counter Speeds for (a) Cars (b) Trucks.

APPENDIX E
LIDAR SPEED PROFILES

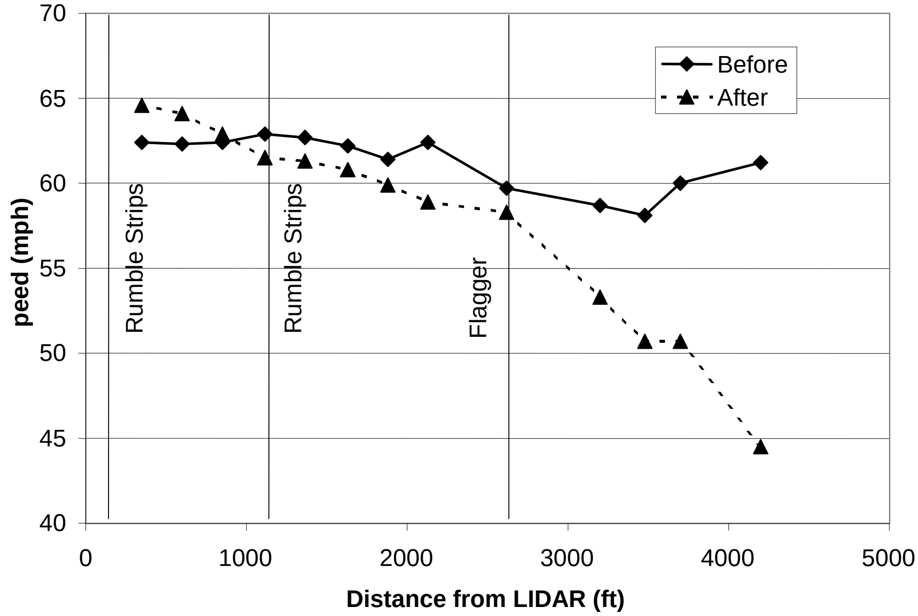


(a)

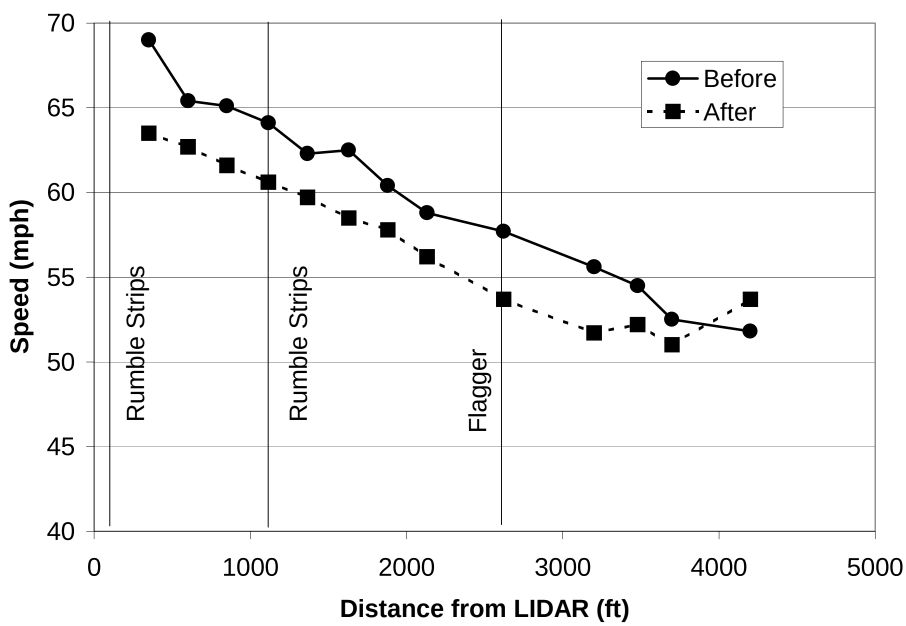


(b)

Figure E-1. RS1 LIDAR Speeds for (a) Cars (b) Trucks.

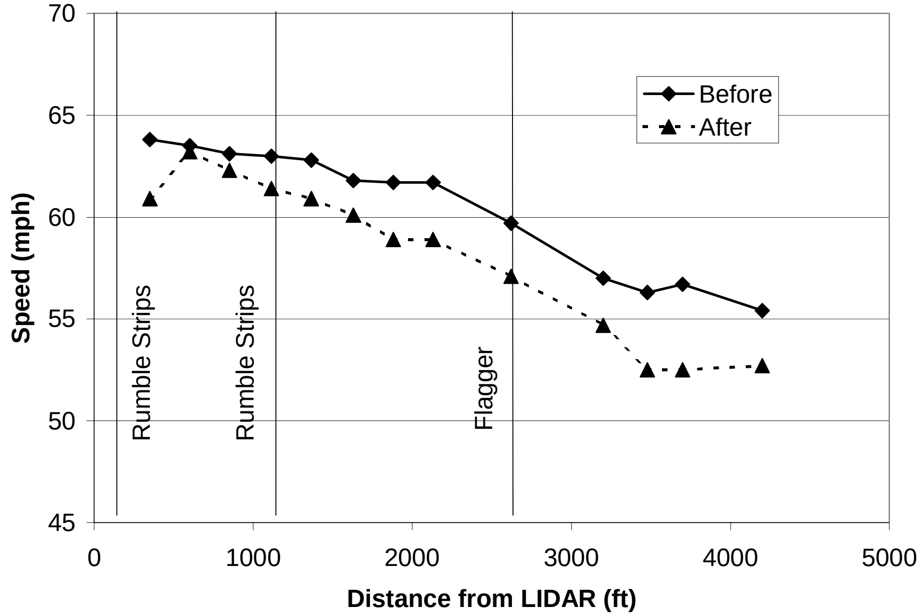


(a)

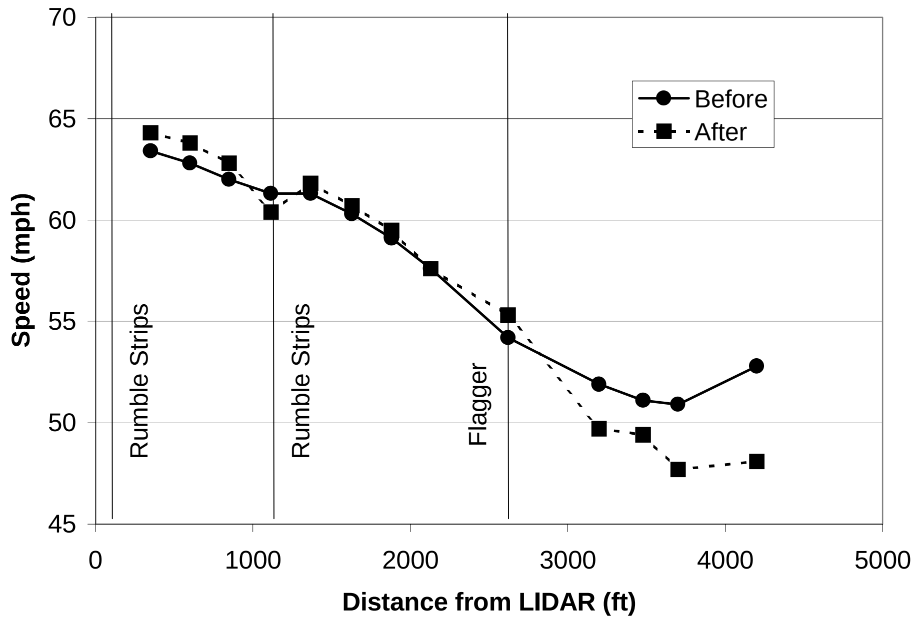


(b)

Figure E-2. RS2 LIDAR Speeds for (a) Cars (b) Trucks.

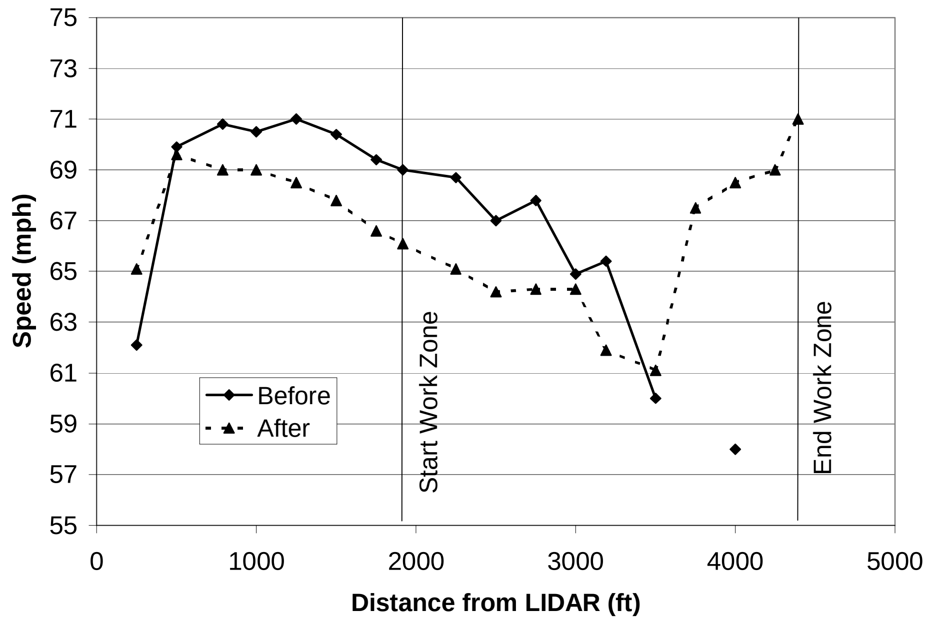


(a)

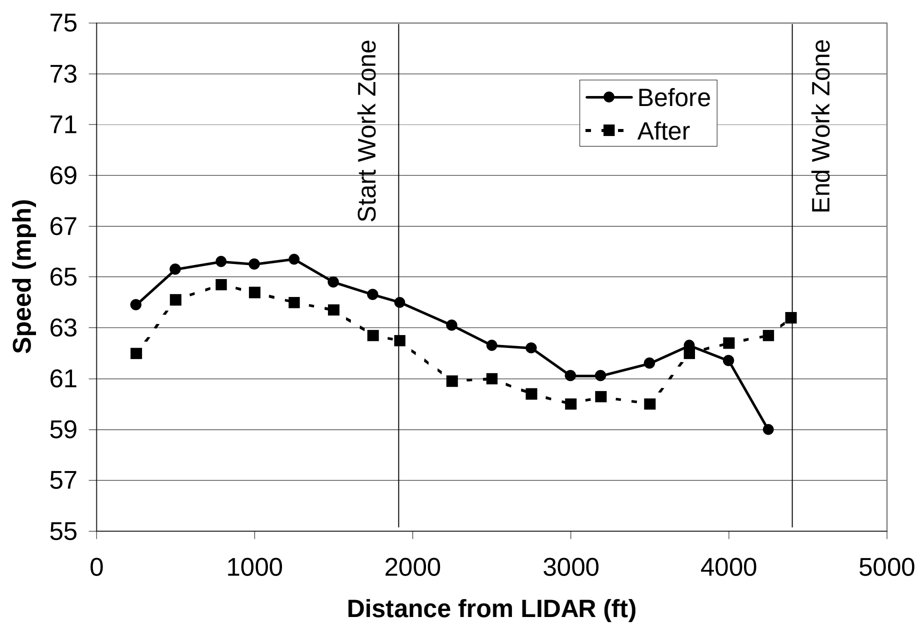


(b)

Figure E-3. RS3 LIDAR Speeds for (a) Cars (b) Trucks.

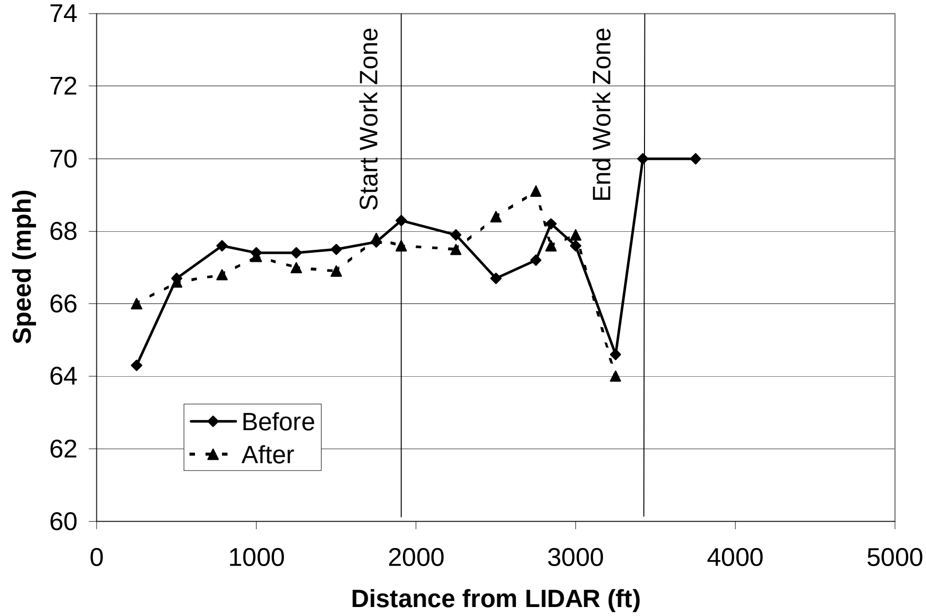


(a)

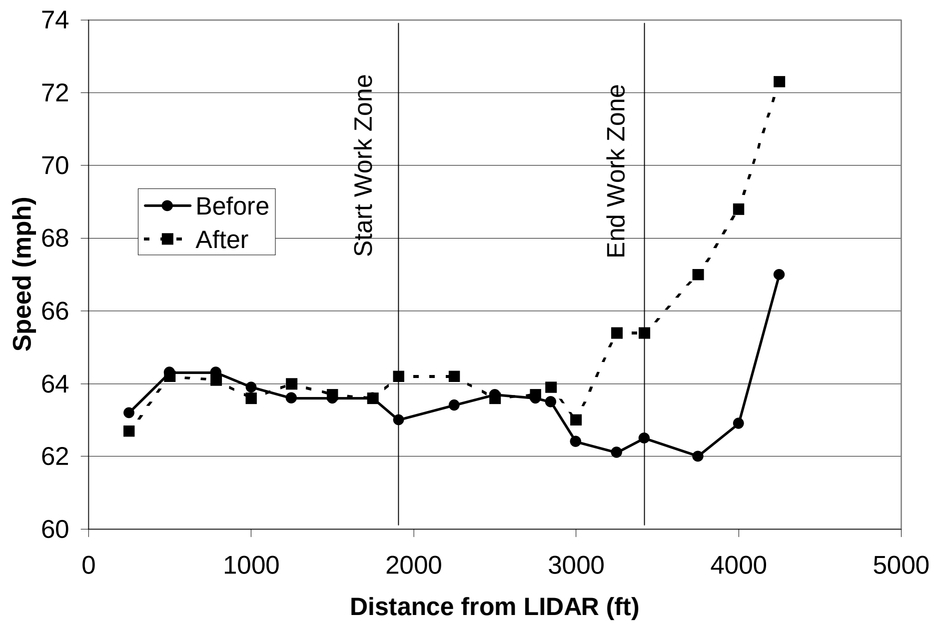


(b)

Figure E-4. VMS1 LIDAR Speeds for (a) Cars (b) Trucks.

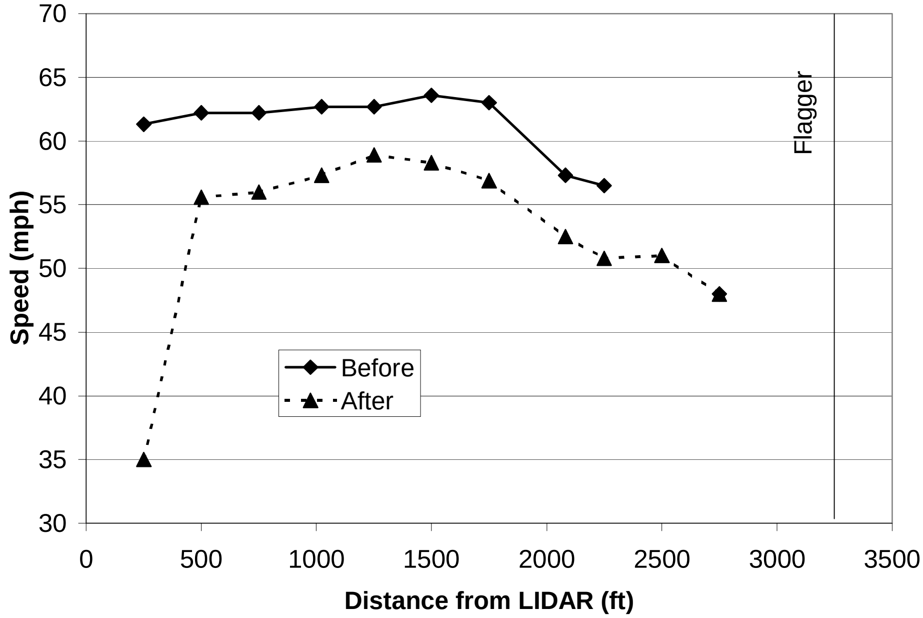


(a)

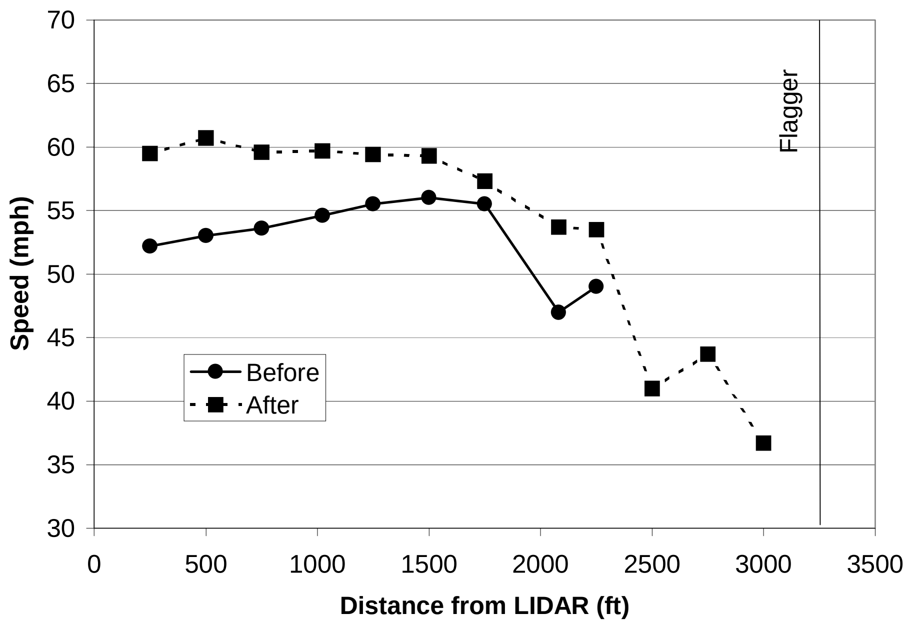


(b)

Figure E-5. VMS2 LIDAR Speeds for (a) Cars (b) Trucks.

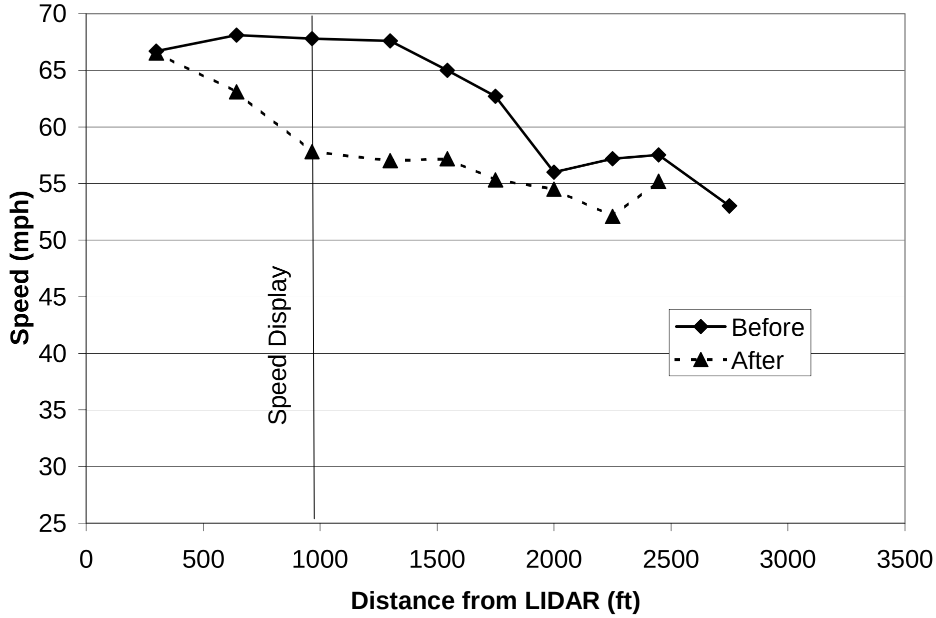


(a)

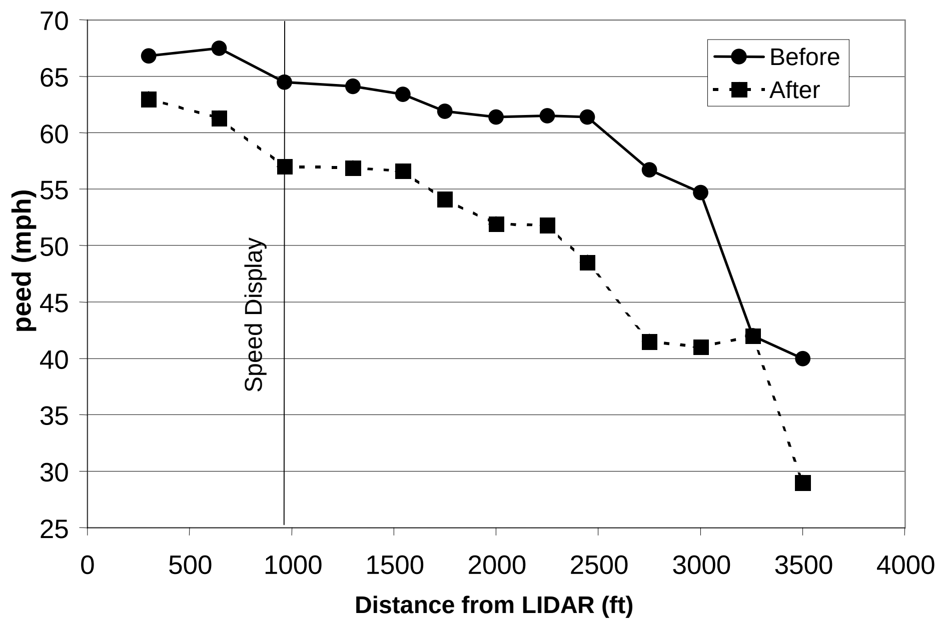


(b)

Figure E-6. RD1 LIDAR Speeds for (a) Cars (b) Trucks.

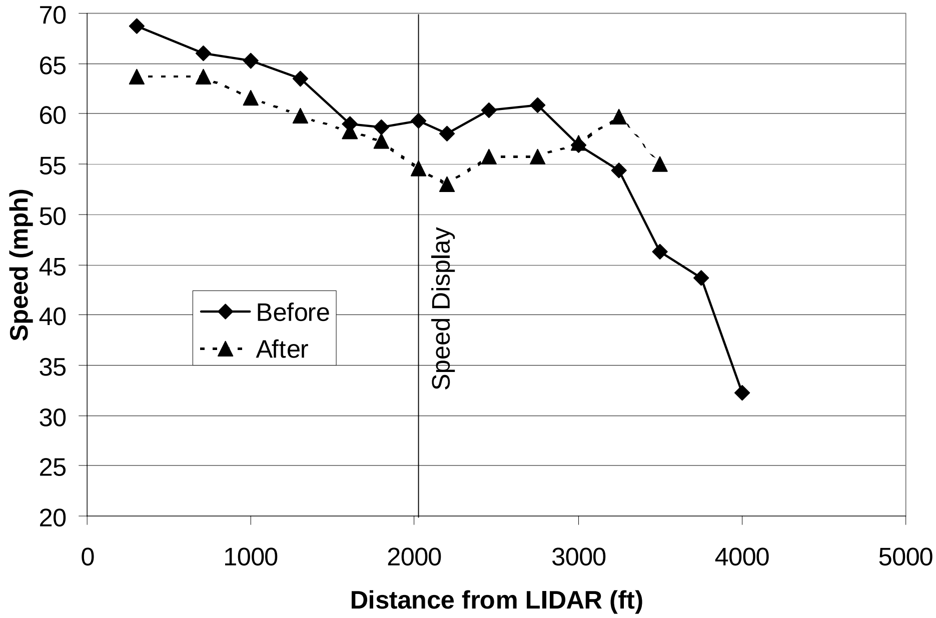


(a)

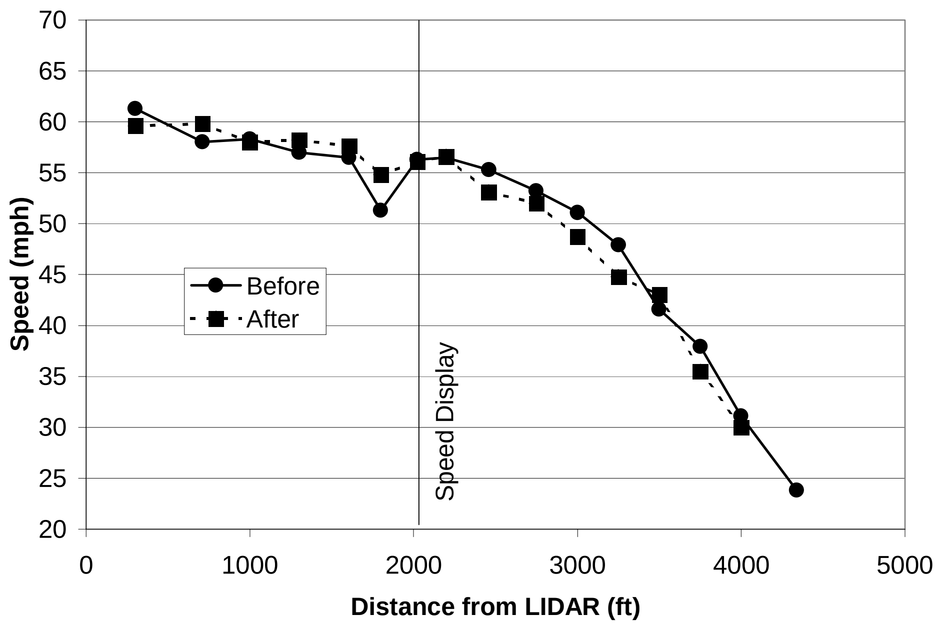


(b)

Figure E-7. SD1 LIDAR Speeds for (a) Cars (b) Trucks.



(a)



(b)

Figure E-8. SD2 LIDAR Speeds for (a) Cars (b) Trucks.

APPENDIX F
PERCENT OF VEHICLES EXCEEDING SPEED LIMIT

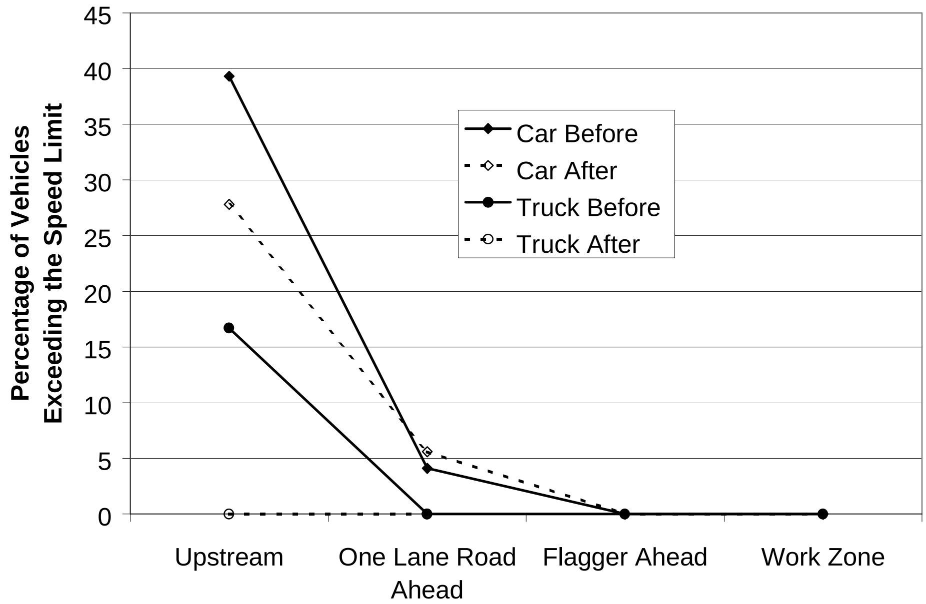


Figure F-1. Percent of Vehicles Speeding at RS1.

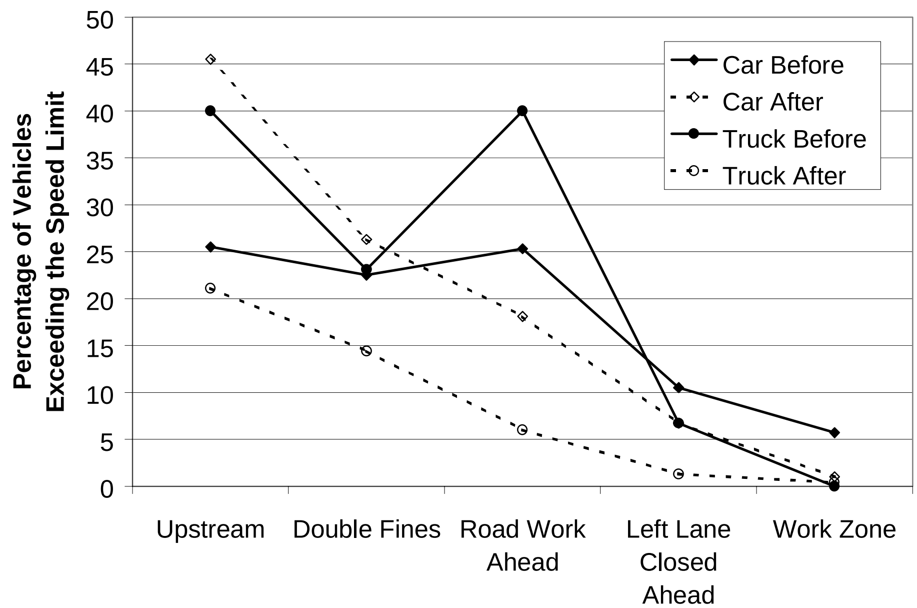


Figure F-2. Percent of Vehicles Speeding at RS2.

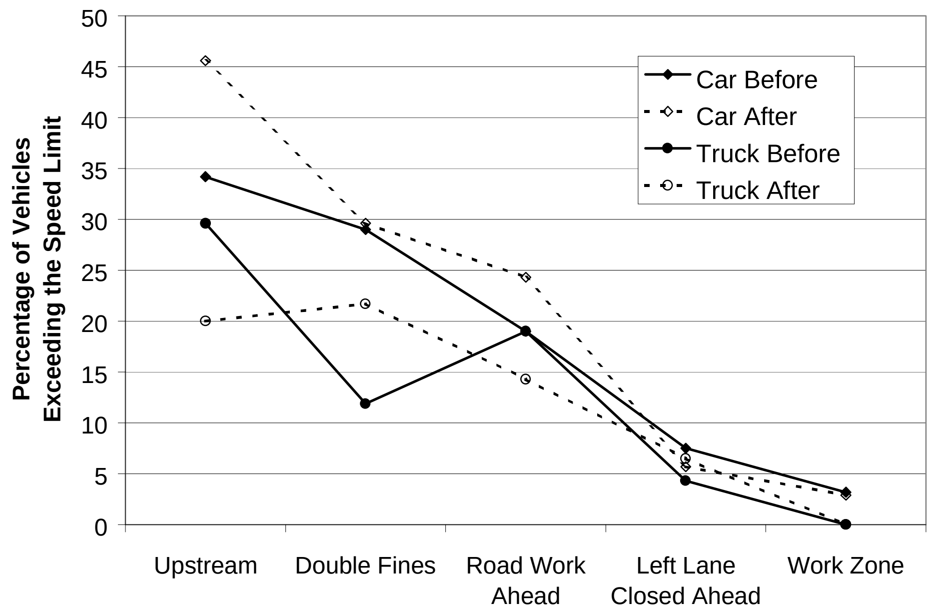


Figure F-3. Percent of Vehicles Speeding at RS3.

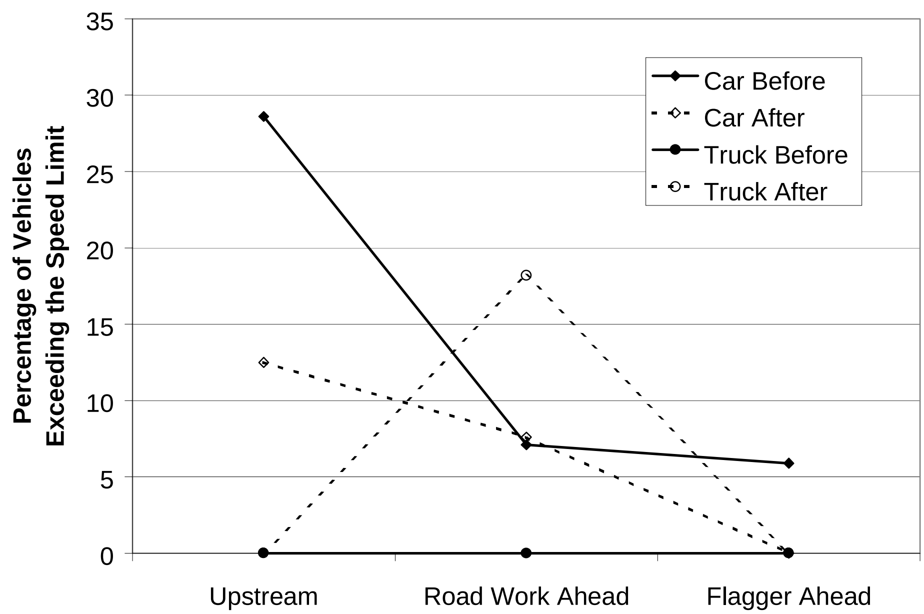


Figure F-4. Percent of Vehicles Speeding at RD1.

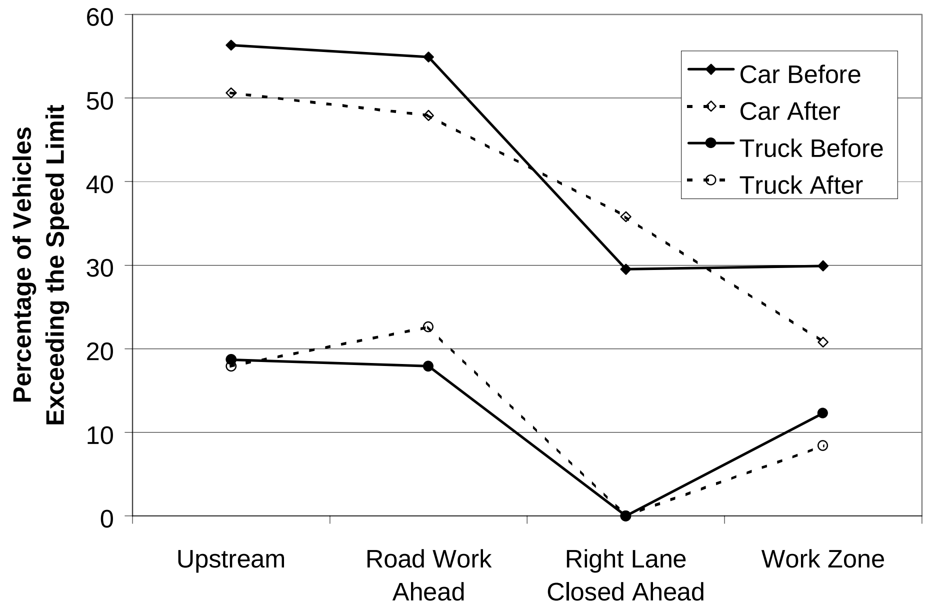


Figure F-5. Percent of Vehicles Speeding at VMS1.

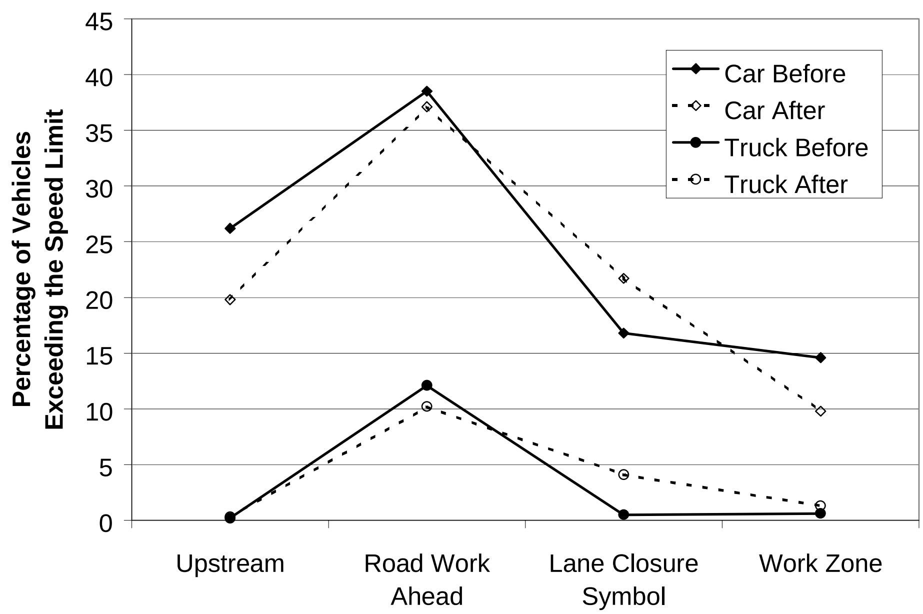


Figure F-6. Percent of Vehicles Speeding at VMS2.

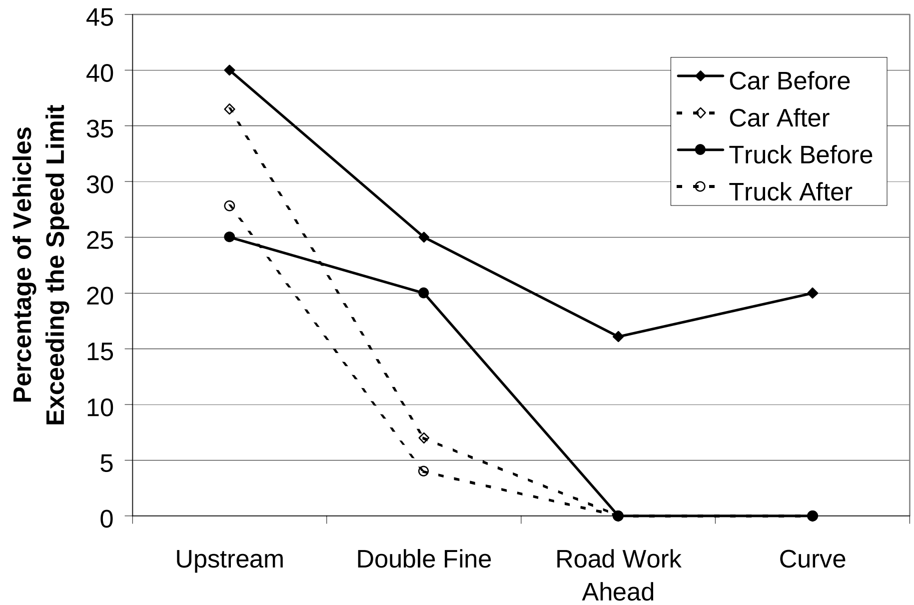


Figure F-7. Percent of Vehicles Speeding at SD1.

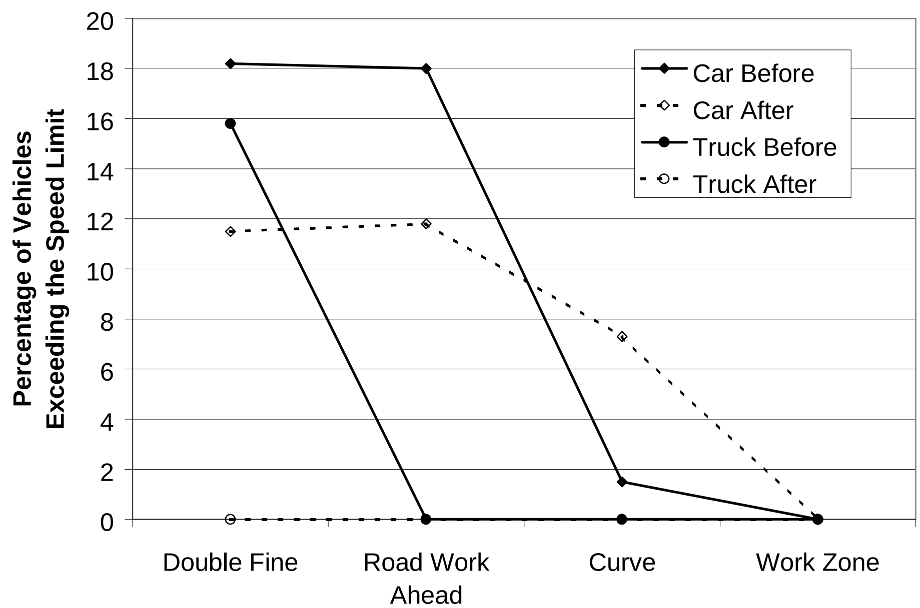


Figure F-8. Percent of Vehicles Speeding at SD2.