

# Better Management of Speed Control in Work Zones



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16. Abstract Statistics from the South Carolina Department of Transportation (SCDOT) for incidents between 1998 and 2002 reveal that a leading cause of crashes in work zones is driving too fast for conditions. In April 2005, a team of researchers led by Clemson University's Transportation Systems Laboratory embarked on research to better manage speed control in work zones. The research tasks included a literature review and survey of states. Based on the literature review and meetings with the project steering committee, a number of devices and strategies were selected for field evaluation. The devices selected were drone radar, changeable message sign with radar (CMR), a speed monitoring display (SMD) with CMS, portable rumble strips, and a novel speed activated sign designed by the researchers. Each of the devices had to be acquired and/or developed for this project and preliminary testing was conducted to identify an acceptable configuration for actual field data collection. After the initial testing, field surveillance of the speed management devices at a variety of different work zone sites on Interstate and State Route highways in South Carolina was done to collect the empirical data needed for evaluation. A statistical analysis of the empirical data was done to quantitatively evaluate the devices. A qualitative evaluation was done as well. Some of the devices were also studied in combination with police enforcement. The results of the analysis show that all of the speed control devices studied during this project has the capability of lowering speeds. This report summarizes the findings of this research and provides several recommendations in choosing a speed control device for a particular work zone application.					
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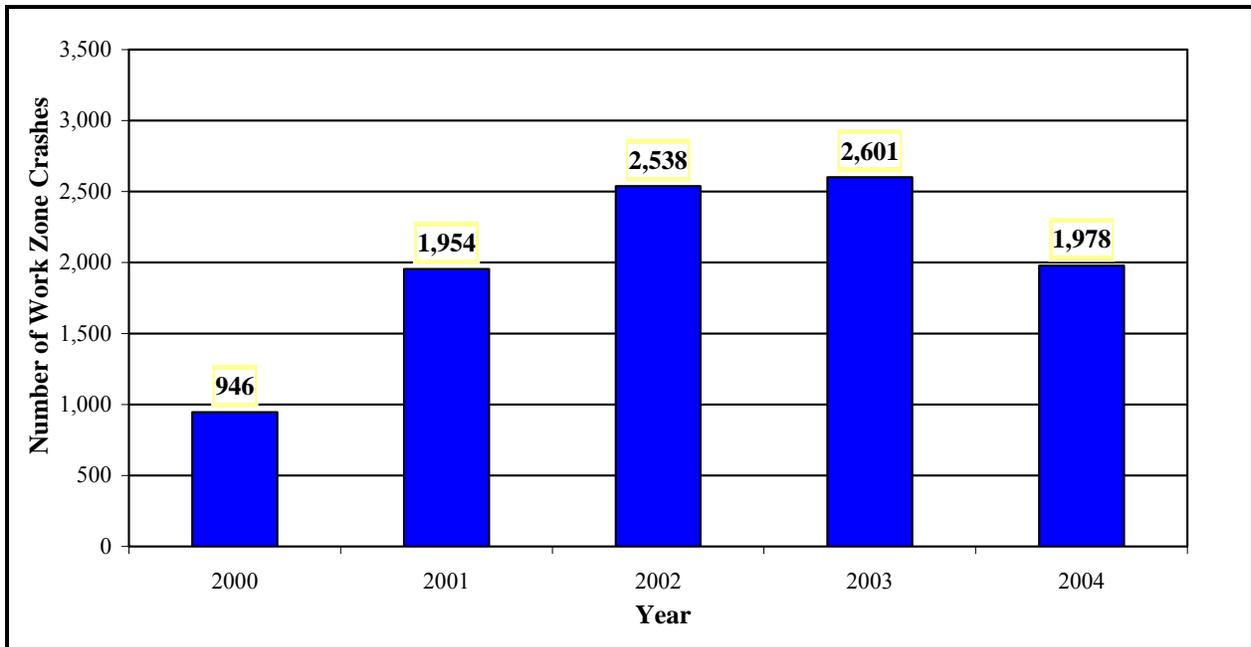
# CHAPTER 1

## INTRODUCTION

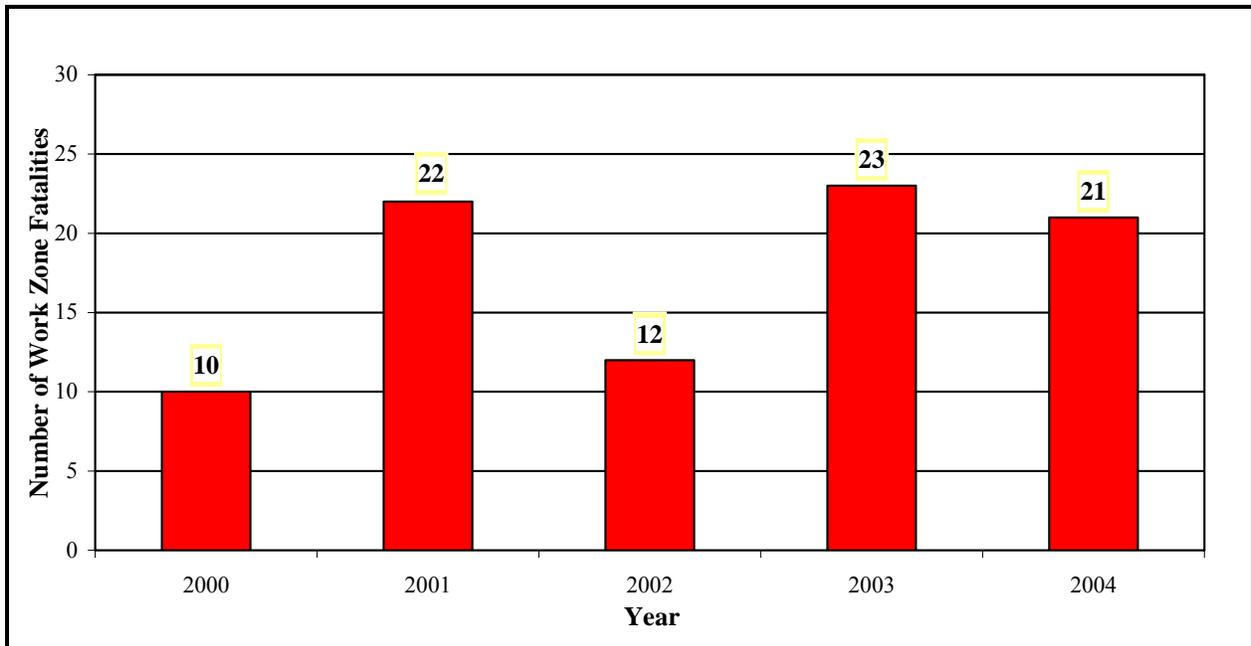
In July 1999, South Carolina leveraged bonds so that 27 years of maintenance and construction activities could be completed in just 7 years. During this time, the number of South Carolina work zone-related crashes and fatalities has been rising. According to statistics provided by the South Carolina Department of Transportation (SCDOT), the number of crashes in work zones has nearly tripled in recent years, increasing from 677 in 1998 to 2,601 in 2003 [1]. In all of these years, a leading cause of vehicle crashes was driving too fast for conditions. Due to this increasing amount of work zone crashes and fatalities in South Carolina, research into innovative ways to improve driver attention and reduce vehicle speeds in work zones has become a priority of the SCDOT.

For the past several decades, transportation agencies have taken different approaches to reduce speeds in work zones, including using traffic control devices, design alterations, and police enforcement. In 2005, South Carolina launched a “High Visibility Enforcement Campaign” for work zone safety. This campaign aimed to slow vehicles down through police enforcement. Previously, a similar program was implemented that may have contributed to the 25 percent decrease in work zone crashes in South Carolina between 2003 and 2004 as shown in Figure 1.1. In addition, Figure 1.2 shows the fatalities from work zone crashes by year, indicating that between 2000 and 2004, approximately 10,000 traffic crashes in work zones resulted in 88 fatalities [2]. Although it is generally agreed that law enforcement has the most significant effect in lowering speeds, this measure is often unavailable due to workforce limitations and cost [3].

Reducing the number of fatalities in work zones first requires changing driver behavior. Based on the data in Figure 1.2, which shows minimal variations between fatalities by year, the South Carolina Department of Transportation (SCDOT) acknowledges that motorists are paying little attention to specific advertisements such as signs saying, “Please slow down, my dad works here.” To address this issue, the High Visibility Enforcement Campaign encourages motorists to follow speed limits during preset times throughout the year called “Blitz Periods” during which police enforcement monitors these work zones and issues speeding fines with “zero tolerance.” [2]



**Figure 1.1 Work Zone Crashes in South Carolina 2000-2004 [3]**



**Figure 1.2 South Carolina Work Zone Fatalities 2000-2004 [3]**

Statistics from SCDOT for incidents between 1998 and 2002 reveal that the majority of work zone related crashes occurred due to driver inattention. The next five leading causes were:

1. Driving too fast for conditions,
2. Failure to yield to the right-of-way,
3. Following too closely,
4. Improper lane change, and
5. Driving under the influence of alcohol.

In April 2005, a team of researchers led by Clemson University's Transportation Systems Laboratory embarked on research to better manage speed control in work zones. Disregard for speed limits in work zones by motorists is a significant problem, not only in South Carolina but nationwide. As outlined in the original research problem statement, SCDOT is interested in developing methods for improving observance of posted speed limits by motorists traveling through work zones to include both construction and maintenance work zones on interstate and non-interstate routes.

Specifically, SCDOT intends that this project:

- Develop methods for reducing speed violations by identifying traffic control devices such as signing and pavement markings, use of radar activated speed signs, changeable message signs, drone radar units, Lidar units which are infrared laser speed detection devices, and any other technological developments that may assist to reduce speeding;
- Determine the current role of law enforcement in work zones and the effectiveness of current methods in enforcing speed limits;
- Determine new methods to better integrate law enforcement and traffic control devices and technology to reduce speed violations; and
- Identify methods for reducing speed violations in other states and the effectiveness of these methods.

The project included several work elements identified as follows:

1. Identify candidate management strategies to consider for field evaluation;
2. Conduct a literature search and survey of other states;
3. Finalize speed management strategies and develop an evaluation plan;
4. Perform field surveillance of speed management strategies at a variety of different work zone sites on Interstate and State Route highways to collect the empirical data needed to evaluate the various strategies;
5. Statistically Analyze the empirical data and identify a "best" combination of technology, traffic control devices, and law enforcement strategies for final evaluation;
6. Perform additional field surveillance and analysis; and
7. Document the findings in a final report.

This report summarizes the findings of this research.

## CHAPTER 2

### REVIEW OF LITERATURE

An initial phase of the project was to conduct a literature review to identify previous or ongoing research activities of a similar nature. This review encompassed a search of the Transportation Research Information Service (TRIS), web searches on the Internet, a review of various trade periodicals, and review of a number of technical reports and papers available to the authors. The purpose of the literature review was to explore how similar research has been conducted and how previous work may influence this research project. The results of the literature review are presented in the following sections.

#### *Traffic Calming by Reducing Lane Width*

Chicanes have been shown to be an effective traffic calming technique in neighborhood traffic calming applications. The work zone equivalent would be using narrower lane widths. The idea is that narrow lane widths require more of the motorists' attention and influence lower speeds. Studies in Houston, Texas reviewed the reduction of speed in work zones due to the effect of narrow lanes. The narrow lanes were not intentionally created to reduce speeds, as they were required by the scope of the project to create more space for the work zone. The data showed a decrease in average speed from 3 to 8 mph in this location. Richards, Wunderlich, and Dudek studied the effectiveness of lane reduction for 12.5 feet and 11.5 feet using cones in six work zones on Texas freeways. The study concluded that this measure achieves a 16 percent speed reduction. The reduction to a 12.5 foot lane width showed a speed decrease of 2.8 mph, while an 11.5 foot wide lane produced a decline of 3.8 mph. The study also noted that devices such as barrels or concrete barriers would be much more efficient and are likely to lower speeds even more. [4,5]

Although inexpensive and relatively easy to implement, narrowing lane widths can reduce roadway capacity. There is also a greater possibility of vehicles striking the cones or other devices, which could increase the number of crashes in these work zones. [6]

On the SCDOT research project, narrow lane widths were not studied, however narrow lane widths required by the work zone were noted during data collection.

#### *Drone Radar*

Drone radars have the ability to emulate radar frequency up to one mile. When detected by in-vehicle radar detectors, drivers are tricked into thinking police enforcement is ahead. Places where drone radars can be used to deceive drivers of police presence are in work zones, ambulances, school buses, unoccupied police cars, agricultural tractors, school zones, and even in neighborhoods. Some examples are shown in Figure 2.1.



**Figure 2.1 Drone Radar Mounting Examples [7]**

The drone radar devices currently on the market shown in Table 2.1 range from basic K-band displaying on a radar detector to ones equipped with a safety warning system (SWS) that voices words such as “Road Hazard Ahead” and/or “K-band”. Studies performed with either the basic drone radar or SWS have contributed to a decrease in speeds within work zones. The amount of reduction varies for these studies depending on the year performed. Prior to 1995, radar detector use was legal in the entire United States, making the drone radar more effective due to the high number of detection devices in the traffic streams. [7]

**Table 2.1 Drone Radar Manufacturers [7]**

<b>Name</b>	<b>Manufacturer</b>	<b>Band</b>
Radar Drone (Solar)	Hill County Research	K
Cobra XT 1000 (SWS)	Traffic Safety Technologies	K
RD-24T	Kustom Signals	K

Over the past twenty years, research conducted on radar devices has changed due to a series of laws passed by the Federal Communications Commission (FCC). A United States Department of Transportation (USDOT) and National Household Travel Survey (NHTS) directive authorized the use of drone radar in August 1991. The Commission continues to require that any radar units used in drone operation must be type accepted and licensed, by the Commission. [7]

The effectiveness of the drone radar in reducing speeding depends on the number of radar detectors in a traffic stream. According to SPEEDLABS.com, approximately 12 percent of tractor trailers still use the device even though radar detectors were banned in all commercial vehicles by all states in a USDOT directive in February 1995. Radar detector use in passenger cars is legal except in District of Columbia, the state of Virginia, and US Military installations according to the FCC. [7]

A second factor influencing the effectiveness of drone radar is the frequency used. The frequency bands assigned by the FCC for police enforcement includes X, K, and Ka. The X-band frequency, used in police radar guns, is one of the older signals; however, the commission allows many other uses of this band, for example, automatic door openers, burglar alarms, and vehicle braking systems, creating many false alerts for the driver’s radar detectors. As a result, the new technology in radar detectors today has made X-band drone radars obsolete due to the new frequency emitted by police radar guns. Today 97 percent of all police radar units emit Ka

or K-band. Of the fifty states, thirty-eight have contracts that mandate the use of the Ka-band. Only New Jersey still requires enforcement to use X-band. [7]

### Northern Kentucky Study

The first study involving the use of unmanned radar in work zones was conducted in 1986, when Pigman et al. attempted to improve the safety of Interstate 75 in northern Kentucky by using five unmanned radar units. Since drone radar was not authorized at this time, the study lasted only three months. Congress gave permission to proceed with the project in the late fall after the President signed the papers allowing further experiments. By 1987, nine radar units had been installed, equally spaced so that the radar emissions did not overlap. [8]

Although this study found that drone radar had a minimal effect on the mean speed of vehicles, it did reduce the speed of those exceeding the speed limit by 15 mph, and the 85<sup>th</sup> percentile speed. The variability of the traffic stream was minimized. When the drone radar was activated, vehicles traveled at more consistent speeds, leading to a safer work zone. The study concluded from visual inspection that 42 percent of tractor trailers and 11 percent of passenger cars were equipped with radar detectors and, on average, those with these devices decreased their speeds when the drone radar was activated. [8]

### Texas Study

Ullman, from the Texas Transportation Institute of Texas A&M University, experimented with different mounting techniques for the drone in 1990. The drone radars, which were placed on a sign, barrel, or railing at the beginning of each work zone studied, consisted of a microwave transmitter, a single on and off switch, and a battery installed in a small box. Each drone emitted a signal up to 2,000 feet upstream under ideal geometric conditions. Within each of the eight sites chosen for the study, the following three data collecting stations were used:

- Station 1, the control station, was located 3000 feet upstream from the work zone.
- Station 2, located 750 to 1,250 feet upstream from the beginning of the work zone, marked the location where the drone radar was first detected.
- Station 3, 2000 feet downstream from Station 2, verified if vehicles returned to normal speeds after radar detection.

At each station, speed data was recorded using a voice recorder to report vehicle descriptions. Additional data collected at the stations included vehicle conflicts, which were classified into four basic groups: severe braking, abrupt lane changes, accelerating around vehicles near the lane closure, and stopping or running off the road. [9].

Conclusions drawn from the data collected among the three stations indicated that, for the majority of the work zones, the mean speeds were reduced less than 2 mph when the drone radar was activated. Unlike for many work zone speed control studies, the standard deviation varied more in this study than when the drone radar was turned off. The variations in speeds represent an unsafe work zone environment. The study was consistent with others in its results, demonstrating that tractor-trailers exhibited a greater reduction in mean speeds than passenger cars. [9]

### South Dakota DOT Study

In 1992, the South Dakota Department of Transportation purchased Signal Pro 65 X-band drones from Kustom Inc., for 500 of the state's 602 vehicles. During the first half of the year, the drones paid for themselves through the savings in work zone incident and liability costs. Results from the research indicate that, while using these drones, South Dakota saw a 21.1 percent decrease in statewide crashes. The Director of Law Enforcement Training believes the drones could have had a greater impact on statewide crashes if they had implemented a K-band frequency rather than an X-band, as drivers associate the latter band as false alarms when their radar detectors are activated. [10]

### Champaign, Illinois Study

Benekohal conducted three experiments in a rural section of Interstate 57, south of Champaign, Illinois, in 1992. A K-band radar gun, which acts as a drone if continuously fired, was used to determine the long- and short-term effects of drone radar usage. In addition, CB radio was monitored in all three experiments to determine if the presence of the drone was communicated. The first experiment evaluated the immediate effects of a drone radar gun on vehicles traveling in and out of work zones. The second experiment evaluated the short-term effects of using a drone radar gun, and the third studied the long term effects by using two radar guns, so that the drivers could not determine the drone's position at different locations. [11]

The setup for all three experiments ranged from one to three stations. Data collection periods lasted less than one hour for experiments 1 and 2 while Experiment 3 involved three hours, but was divided into three intervals [11]. Depending on the study conducted, the following data collection stations were used:

- Station 1, the control station, was located outside the work zone.
- Station 2, a radar gun drone, was located inside the work zone, 2 miles away from Station 1.
- Station 3, a radar gun drone added for experiments 2 and 3, was also located inside the work zone, one mile away from Station 2.

Results from Experiment 1 showed a decrease in mean speeds from 8 to 10 mph, but this reduction may not be completely accurate for several reasons. At both stations, vehicles were exceeding the speed limit by 10 mph, making the drone radar guns more accurately resemble

police enforcement, leading to greater speed reductions. Other reasons for this significant reduction can be attributed to the short-time period and the small amount of tractor trailer data recorded. [11]

The results from Experiment 2 indicated that the drone radar guns had no effect on mean speed reduction over a 30-minute time period. The speeds actually increased during the period rather than decreasing because, as CB radio monitoring indicated, the tractor trailer drivers acknowledged the absence of police enforcement. An early tractor trailer driver is reported as saying, “My radar detector was going crazy but I slowed down; there is no one out here, I missed.” [11]

In Experiment 3, drivers were unable to determine the exact location of police presence with the two drone radar guns continuously firing. As a result, the mean speed in passenger cars was reduced by 3 mph and tractor trailers by up to 6 mph. The communications monitored from the CB radio users indicated that they paid more attention to their speeds in this situation than for Experiment 2, increasing the traffic safety in these work zones. [11]

### Maryland Study

In 1993 Teed et al. investigated the duration of speed reduction in a traffic stream, as well as the behavior of specific speeding vehicles, when exposed to police radar. Both experiments in this study were conducted during clear weather on a level section of Interstate 70 in Maryland. Again, CB radio monitoring on the 55 mph interstate allowed the research team to determine whether information about the police radar was being discussed. [12]

The first experiment was conducted on the eastbound section of Interstate 70. The speeds of the vehicles were measured using inductive loops, which categorized the data based on speeds and type of vehicles. The following five different conditions were examined:

- No police radar,
- Police radar located at inductance loops,
- Police radar one mile before the loops,
- Police radar two miles before the loops, and
- Police radar five miles before the loops.

These conditions were rotated every hour, with the police radar hidden and detected up to one mile upstream. Data collection occurred over a three-week period between 9 A.M and 5 P.M Monday through Thursday. [12]

Experiment 2 monitored specific speeding vehicles traveling on the westbound side of Interstate 70 at five different locations, with four of the locations positioned at inconspicuous places such as highway overpasses. Using undetectable radar guns that would not activate radar detectors, speeds were recorded at each location. Vehicles traveling 10 mph over the speed limit were recorded, and then, using little known CB radio frequencies, descriptions of the vehicles were radioed to the next downstream location. The second location used a radar gun device that recorded speeds and activated radar detectors as well. Vehicles that decreased their speed by

5 mph, or braked immediately after police radar was activated, were marked as using radar detectors. The data collection period for Experiment 2 lasted only four days rather than three weeks. [12]

Both experiments indicated that police-radar had an insignificant effect on vehicular speeds, with Experiment 1 demonstrating speeds decreasing after the first radar detection and later increasing as the vehicle progressed down the interstate. Tractor trailers had the largest reduction in speeds. Experiment 2 determined that 71 percent of the vehicles were traveling at least 10 mph over the speed limit. Of this 71 percent, the braking pattern of 44 percent suggests that these vehicles had radar detectors, with tractor-trailers being thought to have the majority. After one mile of radar exposure, 78 percent of the 81 vehicles with radar detectors were traveling at 5 mph over the speed limit, reinforcing that the effect of police radar is short-lived. [12]

### Missouri Study

In 1994, Freedman et al. studied drone radar in twelve construction and maintenance long-term work zones as well as high-crash locations in Missouri. All twelve interstate locations were selected based on level terrain and adequate sight distances, but locations varied in speed limits, which ranged from 55 to 65 mph. Eleven of the twelve sites had two lanes in each direction while one had three lanes per direction of travel. Data collection included one hour with the drone radar operating and one hour with it off. The drone radars, which were placed on the pavement edge of the road, were painted with camouflaged colors to avoid identification. [13]

Another method for avoiding detection involves the use of a commercially available laser speed measurement gun that eliminated the detection issues of previous studies. These guns gained popularity due to their accuracy in pinpointing one vehicle. Laser guns shoot a 3 milliradian beam of infrared light that diverges to only 9 inches, versus 159 feet with a radar gun; however, they take longer to retrieve a speed [14]. Speeds in the Missouri study were recorded at three different stations:

- Station 1 was placed 0.4 mile from the beginning of a lane closure.
- Station 2 was located downstream from Station 1, 0.2 to 0.8 miles out of the range of the drone.
- Station 3, 0.4 miles upstream from the drone.

Since identifying vehicles with radar detectors was not included in this study, the researchers used previous statistics from other studies to estimate the radar detector usage rate for each site. [13]

Results from the Missouri study demonstrated that the drone radar reduces mean speeds of all types of vehicles in rural and urban high-crash area interstates. Passenger vehicle mean speed reductions ranged from 3.4 mph in work zones with a maximum of 1.8 mph at high-crash locations. Tractor trailer speeds showed greater reduction in mean speed, 3.6 mph at work zones and 2.0 mph at high-crash locations. Tractor trailers also had a greater reduction in the number of vehicles exceeding the speed limit by 10 mph; however, this type of vehicle usually has a higher percentage of radar detector use. [13]

### New Mexico Study

The first study investigating drone radar after the use of radar detectors was banned in commercial vehicles and the state of Virginia, was conducted by Speed Measurement Laboratories between 1995 and 1998. This experiment involved using safety drone transmitters in construction and maintenance zones on Interstate 40 in New Mexico and Interstate 10 in Texas. The drones were mounted on arrow boards, construction barrels, and DOT vehicles. Speed Measurement Laboratories collected speeds for more than 40 hours, finding that tractor trailers reduced speeds from 3 to 4 mph, while passenger mean speeds decreased by approximately 2 mph. This study also involved the recording of CB radio conversations. This monitoring provided evidence that tractor trailer drivers were warning one another of possible police enforcement in the area. [10]

### University of Michigan Study

Streff et al., from the Transportation Research Institute at the University of Michigan, tested the effectiveness of drone radar, police presence, and the combination of the two in reducing speeds. This experiment tested the effect of speed reduction at four sites on two major freeways, Interstate 96 and US Highway 23, in Michigan. Each location had to be some distance from an on- or off-ramp, have open tangent sections to allow early detection with a radar detector, and, finally, the approach area had to be preceded by a hill or curve to block on-coming traffic from the drone radar signal. The site characteristics of the study included a high speed freeway with an AADT of 51,800 vehicles, with 4.7 percent being tractor trailers. Radar detector usage was determined using a radar detector detector (RDD) based on a VG-2 microwave receiver, manufactured by Technisonics Industries Limited. [15]

Three measures of speed were collected: the mean speed, the 85<sup>th</sup> percentile speed, and the vehicles exceeding the speed limit by 10 mph. Vehicle speeds were measured at three stations within each site. [15]

- Station 1 was upstream where drone radar as well as police enforcement could not be detected.
- Station 2 was positioned where both the drone and police enforcement could be detected.
- Station 3 was located approximately 3,400 feet downstream from the drone radar position to check to see if vehicles remained at constant speeds.

Radar detector use on the highway averaged 5 to 7 percent for both passenger cars and tractor trailers. Passenger cars alone ranged from 4 to 5 percent while tractor trailers varied between 16.5 and 19 percent during the day. At night, radar detector use rose to 28 percent for tractor trailers. This percentage of radar detector use led to a minor decrease in mean speed of less than 2 mph. This study found that the combination of drone radar and police enforcement had a positive effect on tractor trailer drivers. Specifically, tractor trailer drivers who were exceeding the speed limit by more than 10 mph decreased in the range of 30 to 70 percent. [15]

### Ohio Study

The 12th District of the Ohio DOT, in the Cleveland area, has used radar drones for nearly six years. These units have been mounted on portable changeable message signs and placed at some distance before the work zone to serve as a warning device. The idea of the advance placement of these drones was to alert commercial vehicles of the approaching work zone, which would influence an early lane change, thus reducing the speed of the traffic flow. The results show that the vehicle speeds decreased in the work zones, especially in hours of darkness. [6]

### Virginia Tech Study

A study conducted in 1997 by Turochy from Virginia Tech, with the help of the Virginia Department of Transportation, researched the effectiveness of unmanned radar and police enforcement presence at three work zones, with maximum speed limits of 55 mph, on Interstate 81. In Virginia, radar detector use is illegal, making this experiment unique because the effectiveness of unmanned radar depends on radar detector usage. The study measured the change in mean speed, standard deviation, percent traffic exceeding the speed limit, percent traffic 10 mph above the speed limit, and the 85<sup>th</sup> percentile speed. [16]

An estimated 15 to 25 percent of vehicles on Interstate 81 were equipped with radar detectors. The Virginia Department of Transportation purchased several unmanned radar units, a Checkpoint Model 2A by PM Design Lab of North Carolina. These types of drone radars emit X-band radio signals up to 2500 feet in each direction. During the study, the drone radar was mounted on either a metal guardrail, shown in Figure 2.2, or a metal sign post on the right shoulder of directional lanes at three sites.



**Figure 2.2 Checkpoint Model 2A Guardrail Installation**

All three work zone sites had lane closures with speed limits ranging from 55 to 65 mph. Data was collected at two stations, separated by 3000 feet, within each site [16].

- Station 1 was positioned several hundred feet upstream from the drone radar detection.
- Station 2 location was located 500 to 1000 feet into the radar detection area.

Conclusions drawn from the speed results indicate that drone radar reduced mean speeds from 0.8 to 2.3 mph. The percent of vehicles exceeding the speed limit reduced from 6 to 20 percent. The largest decrease was found in vehicles traveling at the 85<sup>th</sup> percentile speed. Standard deviations from the data generated by the use of drone radar decreased by 0.5 mph, increasing the safety of the work site. The combination of police enforcement and drone radar equated to a reduction in speeds ranging from 1.4 to 3.1 mph. [16]

### Georgia Tech Study

A newer device, called the Safety Warning System (SWS), which emits K-band and voices alphanumeric messages through radar detectors, was used in a study by The Georgia Institute of Technology Research Institute in 2001. Messages include “Road Hazard Ahead,” “Emergency Vehicle,” and “Train Approaching.” The two safety radars currently marketed are the Safety Alert from Cobra Electronics and the Safety Warning System (SWS) by MPH Industries [10]. The research compared the SWS to basic K-band drone radar. Its overall objective included proposing a methodology to qualify and quantify the reactions of radar detector-equipped vehicles to radar transmissions. [17]

The experiment consisted of three scenarios. The first measured speeds of vehicles with no radar activity. The second examined the basic drone radar while the third test studied the SWS type of drone radar. Data collection for all three scenarios was performed during the daylight hours of workdays over three weeks. The setup for each experiment consisted of three stations: [17]

- At Station 1, volumes were collected using road tubes.
- At Station 2, radar detector usage was determined using an RDD that took a picture of vehicles with radar detectors.
- At Station 3, either of the two drones was used and speeds were collected using a detuned radar gun, which could not be identified by radar detectors.

Results from this study show no significant decrease in speeds with either of the two drone radars activated. These results may be attributed to the 1 percent radar detector usage; however, the research did show that individuals equipped with radar detectors decelerated more in response to the SWS, as compared to the basic drone radar unit [17].

### Midwest Smart Work Zone Deployment Initiative Study

The most recent study, was conducted in 2002 under the Midwest Smart Work Zone Deployment Initiative. Speed Measurement Labs was hired to conduct a field investigation on the effectiveness of drone radars on speed reduction. Two drone radar units were placed at either end of a one-mile segment in an interstate work zone, which included 5 miles of roadway with an ADT of 18,000 and a speed limit of 60 mph during construction. Methods of collection entailed the use of pneumatic and automatic traffic recorders. Data collection consisted of four days before and after the deployment of drones. Between the two drones, the evaluation team collected speeds at ten different locations. Statistical measures of interest included mean speeds, 85<sup>th</sup> percentile speeds, and standard deviations [18].

Results from the experiment showed that the mean and 85<sup>th</sup> percentile speeds changed, but not consistently. The change in mean speeds was not statistically significant at the 95 percent confidence level, and, in the majority of the cases, mean speeds increased with the deployment of the drone radars. The data suggests that drone radars may reduce 85<sup>th</sup> percentile speeds near the devices, but the speeds increase as one passes the drone radar. Overall, the drone radar was seen as being an ineffective way to slow down drivers through work zones [18].

### *Summary of Drone Radar*

Twenty years of research has been conducted to determine if drone radar reduces vehicular speeds. Several studies choose to examine speeds before the drone radar detection, at the drone radar, and after detection to determine if the device has a lasting effect on speeds. The effectiveness of the drone radar is directly related to radar detector usage. A study performed by Pigman et al. included previously observed radar detector densities in a rural section of Kentucky that found 42 percent of tractor trailers and 11 percent of passenger vehicles were equipped with the devices [8].

In addition to radar detector usage rates, the type of frequency used and vehicle have an effect on the amount of speed reduction from drone radar. Most drivers associate K or Ka-band with police enforcement, where as X-band is normally an automatic door opener. Tractor trailer drivers use CB radio to relay messages pertaining to the drone radar, possibly verifying the absence of police enforcement.

The mixed results of drone radar indicate that there is a lot of variability in the experiments conducted. Clemson researchers believe that drone applications combined with other strategies offer good potential for reducing speeds. Drone units are relatively inexpensive—typically less than \$300 per unit. Discussion with one manufacturer gave insights about drone unit effectiveness. The manufacturer indicated that most trucks have radar detectors, making a truck act as a “pace car” which will lower overall speed. Higher success at night could be because of the higher percentages of truck traffic as well as the perceived difficulty in identifying the location of law enforcement. Clemson researchers conducted experiments with drone units in a variety of configurations on this project.

### ***Determining Radar Detector Usage***

In the past, radar detector usage was determined through visual inspection. Though seemingly simple, visual inspection, can be complex, if not impossible, depending on the type and speed of a vehicle. Tractor trailers often have multiple devices hanging from their front windshields, while the tinted windows of many passenger cars can seem virtually opaque. Even by visually spotting a radar detector, one cannot be certain the device is activated. Without a device to sense the radar detector, one cannot accurately determine the percentage of vehicles for a highway equipped with these devices.

In recent years, the development of the radar detector detector (RDD) has made it possible to detect vehicles possessing radar detectors illegally. The RDD works by detecting the local oscillator frequency leaked by a radar detector. The first RDD, manufactured by Kustom

Signals, Inc., operated using a VG-2 to search for leakage around 11.55 GHz. Radar detector companies responded by adjusting leakage frequencies to remain invisible to this RDD [14]. In 2002 a new RDD made in Australia, called the Spectre III, was able to detect all radar detectors until 2004. Some radar detectors, known as RDD detectors, have built-in sensors that shut off the device when a VG-2 is detected. Another RDD manufacturer from Hill County Research in Fredericksburg, TX, developed a model that uses a VG-4 frequency. The state of Texas purchased 185 of these RDD, shown next to the Spectre III in Figure 2.3, for its commercial enforcement officers. [14]



**Figure 2.3 Spectre III and Hill County Research Radar Detector Detectors [7]**

Using all three types of RDD, Speedzones performed tests to determine which one was the most effective. The test included police vehicles traveling at 30 mph, a half mile upstream from the RDD. Once the radar was detected, the vehicle was told to stop. Averages of the distance to detection were recorded using multiple types of radar detectors. Table 2.2 shows the results from these tests [14]:

**Table 2.2 Radar Detector Detector Tests [14]**

<b>Detector</b>	<b>VG-2</b>	<b>VG-4</b>	<b>Spectre III</b>
Cobra 9700	Not Detected	722 feet	917 feet
Cobra 9400	Not Detected	1,019 feet	946 feet
Bel 895	Not Detected	Not Detected	1,131 feet
Bel RX 65	Not Detected	Not Detected	517 feet
Bel Vector 995	Not Detected	Not Detected	426 feet
Passport X50	Not Detected	Not Detected	954 feet
PNI RW 3000	Not Detected	1,176 feet	1,362 feet
Valentine One	Not Detected	Not Detected	166 feet
Whistler 1788	1,237 feet	1,315 feet	1,321 feet
Whistler 1776	1,237 feet	335 feet	485 feet
Whistler 1778	1,391 feet	470 feet	1,362 feet

*Insurance Institute of Highway Safety*

The Insurance Institute of Highway Safety developed a type of RDD, called the VG-2 Interceptor, to determine the radar densities of commercial trucks. The Institute’s findings show that 56 percent of the tractor trailers were equipped with radar detectors. Another study tested for radar detector densities on four interstate sections in the states of Maryland and Virginia.

The research concluded that 5 percent of passenger cars and light trucks had radar detectors, while 24 percent of tractor-trailers carried these devices. [19]

Georgia Institute of Technology Research Institute

A study performed by the Georgia Institute of Technology Research Institute (GTRI) in 2000 used an RDD to determine the radar detector use on Georgia highways. The researchers examined three sites in the Atlanta metro area: a rural two-lane road, a four-lane state route, and a six-lane interstate. The GTRI developed a unique VG-2 RDD, capable of storing data to a computer and taking pictures of each car detected to help check for interference if detection occurred accidentally in the opposing lanes of traffic. Data collection lasted over a period of 9 days, with each site being studied approximately one third of this time. Data was collected only during the daylight hours of workdays. Traffic counts for the site were determined using PEEK Video Trak where volumes and vehicle types could be classified. The radar use statistics found by the study are shown below in Table 2.3. [20]

**Table 2.3 GTRI Overall Radar Detector Densities [20]**

	<b>Passenger Cars</b>	<b>Light Trucks</b>	<b>Tractor Trailers</b>	<b>Total</b>
<b>Rural Route Site</b>				
Volume	1574	1779	68	3421
# of Detections	25	19	0	44
% Detection	1.59%	1.07%	0.00%	1.29%
<b>State Route Site</b>				
Volume	6618	7679	1574	15871
# of Detections	98	158	32	288
% Detection	1.48%	2.06%	2.03%	1.81%
<b>Interstate Site</b>				
Volume	11994	12430	7429	31854
# of Detections	322	467	401	1190
% Detection	2.68%	3.76%	5.40%	3.74%
<b>All Sites</b>				
Volume	20186	21888	9071	51146
# of Detections	445	644	433	1522
% Detection	2.20%	2.94%	4.77%	2.98%

Table 2.3 indicates that tractor trailers are more likely to be equipped with radar detectors than passenger cars and light trucks; however, the total percent detection for all three types of vehicles consists of only about 3 percent of the roadway traffic. This low percentage of radar detector usage makes the drone radar technique ineffective in decreasing the mean speeds on highways; however, more detailed research needs to be conducted to determine if individual vehicles equipped with radar detectors reduce speed significantly, in rural and interstates work zones for both day and night time conditions.

## *Changeable Message Signs*

Changeable Message Signs (CMS) are control devices that give drivers up-to-date information about the current driving conditions. They have been in use for decades and exist in two forms: portable and permanent. Permanent changeable message signs are often fixed along or above roadways and relay information pertaining to roadway conditions, travel times, and special events. Portable changeable message signs are most often found in work zones, providing special instructions, warnings, or other information to motorists. A CMS can take the place of static signage along work zones where a sign needs to be more clearly seen or where changes occur frequently. Many DOTs use these signs to warn drivers of an approaching work zone by displaying short messages such as “SPEED LIMIT 45 MPH, WORK ZONE AHEAD.” These message signs can also convey, or at least emphasize, special safety information.

Benekohal and Shu’s research found that displaying messages such as the one mentioned above caused a decrease in speed near the CMS of 2.8 mph for trucks and 1.4 mph for cars [21]. Their research also concluded that vehicles traveling over the speed limit were reduced by 20 percent. Other studies by Richards and Hanscome found that the implementation of a CMS in advance of work zones reduced speeds up to 3 mph and 7 mph, respectively.

## *Speed Monitoring Display*

Speed monitoring displays (SMD) are usually stand alone units that can be placed individually or in a series. They consist of a trailer unit equipped with a radar device to determine the speeds of approaching vehicles and a display board that uses large numbers to display those speeds to approaching drivers. This type of reduction measure assumes that drivers will slow down to an acceptable speed level once they are aware of the speed at which they are traveling. Similarly, some LED speed display panels can be set to flash when speeds exceed a certain threshold. Some states utilize this type of device with a camera system for automatic enforcement. One particular drawback of this type of unit is that some drivers may intentionally exceed the speed limit to test both the radar and their vehicles. Figure 2.4 shows an example of a speed monitoring display [22].



**Figure 2.4 Speed Monitoring Display [22]**

### South Dakota Study

Dr. Patrick McCoy conducted research through the South Dakota Department of Transportation on speed display units in South Dakota work zones [23]. The speed display tested was a display unit mounted on a trailer, with an attached work zone advisory sign that the South Dakota DOT manufactured. The study team tested two units, both positioned 310 feet in advance of the first taper. Speed data was collected prior to the placement of the units and then again after the units were set up. The study concluded a mean speed reduction of 4 mph and 5 mph, for vehicles with two axles and vehicles with more than two axels, respectively. Researchers also noted that the study found a notable decrease in the number of vehicles traveling at excessive speeds at least 10 mph over the posted speed limit.

### Nebraska Study

Under the Midwest Smart Work Zone Deployment Initiative (MWSWZDI), Nebraska evaluated the long-term effectiveness of SMDs in long-duration work zones located in rural areas [24]. Researchers placed three SMDs in a work zone on Interstate 80, near Lincoln, studying the site for approximately 5 weeks. The SMDs had an LED numeric display that reported travel speed with an advisory sign and a message sign stating “YOUR SPEED.”

The researchers tested a four-lane divided interstate that drivers routinely used for passing maneuvers. Authorities considered speed compliance on this section to be a problem because most drivers accelerated well above the posted 55 mph work zone speed limit. Data were collected once before the SMDs were positioned and once per week for five weeks afterwards. The measures of effectiveness (MOE) defined by the researchers were as follows:

- Mean Speed,
- Standard Deviation,
- 85<sup>th</sup> Percentile Speed,
- Percent complying with speed limit,
- Percent complying with speed limit plus 5mph, and
- Percent complying with speed limit plus 10mph.

The analysis yielded improvements in all MOEs at sites downstream of SMDs. The improvements were 3 to 4 mph reductions in mean speed and 2 to 7 mph reductions in 85<sup>th</sup> percentile speed. A 20 to 40 percent increase in speed compliance was also recorded. The study team noted that 78 percent of traffic was non-commuter traffic and drivers may have been seeing the SMDs for the first time.

### Kansas Study

In Kansas, a data collection effort was conducted under the MWSWZDI [24]. Researchers collected one week of baseline data before deploying SMDs. The SMDs used were equipped with a strobe that activated when speeds exceeded a preset threshold. Immediately following the removal of the SMDs, Kansas Highway Patrol monitored the area.

The SMDs resulted in considerable reductions in mean speeds, 85<sup>th</sup> percentile speeds, and percent of drivers exceeding the speed limit. Researchers noted that the impact of law enforcement was almost identical to that of the SMD, however post law enforcement speeds increased to normal and, in some cases, exceeded baseline speeds.

### ***Changeable Message Signs with Radar***

A changeable message sign equipped with radar (CMR) is similar to the SMD in that it has the capability to determine the speeds of approaching vehicles. It processes the radar signal onboard, and, depending on the settings and detected speed, the device can display a variety of programmed messages. Typical default messages include:

- ACTIVE WORKZONE, REDUCE SPEED
- REDUCE SPEED
- RIGHT LANE CLOSED, KEEP LEFT

A secondary message that can be displayed when the threshold speed is exceeded is “YOU ARE SPEEDING, SLOW DOWN.” Typically, this type of sign does not display the actual speed of the approaching vehicle, but instead a message that alerts the driver of his speed.

A CMR has the potential to reduce the 85<sup>th</sup> percentile speed of passenger vehicles, decrease variability in speed, and reduce the number of speeders within work zones [25]. With the observed impact remaining consistent for at least three weeks, the use of these signs in a short-term work zone should maintain a speed lower than that observed without their presence. However, drivers do not maintain their reduced speed after passing such signs. This momentary reduction in speed makes this measure ineffective for long sections of roadwork. Even when using multiple signs, the effects continue to be localized to the placements of those signs. [26]

### **Virginia Study, 1995**

In Virginia, researchers determined that CMR setups in interstate highway work zones were more effective in reducing speeds than static signs approved by the Manual of Uniform Traffic Control Devices (MUTCD). The study team chose tests sites based on several predetermined site criteria. The criteria dictated a minimum work zone length of 1,500 feet, with 30 percent of the traffic considered free flowing. The work zone length governed the amount of space needed for a safe CMR setup. The overall objectives of the study were to:

- Determine mean speed and 85<sup>th</sup> percentile speed.
- Analyze success of CMR with speed reduction in work zones
- Analyze effect of CMR on driver behavior.
- Determine conditions where CMR works best.

The team recorded speeds at three locations within the work zone, including the beginning of the first taper, the middle of the work zone, and the end of the last taper. Additionally, the vehicles were video taped to record any changes in vehicle speeds and maneuvers.

The team examined the effects of the following four messages:

- YOU ARE SPEEDING, SLOW DOWN
- HIGH SPEED, SLOW DOWN
- REDUCE SPEED IN WORK ZONES
- EXCESSIVE SPEED SLOW DOWN

When comparing driver responses to each of these four messages, there is not a significant statistical difference in the ability of the messages to reduce vehicle speeds. The first, and most successful, message reduced the mean and 85<sup>th</sup> percentile speeds by 5 mph or more. In addition, the speed variance between drivers decreased. This message successfully singled out drivers, and the words “YOU ARE” conveyed the meaning that this message was not a general warning. The “HIGH SPEED” message returned nearly the same results as the “YOU ARE” message. [26]

The four messages examined produced speed reductions of 5 to 10 mph. In general, the CMR reduced the number of observed speeders by half. [26]

The team recommended that the threshold for activation of the message should be 3 mph above the posted speed limit. The vehicles that activated the message reduced their speeds an average of 15.3 mph, which caused the mean speed of the overall stream to decrease by 4 mph.

### Virginia Study, 1998

In 1998, Garber and Srinivasan, continued the 1995 study with more research of message content in the CMR over long term work zones [27]. This study differed from the 1995 study in that it added the effect of repeat drivers.

The research team took surveys at rest stops, on/off ramps, and commercial businesses in the area to determine approximate percentages of repeat drivers at the evaluation sites. The researchers were able to select three sites based on the surveys, two sites on Interstate 81 with 65 percent repeat drivers, and one section on Route 19 with 80 percent repeat drivers. Data was collected for 3 to 4 weeks at each site and the measurements were taken at three locations within the work zone, as in the 1995 study. The speed threshold was set at 3mph over the set speed limits of 55 mph and 45 mph on Interstate 81 and Route 19 respectively. The radar triggered the CMR message of “YOU ARE SPEEDING, SLOW DOWN.” The CMR produced speed reductions of 8 to 9 mph and notable responses from all vehicles. The 95 percent confidence intervals for speed reduction at the sites ranged from 4.8 to 11.6 mph. Average speeds and 85<sup>th</sup> percentile speeds decreased at all sites. [27]

### South Dakota Study

Wertjes studied the CMR in work zones in South Dakota in an effort to identify a speed monitoring display suitable for interstate work zone activities [5]. Wertjes’s study team concentrated heavily

on different types of equipment combinations in terms of their power source, structure, communication features, and cost effectiveness. The device deemed most appropriate was a Lidar Laser radar mounted on a CMS. When approaching vehicles exceeded 70 mph, the radar triggered the CMR to change from “RIGHT LANE CLOSED, KEEP LEFT” to “YOU ARE SPEEDING, SLOW DOWN.”

The unit was tested in short-term work zones and 24 hours of data was collected before and after the unit was implemented into each work zone. The data showed that the CMR was activated by approximately 20 percent of approaching vehicles. Speed reductions ranging from 0 to 1.7 mph were observed from the before and after studies and were deemed not significant. There was a substantial effect in the speed reduction of vehicles traveling at speeds greater than 70 mph in the before and after periods. Motorists traveling at speeds well over the threshold were influenced greatly by the CMR, and the 85<sup>th</sup> percentile speed decreased. The study team noted that a lower speed threshold set in the CMR could further reduce speeds.

### Georgia Study

A 1998 study funded by the Georgia Department of Transportation examined the impact of different messages on driver speeds for three consecutive weeks. The longer study period evaluated the novelty effect of the sign on drivers over time. Data were collected at stations located before, at, and after the sign. Speeds, volumes, and vehicle lengths were collected using Nu-Metrics Hi-Star portable traffic classifiers. At the sign location, speeds were reduced by 6 to 7 mph, but the reduction was not maintained throughout the work zone. The sign was set up 6 miles prior to the active area of the work zone, and no reductions were observed after the vehicles reached the work zone. This study recommended using a CMR near locations where a speed reduction is most needed. [28]

The CMR were set to display the message, “YOU ARE SPEEDING, SLOW DOWN NOW” for vehicles traveling 5 mph or more over the posted work zone speed limit of 45 mph. For vehicles traveling below 50 mph, the message displayed was “ACTIVE WORK ZONE, REDUCE SPEED.” Evaluation sites were based on crash fatality statistics and researchers found that the largest fatality rate was on rural non-interstate principle arterial construction zones. As a result of their findings, researchers chose a work zone on a two-lane rural arterial with adjacent construction.

CMR combined with speed monitoring is a relatively new innovation. There has only been limited research on its use, with the results being promising; long-term effects are still unknown.

### ***Vehicle Activated-Signs***

Vehicle Activated Signs (Figure 2.5), similar to changeable message signs with radar, are dynamic message signs that display a simple message corresponding to road conditions. Historically, these signs have been used to display speed limits, provide bend and junction warnings, and display safety camera information. The main assumption is that drivers are heavily influenced to decrease speeds when they are specifically targeted [29].



**Figure 2.5 Vehicle Activated Signs [29]**

### England Studies

In 1984, a research team tested speed limit warning signs and close following signs on arterial highways in Berkshire, England [29]. The team found the signs to be successful in reducing speeds even after vehicles had become accustomed to them. The analysis indicated a 50 percent reduction in accidents following the sign installation.

A similar study was undertaken a few years later in Warwickshire using the messages “TOO FAST” and “SLOW DOWN” [29]. Researchers noted that a statistical significant decrease in average speeds occurred over a 12-month period.

A 2001 study evaluated vehicle activated signs on rural two-lane roads in four England cities: Norfolk, Wiltshire, West Sussex, and Kent [29]. The research team selected sites based on accident statistics where excessive speeds were the contributing factor. Researchers collected a minimum of seven days worth of data at each of the test sites before and after the implementation of the signs. The junction and bend warning signs reduced the mean speeds up to 7 mph. These signs significantly reduced the number of vehicles exceeding the speed limit. The study team noted that there has been a one-third reduction in accidents across all of the Norfolk sites.

### ***Wizard CB Alert System***

The Wizard Work Zone Alert and Information Radio was designed by Highway Technologies Inc. to provide advance warning of approaching work zone activities. The system, shown in Figure 2.6, targets mostly truck drivers monitoring CB radio frequencies. The advance warning enables them to slow down to a safe speed prior to entering the work zone. The range for the wizard is approximately 4 miles in areas of level terrain.



Figure 2.6 Wizard CB Alert System [9]

### Iowa Study

In 1999, under the MWSWZDI the Iowa DOT experimented with the Wizard CB alert system on a section of Interstate 35 during work zone lane closures [30]. The Wizard was set to broadcast at 30-second intervals on Channel 19, which is the frequency most truckers use. The message broadcast was:

*This is an Iowa DOT road work alert. Northbound drivers on Interstate 35: you are approaching a slow moving paint crew in the right lane. Please use caution.*

Throughout the study, surveys were taken of truckers at interstate rest areas. The research team found the following results:

- Of the drivers surveyed, 94 percent had a CB radio in their truck
- 80 percent had their radios tuned to Channel 19
- 75 percent stated that they heard the Wizard CB announcement
- 39 percent thought the message was effective at warning them of the approaching paint crew
- 99 percent said that the message was not annoying in any way

### Texas Study

In 2001, Texas Researchers evaluated CB Wizard at four interstate work zones [31]. The study team collected truck volume data and speed data at .05 miles and 3.5 miles after the start of the work zone. The unit was set to broadcast a message such as the following:

*This is the Texas Department of Transportation. All Northbound trucks on Interstate 35 should use the left lane through the next work zone. The speed limit through the work zone is 45 miles per hour.*

The study team assessed the impact of the CB Wizard on truck travel speeds. Based on the results, researchers determined that the CB Wizard produced no notable decrease in speeds 3.5 miles into the work zone. However, the researchers noted a significant reduction of speed between the start and middle of the work zone when the CB Wizard was active. The team also noted a reduction of the number of vehicles traveling at speeds greater than 10 mph over the posted speed limit.

### ***Temporary Rumble Strips***

Temporary rumble strips are self-adhesive strips that create an audible, visual, and physical alert when driven over. These brightly colored strips are intended to warn drivers of an approaching work zone where they may be required to stop, merge, or simply slow down. Figure 2.7 shows the typical setup of the temporary rumble strips [32].



**Figure 2.7 Portable Rumble Strips [32]**

### ***Texas Study***

Michael Fontaine of Texas A&M University tested temporary rumble strips on Texas interstates [32]. The rumble strips, manufactured by Advanced Traffic Markings, were 12 feet long, 4 inches wide, and 1/8 inch thick. Researchers chose rumble strips that were orange in color and had a pre-applied adhesive backing that bonded the strips to the pavement. Using a 200 lb weighted roller to attach the strips, a three-man crew was able to complete the installation in 40 minutes under light traffic. The study found that the temporary rumble strips had the most effect on trucks, producing a mean speed decrease of 3 to 4 mph. In addition, the rumble strips caused the percentage of cars exceeding the posted speed limit to decrease by 1 to 7 percent. The study concluded that temporary rumble strips are most practical when implemented in long-term work zones because they are not reusable.

In a different study, Richards et al. tested temporary rumble strips at a rural work zone in Texas [5]. The research team installed the rumble strips in a group of eight across the traveling lane. The study found only a 2 mph decrease in mean speeds, and researchers deemed the rumble strips ineffective.

### *Additional Studies*

The New Hampshire Department of Public Works (DPW) has experienced immense success by installing temporary rumble strips as work zone safety devices to reduce speeds. The Director of the New Hampshire DPW suggested using a combination of 4 strips and fluorescent orange signs to maximize the speed reduction [33].

By contrast, The Indiana, Maryland, Utah, and Arkansas Departments of Transportation found that the portable rumble strips cracked very easily and moved when traversed by heavy vehicles. The New Mexico Department of Transportation discovered that the portable rumble strips wore out rather quickly, thus creating a safety hazard since the devices used to hold the strips down were exposed [5].

The mixed results of temporary rumble strip effectiveness indicate that further study is warranted. The extensive setup time makes rumble strip use highly undesirable during high volume applications, unless installation can be accomplished during a very low volume period. Their use is likely not practical for short-term work zone applications but has significant potential for construction projects carried over several weeks (or longer).

### ***Optical Speed Bars***

Common more to Europe than the U.S., optical speed bars are innovative pavement markings that have been known to reduce speeds and decrease the number of accidents in work zones. Also known as transverse strips, optical speed bars can lower the number of accidents when placed on curves. Gradually decreasing the distance between the strips creates the illusion of speeding and causes drivers to decrease their speed [5].

### *Scotland Study*

In Scotland, studies conducted by Denton implemented optical speed bars in a roundabout [5]. Yellow stripes were placed at the approach of a roundabout, with the spacing between stripes decreasing exponentially from 20 to 10 feet. Results from the study include a reduction in the 85<sup>th</sup> percentile speed. Speeds dropped from 47 to 33 mph. Fewer accidents took place following the installation of the strips.

### *England Study*

H.C. Pyne conducted studies on the effects of transverse strips on sharply curved roads [26]. Pyne used a driving simulator for the data collection in the experiment. The simulated road entailed an 800-meter highway followed immediately by a 200-meter curve. The experiment used a 300-meter radius for the curve. The study tested 17 subjects, varying the type of experiment based on several speed reduction measures. Speed reduction measures included

different signs, transverse strips, and chevrons with increased angles. The placement of the transverse lines created an illusion of speeding while the chevrons made the lanes appear to be narrowing. The 85<sup>th</sup> percentile speeds decreased 7 mph due to the combination of transverse lines and chevrons. Pyne noted that the addition of either a “SLOW” or a triangular warning sign could reduce the speeds more than 7 mph.

### *New Brunswick Study*

The University of New Brunswick Transportation Group installed transverse speed bars on one rural highway work zone [34]. The length of time of the study elapsed over a five-week period. The experiment involved comparisons of effectiveness between night and day. The results showed that the nighttime conditions had a greater reduction in speed in comparison to daylight hours. The transverse speed bars appeared to improve the safety of the facility users as well as reduce the mean speed. The study group acknowledges that the increased contrast of reflective marking tape during nighttime conditions contributed to the improved results.

### ***Police Enforcement***

Maze, Kamyab, and Schrock evaluated speed reduction measures in work zones and determined that one of the most effective measures in reducing vehicle speeds was police enforcement. This strategy can involve mobile or stationary police cars, although stationary police have had the most success. The ghost police car, a type of stationary enforcement, involves a parked police car with no officer present. Richard’s et al research showed that a stationary police officer in a work zone decreased the mean speeds between 4 to 12 mph, while the circulating police reduced speeds only 2 to 3 mph. Noel et al conducted a study on Delaware’s interstates using two modes of police enforcement:

- Police car equipped with radar and flashing lights, and
- An officer standing at the entrance of the work zone, motioning vehicles to reduce their speeds.

The study declared that both of these measures reduced speeds in single- and multi-lane closures on interstate work zones [5].

Benekohal, Resende, and Orloski studied the effects of the presence and absence of police enforcement in work zones. The study found that the presence of police decreased the mean speeds 4 mph, and the mean speed increased approximately 2.5 mph within an hour of removing the police [35].

Many states use some form of police enforcement, shown in Figure 2.8, in work zones to reduce speeds [36]. In Hawaii, police cars with flashing blue lights are parked along roads, while in New York ghost police cars are used in work zones. Both states have had success with these measures [37].



Figure 2.8 Ghost Police Car [36]

The Iowa State Department of Transportation conducted a survey of 63 state transportation agencies. With a 62 percent response rate, the survey concluded that 70 percent of the agencies consider police enforcement to be the most effective speed reduction measure [38].

Researchers anticipate that the use of law enforcement will be a critical aspect of this project, but coordination will be determined during the initial strategy sessions with the project steering committee.

### *Summary of Literature Review*

With work zone crashes and fatalities on the rise in South Carolina, it is important to face the issue head-on and to develop ways to mitigate this continuing problem. The literature review reveals that there are many measures that can be incorporated into work zones to decrease vehicle travel speeds.

Common work zone speed reduction measures include lane reduction, drone radar, speed monitoring display, changeable message signs with radar, vehicle activated signs, CB alert systems, temporary rumble strips, optical speed bars, and police enforcement. Implementation goals for each of these measures include:

- Better informed traveling public (assuming improved overall traffic management practices in work zones),
- A lower 85<sup>th</sup> percentile speed,
- Reduced speeding violations, and
- Better coordination with law enforcement agencies.

Though the conclusions by previous researchers for various speed reduction strategies are diverse, depending on various factors, it appears that in no case did the deployment of these strategies worsen the existing operational conditions. As a result, the application of similar techniques in South Carolina work zones appears promising. It is clear to Clemson University researchers that there is a need to define the specific benefits of each technique and to better identify when certain technologies should be implemented to provide maximum benefits with minimal expense.

## CHAPTER 3

### SPEED REDUCTION DEVICES AND FIELD CONFIGURATION

Based on the literature review and meetings with the project steering committee, a number of devices were selected for field evaluation. The devices selected were drone radar, changeable message sign with radar (CMR), a speed monitoring display (SMD) with CMS, portable rumble strips, and a novel speed activated sign designed by the researchers. Each of the devices had to be acquired and/or developed for this project and preliminary testing was conducted to ensure optimal configuration during actual field data collection. The devices and configurations are discussed in the following sections.

#### *Drone Radar*

The literature review has indicated that drone radar has been studied extensively over the last 20 years but only one published study has been conducted in the last 5 years. Further, only a few studies have actually looked at radar detector usage which is a critical factor in the effectiveness of drone radar. The primary purpose of the drone radar evaluation was to investigate the effectiveness of the device in multiple types of work zones under both day and night conditions to determine the potential successful scenarios for deployment. Research was conducted to identify various types of drone radar and radar detectors to be purchased for the study. The second step in the evaluation process included an investigation of the operating limitations of drone radar to enable comparative test environments in the experimental tests. The third step included the development of a methodology for testing several qualitative and quantitative measures with the aid of a radar detector, a radar detector detector (RDD), a laser and a radar speed gun, CB radio, and a communication device to relay messages between data collectors.

The researchers chose the Cobra XT 1000 Safety Alert Traffic Warning Systems drone radar, which emits K and KA-band. A series of tests were conducted to determine the optimal mounting specifications of the drones in the field. The tests included placement of the drones on different objects and in different terrains while using multiple brands of radar detectors to test the signal strength of the drones. The preliminary tests objective was to discern which radar detectors worked the best with the drone radar and to find placement locations (direction, mount, and terrain) where the drone signal transmitted the best.

The preliminary tests using the drone radar showed that it has limitations; it works best in flat areas where hills and other objects do not obstruct the signals; as well, it works best if elevated to avoid low-lying obstructions. Orientation of the drone radar also affects its performance. Based on these results, a simple mounting structure was developed to provide optimal signal detection length, as well as allow for quick installation of the drone. The complete apparatus, as shown in Figure 3.1, costs approximately \$250. The drone is attached to the top of a steel post that is mounted with a rechargeable battery pack. The post and battery assembly is painted green to blend with surrounding vegetation in an attempt to make it difficult for drivers to identify the drones.

One serious limitation found in the preliminary tests was that not all radar detectors that are specified to detect K and KA-band detect the drone. This was found to be most apparent in low cost radar detectors. This was especially problematic for this study because there was no way to know whether or not a radar detector that is in use in a vehicle is actually sensing a drone.



Figure 3.1 Cobra XT 1000 Safety Alert Warning System attached to mounting structure in the field

### *Changeable Message Sign with Radar*

The literature review indicated that a changeable message sign equipped with radar (CMR) is a relatively new innovation. There has only been limited research on its use, with the results being promising. The trailer-mounted CMR used in this study was manufactured by Solar Technology Incorporated. The Silent Messenger CMS (Model number MB-22-905) was equipped with their radar unit package. The sign's message panel measures 126 inches wide by 76 inches high and is capable of displaying one, two, and three lines of text as well as graphical messages. Standard messages are 8 characters. The sign is capable of displaying different messages based on speed thresholds triggered by vehicles. The Silent Messenger CMR is shown in Figure 3.2. The sign is also capable of displaying a vehicle's speed. One of the intents of the evaluation for CMR is to investigate the effectiveness of different combinations of messages. This is discussed in detail in Chapter 4.



**Figure 3.2 Silent Messenger Portable CMR**

### ***Novel Speed-Activated Sign***

As part of this project, the researchers developed and evaluated a fixed-message, speed-activated sign (referred to from this point forward as speed-activated sign) that triggers a flashing beacon when a pre-determined speed threshold is exceeded. The objective of this evaluation was to determine the effectiveness of this affordable technology while maintaining the goal of providing the SCDOT with a proven strategy to heighten safety and lower speeds in work zones.

The resulting speed-activated sign, shown in the left pane of Figure 3.3, was a 4-foot by 4-foot corrugated plastic reflective sign with 6-inch lettering reading “YOU ARE SPEEDING IF FLASHING.” The research team and SCDOT considered alternative messages including “SPEEDING IF FLASHING” but decided the “YOU ARE” would make it more obvious to drivers that they were being specifically targeted. Although the alternative message was not tested in this project, consideration should be given to using the simpler message in work zones with complex signing and traffic control schemes.

To increase the speed-activated sign’s visibility, the study team added two 1-foot by 1-foot orange plastic flags. The beacon atop the speed-activated sign was a solar-powered high-intensity type B flashing beacon light.



**Figure 3.3** The speed radar (right) activates a flashing beacon atop the work zone sign (left).

The speed-activated sign's radar system, shown in the right pane of the figure, contained a dual switchboard that allowed setting of the speed threshold, on-delay, and off-delay. When the programmed speed threshold was reached, the radar system paused for a time period equal to the on-delay and then activated a relay that turned on the beacon, which flashed at a fixed rate based on its built-in capacitor. The relay opened after the off-delay period passed and the beacon turned off. The radar system was enclosed in a hard-shell waterproof box that allowed for mounting the system directly to the sign post. Two 12-volt gel batteries wired in parallel powered the radar. The battery pack, which cannot be seen in Figure 3.3, sat at the base of the sign. The speed-activated sign met all of the established objectives for development and the prototype sign assembly, including the portable stand, cost approximately \$1,500. Nearly two-thirds of this cost was for the speed-activated radar, which would be reduced if the radar assembly were produced in quantity. With the prototype system established, preliminary testing showed that the sign worked exactly as planned. Some difficulty was found in finding ideal settings for on-delay and off-delay values. For the most part, a trial-and-error approach was used to do this. Once the preliminary testing was done, the Clemson research team took the sign to the field to test its effectiveness as a speed reduction measure in work zones.

Modifications to the original design were made after an initial data collection phase of the project. These modifications are discussed in Chapter 5.

### ***Speed Monitoring Display with CMS***

Speed monitoring display (SMD) trailers are becoming very common. Many law enforcement agencies use SMD trailers on roads that exhibit excessive speeding. School zones and work zones are also common applications of SMD trailers. For this research project, a unique SMD display that incorporates a CMS was evaluated as a work zone speed reduction device. The hypothesis was that by displaying credible information in the CMS, the display could result in more favorable speed reductions than a conventional speed monitoring display. The research indicated that there are very few manufacturers of SMDs that incorporate CMS. The V12C-2M alphanumeric sign manufactured by Ingram Technologies was chosen as the SMD with CMS

evaluated on this project. The sign, shown in Figure 3.4, is equipped with a programmable two-line message panel capable of displaying five 12-inch characters per line. Speeds are displayed below the lines of text by two 24-inch digits. The SMD with CMS is equipped with Doppler radar for detecting vehicle speeds and is programmable to display various text messages for preset speed thresholds. The messages used in this research are discussed in Chapter 4.



**Figure 3.4 Ingram Technologies Speed Monitoring Display with CMS**

The sign evaluated on this project was purchased without a trailer. Instead, a hitch mounting kit was purchased to mount the sign to the back of a vehicle. The sign could also be mounted to a utility trailer. Both configurations are shown in Figure 3.5. The sign requires a 12 volt DC power supply.



**Figure 3.5 Mounting Configuration for SMD with CMS**

Prior to using the SMD in the field, a series of tests were performed at locations around Clemson to determine the visibility of the message display from a distance and the detection range of the radar. The locations chosen differed from each other with respect to the horizontal curves and

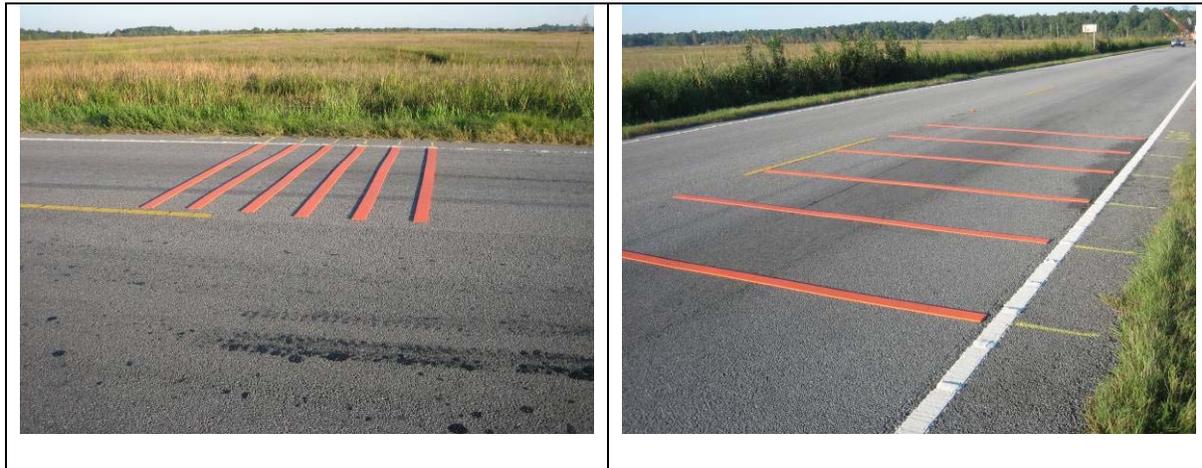
width of shoulder. Table 3.1 summarizes the visual and radar detection ranges at each location assuming 20:20 vision.

**Table 3.1 Visibility and Radar Detection Distances for SMD with CMS**

<b>Location</b>	<b>Distance at which vehicle was detected</b>	<b>Distance from which numbers were visible</b>	<b>Distance from which message was visible</b>
Hugo Drive	0.27 miles	0.20 miles	194 feet
	(1425 feet)	(1056 feet)	
Greenville Highway	0.23 miles	0.19 miles	198 feet
	(1214 feet)	(1003 feet)	

***Portable Rumble Strips***

The Texas A & M research gives great insight into the use of portable rumble strips as a speed reduction measure. The Clemson Research team purchased portable rumble strips on this project to evaluate their effects on speed here in South Carolina. Because of their simplicity, no preliminary testing of the portable rumble strips was done (or needed). Due to their expense (they are not recyclable) and installation requirements, the portable rumble strips were only evaluated on a single long-term construction project in this research. Figure 3.6 shows the portable rumble strips used on this project.



**Figure 3.6 Portable Rumble Strips**

## CHAPTER 4

### DATA COLLECTION METHODOLOGY

#### *General Methodology*

##### *Data Collection Sites and Descriptions*

The intent of this project was to collect data to analyze a wide range of roadway conditions and work zone types on rural highways, and interstate freeways. A single data collection process lasted from three to four hours; therefore, it was important that work zone activity during this period be continuous and similar in nature. In addition, there needed to be limited activity within each work zone so that vehicle speeds were not influenced by the presence of workers and large machinery. Both construction and short-term maintenance activities were included in the evaluation of the speed reduction devices.

##### *Construction Work Zone Site Descriptions*

The first site studied was located near the University of South Carolina's Upstate Campus along Interstate 585, also known as Highway 176. The I-585 work zone was used to collect data for the drone radar and radar equipped CMS (CMR) setups. The speed limit through the work zone was 45 mph. I-585 extends from Spartanburg across I-85 and I-85 Business. The work zone for this area included the design and construction of a new interchange access to the USC-Upstate campus, providing controlled access from I-85 Business to the I-85 Relocation along existing US 176. Orange barrels were used on the outside lanes of travel while Jersey barriers separated both directional flows of traffic. Traffic control signs "BEGIN ROAD WORK" and "END ROAD WORK" were used in addition to "REDUCED SPEED LIMIT" and "SPEED LIMIT 45" at the entrance of the work zone from both sides. During the data collection with the drone radar at night, an hour of data was lost due to a change in location at Station 1. Security forced the project team to change locations because the frontage road did not allow parking after 6:00 pm.

The second site considered in this study was located along South Carolina State Route 72 in Laurens County, approximately twelve miles east of Greenwood, SC. The drone radar, speed activated sign, and CMR were all used at this location. The construction will convert SC-72 from a two-lane road to a four-lane divided facility. During data collection, the road still had only two lanes. Roadwork occurred on only one side of the highway because the additional lanes being added were directly adjacent to the existing roadway, requiring the use of cones only on the northbound approach. The fact that the road widening construction took place on only one side of the highway has contributed to increased speeds through this work zone. Typical work zone traffic control was present, including "BEGIN ROAD WORK," "END ROAD WORK," "REDUCED SPEED LIMIT," and "SPEED LIMIT 55" designation signs [39]. Construction activities included paving the new lanes and constructing a bridge, but both activities occurred approximately one mile west of the sign location during data collection.

The third work zone evaluated was on South Carolina State Route 290 in Spartanburg County. The speed activated sign and CMR were used at this location. The six-mile work zone was being

widened from a two-lane roadway to a five-lane road, including a two-way left turn lane. The majority of the road will have curb and gutter when finished. During data collection, the road was still a two-lane facility, but most of the work was finished for the adjacent three lanes. A half-mile area was studied south of the intersection of Dice Miller Road and SC-290. Data from this site were used in a two-message comparison.

The fourth work zone was also in Spartanburg county, along South Carolina State Route 101, six miles north of Woodruff, South Carolina. Data from this location were collected for the CMR, the speed activated sign, and the speed monitoring display (SMD) with CMS.. The construction work will transform the two-lane rural facility into a five-lane roadway, including a two-way left turn lane. The portion of the road studied was still two lanes, but the full width of the future road was already paved. Work in the immediate area of the sign involved relocating minor intersections and driveways. During data collection, an earth moving operation was grading an embankment adjacent to the roadway. The section of road studied began near Greenpond Road and continued south three quarters of a mile towards Woodruff, SC.

The fifth site was along Interstate 385 in Greenville County, South Carolina. The location was used in the evaluation of the drone radar setup. I-385 is a four-lane interstate highway that connects I-26 and I-85. Construction included an upgrade from a partial interchange to a full diamond, frontage road relocation, and the improvement of secondary road bridges that cross I-385. Existing traffic control included orange barrels lining the outside lanes and Jersey barriers along the inside travel lanes. Traffic control signs included “BEGIN ROAD WORK” and “END ROAD WORK” designation signs. “REDUCED SPEED LIMIT” and “SPEED LIMIT 65” were placed at the entrance of the work zone at both sides. During a night study for baseline data, the work zone was significantly changed by a lane closure, influencing the speeds by approximately 15 mph. As a result, this data collection period was not included in the analysis.

The sixth site was near the Greenville-Spartanburg Airport on Interstate 85, where a modification to the existing interchange, as well as a new directional interchange just north of the airport, were under construction. The site was used only in the evaluation of the drone radar setup. This six-lane freeway used Jersey barriers on both sides of the road, separating the construction work from the vehicles. Traffic control signs included “BEGIN ROAD WORK” and “END ROAD WORK” designation signs. “REDUCED SPEED LIMIT” and “SPEED LIMIT 60” were located at the entrance of the work zone from both sides.

The seventh data collection site, located in Oconee County, was not planned for the study but, because of its close proximity to Clemson University, was used in the evaluation of the drone radar. S-488, a secondary road in Seneca, SC, was being widened from its existing two lanes to five lanes. During the data collection, this construction had been completed except at one bridge location. Orange barrels were placed in the newly constructed lanes until the bridge was completed. At the bridge location, Jersey barriers were used, reducing the lane width on the existing bridge while construction took place in the middle of the highway. As with the previous sites, the traffic controls signs “BEGIN ROAD WORK” and “END ROAD WORK” were placed at their respective locations. “SPEED LIMIT 35” signs were located at the entrances of the work zone from both sides.

The eighth work zone chosen for data collection was SC Route 219 in Newberry, South Carolina which provides a primary access route to Interstate 77. Data were collected for the speed activated sign. Construction on this secondary highway consisted of widening the route from two lanes to four lanes. The terrain of the work zone was considered rolling. Observed traffic control included orange barrels spaced ten feet apart and lining the outside of the two existing travel lanes. "ROAD WORK AHEAD" warning signs were placed at both ends approximately 1,000 feet from the "BEGIN ROAD WORK" designation signs. "REDUCED SPEED LIMIT" and "SPEED LIMIT 45" were placed at the entrances of the work zone from both sides.

The ninth data collection site was located on US Route 278 in Hilton Head, South Carolina, east of Interstate 26. US-278 serves as the primary road connecting I-26 to Hilton Head Islands. The six mile work zone was used in evaluating dual speed activated signs and SMD with CMS. Existing traffic signals were observed as affecting the flow of traffic in the morning, and thus the data collection site was shifted downstream of US-278 to get a better site. The work zone was active during the night time with paving operations carried out with one lane closed whereas simple excavation and mowing work was carried out throughout the day. Exclusive turning lanes were also being constructed. The peak hour traffic was avoided as it formed long queues. The influence of traffic signals was taken into consideration with platoons of vehicles being avoided. Speeding was evident due to the lesser amount of work being carried out through the day. Barriers and cones were strategically placed to allow access to local businesses. The speed limit for the work zone is 45 mph. The data collection was done at a site on Fording Island road, just after Bluffton road.

The tenth data collection site was located along South Carolina State Route 121 in Newberry County, South Carolina. The four mile work zone was located near exit 72 off I-26. Data were collected for the SMD with CMS. The two-lane highway was being widened to four lanes. The terrain was flat. Excavation along the edges of the roadway was in progress at the time of data collection. "SPEED LIMIT 45" "ROAD WORK AHEAD" signs were placed at the ends of the work zones. This site proved to be a good site for data collection as there were not many terrain features which would affect the speeds of the vehicles.

The eleventh work zone was located along South Carolina State Route 295, about 4 miles west of Interstate 26. Data were collected for the SMD with CMS in conjunction with police enforcement. The work zone included approximately three and a half miles, ending at an intersection with US-176. Construction work consisted of widening the roadway from two lanes to four. The terrain was level through most of the work zone with a slight upgrade towards the end. Leveling activity was in progress, and the construction was being carried out in sections of the road. The work zone had a posted speed limit of 45 mph. The existing traffic control included orange barrels and removable concrete barriers. The beginning of the work zone site had a single lane and a traffic signal and thus lower speeds were observed. Data collection was conducted farther downstream from the traffic signal along a two-lane section of the road.

The twelfth site was used to evaluate the combined effects of SMD with CMS with police enforcement and was located along South Carolina State Route 292, north of Interstate 85. The work zone covered a 2.5-mile section of SC-292 between Greenville Highway and Interstate 26. Construction was nearing completion and consisted of widening the two-lane highway to four

lanes as well as a small bridge extension. At the time of data collection, most of the work had been completed and the widened section of the bridge was being surfaced. The terrain was mostly level with a speed limit 45 mph. Few heavy vehicles were observed on this route. Traffic control measures included orange barrels and cones with ‘WORK ZONE AHEAD’ signs positioned at both ends of the work zone.

The thirteenth site selected for data collection was along US Highway 17 in Charleston, South Carolina. This location was used to study the Portable Rumble Strips. There was no shoulder at this site; therefore SMD could not be tested. Construction work took place along the southbound direction of travel and involved widening a bridge to increase the number of lanes. The speed limit was reduced to 45 mph and extensive signage including “ROAD WORK AHEAD” and “INCREASED FINES,” was located before the start of the work zone. Heavy machinery was used both on and off the road, resulting in temporary lane closures. US-17 is a major connector for the city of Charleston, creating heavy traffic on the roadway. The site had level terrain.

An additional site that was considered for use in evaluating police enforcement was South Carolina State Route 215, in Spartanburg County. Construction activities included bridge repair and widening of the lanes leading to the bridge. Researchers decided not to include this site in the study because the road had too many sharp curves causing traffic to slow down. Another major reason was the presence of a CMS at the site for traffic control. A large CMS displayed “CAUTION” and “REDUCE SPEED” messages. The CMS was present at one end of the work zone, thus preventing the study of another sign at the same site.

Table 4.1, shown following the maintenance site descriptions, summarizes the construction data collection efforts stratified by site.

#### Maintenance Work Zone Site Descriptions

The first maintenance data collection site was located on US Highway 72 in Abbeville County.. The work zone extended for 2 miles. Temporary maintenance work consisted of cutting trees extending onto the road. Lane closures were present for sections of road, depending on the location of the cutting equipment. Barriers were used for traffic control. The roadway was two lanes in each direction. The temporary work lasted for not more than 5 hours. Medium traffic with few heavy vehicles was observed. There was no reduction of speed limit for the section of the road, but the traffic was often slowed by the temporary lane closures. Rolling terrain was observed at the site.

The second maintenance data collection site was located on US Highway 221 in Laurens County. The site was a single lane in both directions. The maintenance activity that was in progress was ditching operations with heavy machinery. Work was carried out on one side of the road at a time and required that a travel lane be closed. Flaggers were present to direct traffic. As a result, the traffic was stopped in one direction while the maintenance activity was being carried out and a single lane was used for both directions of traffic. Also, the traffic volume observed on the roadway was extremely low with no speeding at all. Due to the single lane usage for traffic flow and the low traffic volumes and absence of speeding, the data collection was called off.

The third location intended for study was located near US Highway 78 in Lexington County, South Carolina. The maintenance was scheduled to take place on Mill Stream Road near US-78, but was canceled due to a machine failure while working at the site. There was no alternative machinery available to continue with the maintenance operation.

The fourth maintenance site was located on US Highway 123/76 in Pickens County, South Carolina. Data were collected for the modified speed-activated sign setup. The temporary maintenance was carried out along the southbound direction of travel and involved minor bridge repair and cleaning. Work lasted for almost six hours, and one lane was closed for a portion of this time. The work zone started just before the bridge. The speed limit was 35mph.

The fifth maintenance work zone was also in Pickens County along US Highway 123. Pickens County Maintenance Department informed the researchers about the temporary activity that was to be carried out for two days on Clemson Boulevard just before the bridge. The work zone site was relatively small and had a lane closure for some distance. Maintenance activities included tree cutting and cleaning the bridge. A large flashing arrow sign guided the traffic through a single lane. Sufficient advance warnings signs indicative of the lane closure were present. The research team placed the SMD at a location where many vehicles were speeding at the beginning of the work zone. The work was carried out in the direction towards Clemson.

Table 4.2 summarizes the maintenance data collection efforts stratified by site.

**Table 4.1 Construction Work Zone Summary**

Site #	Location (County)	Rt.	Type of Work Zone	Length (miles)	Measure Tested	Data Collection #	Dates of Collection	Time of Day
1	Spartanburg	I-585	Interchange Construction	2	Police	10	22 Oct. 2005	Morning
					Drone Radar	19, 20	2, 16 Feb. 2006	Morning
						21	21 Feb. 2006	Night
					CMR	22, 23	8, 22 Feb. 2006	Morning
						29, 30, 31	6, 7, 15 Mar. 2006	Morning
Speed-Activated	37, 39, 40, 41	8, 10, 11, 16 May 2006	Morning/Afternoon					
2	Laurens	SC-72	Widening, 2 to 4 lanes with grass median	8	Drone Radar	09	20, 28 Oct. 2005	Morning
					Speed-Activated	11	19, 20 Oct. 2005	Morning
					CMR	24	21 Feb. 2006	Morning
						25	28 Feb. 2006	Morning
						26, 27, 28, 33	1, 9, 16, 21 Mar. 2006	Morning
3	Spartanburg	SC-290	Widening, 2 to 5 lanes	4.5	Speed-Activated	05, 06, 07, 08	1, 8, 9 28 Sept. 2005	Morning
					CMR	33	22 Mar. 2006	Morning
				5.3	SMD	62	9 Nov. 2006	Morning
4	Spartanburg	SC-101	Widening, 2 to 5 Lanes	6	CMR	34	23 Mar. 2006	Morning
					SMD	35,36	18, 20 April 2006	Morning
						38	9 May 2006	Morning
5	Greenville	I-385	Paving, Single Lane Closure	1	Speed-Activated	04	24 Aug. 2006	Night
			Widening, 2 to 4 lanes	2.2	Drone Radar	11, 12	7, 14 Nov. 2006	Morning

**Table 4.1 (continued) Construction Work Zone Summary**

Site #	Location (County)	Rt.	Type of Work Zone	Length (miles)	Measure Tested	Data Collection #	Dates of Collection	Time of Day
6	Greenville	I-85	Interchange Construction	3	Drone Radar	13	10 Nov. 2005	Morning
						14	19 Jan. 2006	Morning
				1		15, 16	26 Jan. 2006	Night
7	Oconee	S-488	Widening bridge 2 to 4 lanes	1	Drone Radar	17	31 Jan. 2006	Morning
						18	7 Feb. 2006	Morning
8	Newberry	SC-219	Widening, 2 to 4 Lanes	2.1	Speed-Activated Sign	01, 02, 03	15, 16, 19 Aug. 2005	Morning/Afternoon
9	Hilton Head	US-278	Widening, 4 to 6 Lanes		SMD	44, 45	1, 2 June 2006	Morning
					Speed-Activated	46, 47	1, 2 June 2006	Afternoon
10	Newberry	SC-121	Widening, 2 to 4 Lanes		SMD	42, 43	22, 23 May 2006	Morning/Afternoon
11	Spartanburg	SC-295	Widening	3.4	SMD + Police	59	1 Nov. 2006	Morning
12	Spartanburg	SC-292	Widening	2	SMD + Police	60	6 Nov. 2006	Morning
13	Charleston	US-17 S	Bridge Extension	3	Rumble Strips	56, 57	19, 20 Sept. 2006	Morning/Afternoon
						58	24 Oct. 2006	Morning/Afternoon

**Table 4.2 Maintenance Work Zone Summary**

Site #	Location (County)	Rt.	Type of Work Zone	Length (miles)	Measure Tested	Data Collection #	Dates of Collection	Time of Day
1	Abbeville	US-72	Tree Cutting	2	Failure at Site	48	11 Aug. 2006	Afternoon
					Speed-Activated	49	14 Aug. 2006	Morning
2	Laurens	US-221	Ditching Operations		Failure at Site	51	24 Aug. 2006	Morning
3	Lexington	US-78	Maintenance site		Failure at Site	55	13 Sept. 2006	Morning
4	Pickens	123/76	Bridge Repair	2	Speed-Activated	52	7 Sept. 2006	Morning/Afternoon
5	Pickens	US-123	Tree Cutting	2	SMD	53, 54	8 Sept. 2006	Morning/Afternoon

## Data Collection

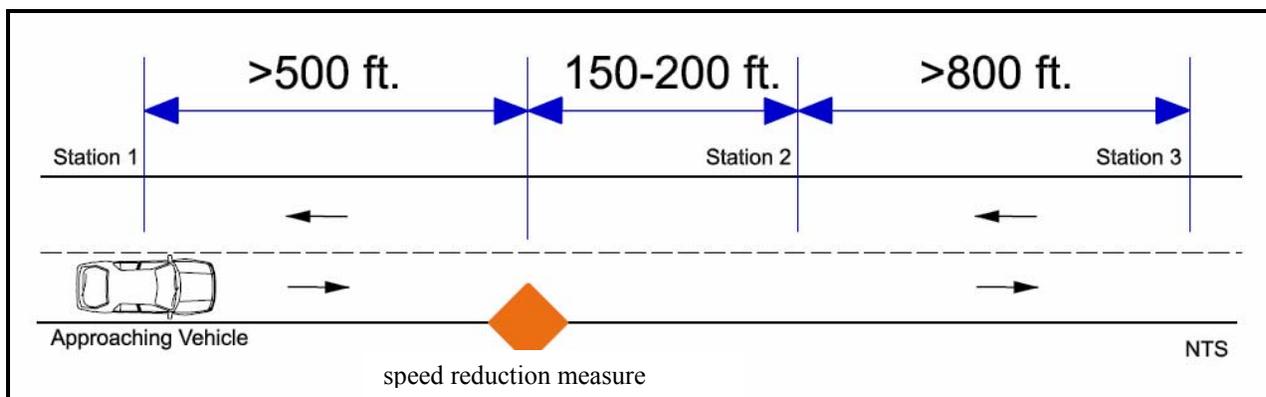
Data was collected at up to three stations in each work zone studied. The stations were typically positioned before, at, and after the deployed speed reduction measure. The first station was used to collect information about the initial condition of the vehicle speeds. The second station was used to determine the immediate impact of the device on driver speeds. Finally, the third station provided data about the continued impact of the speed reduction measure on observed speeds.

Station 1 was positioned in advance of the impact zone and was clear of all impacts from the deployed countermeasure. For example, the drone radar's emissions needed to be out of range and the CMR had to be either illegible or obscured from view at the first location. Data was collected from the first location using a laser speed gun to minimize the possibility of detection from radar detectors. No major interchanges or signals were allowed between this location and Station 2.

Station 2 was positioned either at or immediately after the speed reduction measure being evaluated. It was assumed that the major speed reduction occurred by the time a vehicle reached this location, and that, if the vehicle were to accelerate, the acceleration would not occur until after this point. The data at this point was collected using either a Bushnell speed radar gun or an Autoscope unit for video detection of vehicle speeds and type.

Station 3 was located downstream from the speed reduction device. This location also used either a Bushnell speed radar gun or an Autoscope video detection setup. Data from this location was used to draw conclusions about the continuing impact of the countermeasure on drivers.

The positioning of the speed collectors varied based on the type of work zone. In general, three individuals were positioned, one at each station, as shown in Figure 4.1.



**Figure 4.1 Typical Layout for Data Collection**

In most cases, speed data was collected for two conditions—one without any countermeasure and one with a countermeasure—to allow the researchers to determine the effect of the speed control device on driver behavior. In the event that topography and roadway geometries were similar, Station 1 was used for baseline data collection, allowing data collectors to record speeds for both conditions simultaneously. In some cases, the topography of the site prevented the use of Station 1 as a point for baseline data collection. For these sites, baseline data was collected on

a preceding day, allowing researchers to compare the data for the two conditions for the same one-hour time intervals. Conditions such as work zone location, type of work activity, time of day, weather, speed limit, and existing traffic control were recorded at each site.

Vehicle speeds at the three stations were measured using trigger engaged speed guns, shown in Figure 4.2. An Atlanta SpeedLaser speed gun was used at Station 1 to avoid detection by radar detectors and was capable of measuring speeds up to 4,000 feet away, more than double the measurement range of a radar gun. The Bushnell Velocity Radar speed guns used to collect data at Stations 2 and 3 were rated at an accuracy of  $\pm 1$  mph and allowed instantaneous speeds to be collected on a vehicle; however, they could be detected by K-band frequencies used on radar detectors.



**Figure 4.2 Laser and Radar Speed Guns**

Concealment of the radar unit was important to this project in preventing skewed or biased data as well as motorist distraction. Data collectors attempted to hide behind vegetation and roadside structures to avoid identification. As a result, some speed readings were recorded at an angle to the vehicle. This angle was measured, and those speeds were adjusted using the cosine error. When possible, speeds were measured as vehicles were moving away from the gun, rather than approaching, making it more difficult for a driver to see the gun as his speed was being monitored.

The method of sampling chosen for this study was all-vehicle type, platoon leader sampling, including single-vehicle platoons when traffic volumes did not support queuing. This technique of sampling gathered data by measuring speeds of all platoon leaders passing a point for a given time period.

### Sample Size

Sufficient data was collected to ensure a confidence level of 95 percent. According to the Institute of Transportation Engineers *Manual of Transportation Engineering Studies*, a minimum sample size can be determined for a desired degree of statistical accuracy by using the following equation [40]:

$$N = \left( S * \frac{K}{E} \right)^2 \quad (1)$$

where

- $N$  = minimum number of measured speeds  
 $S$  = estimated sample standard deviation, mph  
 $K$  = constant corresponding to the desired confidence level  
 $E$  = permitted error in the average speed estimate, mph

Previous speed studies under similar conditions indicate that an estimate of the standard deviation was approximately 5.0 mph. For this study, a value of 5.0 mph was used for  $S$  and from preliminary data collection, an average standard deviation of 4.2 mph during the first data collection study supports this as a safe assumption. This estimate proved correct throughout the entire project. For a 95 percent confidence level,  $K$  equals 1.96.  $E$ , which reflects the precision of the observed speeds, is the maximum tolerance for errors in the data collection process. For the speed study technique used in this study, a value of 1.0 mph was assumed for  $E$ . Thus, the minimum sample size at the 95 percent confidence level based on the above equation is as follows:

$$N = \left[ 5.0 * \frac{1.96}{1.0} \right]^2 = 96.04 \quad (1)$$

The typical data collection was one hour for each condition, both with and without the countermeasure implemented. Most sample sizes obtained exceeded this value to ensure statistical validity; however, tractor trailers had to be evaluated based over longer periods because one hour provided an insufficient number of samples for a 95 percent confidence level.

### ***Drone Radar Methodology***

As discussed in Chapter 3, Clemson researchers chose the Cobra XT 1000 Safety Alert Traffic Warning Systems drone radar, which emits K and KA-band frequencies, for use in this study. Police radar guns used in South Carolina also emit K and KA-band frequencies. Evaluation of the drone radar began in August of 2005 after contacting SCDOT construction and maintenance engineers to determine the locations of work zone projects throughout South Carolina. One criterion for selecting work zone sites required a high level of service within the site to allow vehicles to travel at free-flow conditions, thereby verifying the drone radar independence from other factors that may influence speeds.

Early testing on rural roads indicated a low percentage of both radar detectors and tractor trailers within the stream of traffic, making interstates the primary type of roadway used for future data collection. Interstates provided the study with a larger sample size for both passenger cars and tractor trailers, allowing for more radar detectors and communication on CB radio.

Speed data was collected for two conditions at each site: with the drone radar activated and without the drone activated. Initially, the research team attempted to test drone radar on an hourly basis by turning it on and then off, but this method gave erratic results. Vehicles tend to travel at different speeds depending on the time of day and fluctuations in traffic, making it inaccurate in some cases to compare subsequent hours. To address this issue, baseline data was

collected using the previously described method. The collections occurred between the hours of 9:00 AM to 12:00 PM during the day, and between 7:00 PM to 10:00 PM during the evening.

Other methods used to verify the effect of drone radar included monitoring the number of radar detectors, CB radio users, and the volume of both passenger cars and tractor trailers in the traffic stream to stratify the results among the various locations. Radar detectors were identified with a radar detector detector (RDD) from Hill County Research that uses a VG-4 frequency. The RDD, shown in Figure 4.3, was positioned at Station 1, perpendicular to traffic flow, and made a beeping noise when a radar detector was identified. Using visual inspection, the researcher then separated the vehicles into passenger car or tractor trailer. In addition, individual speeds of those equipped with radar detectors were recorded to see if they decreased their speeds upon encountering the drone radar. After the RDD identified a vehicle containing a radar detector at Station 1, the speed was recorded and a description of the vehicle was radioed to Station 2. CB radio transmissions provided the researchers with any communications that may confound the results of the study. Specifically, the researchers listened for any messages about police enforcement, the identification of the drone, or a data collector being spotted. All vehicular volume was recorded for both passenger cars and tractor trailers using a handheld clicker counter.

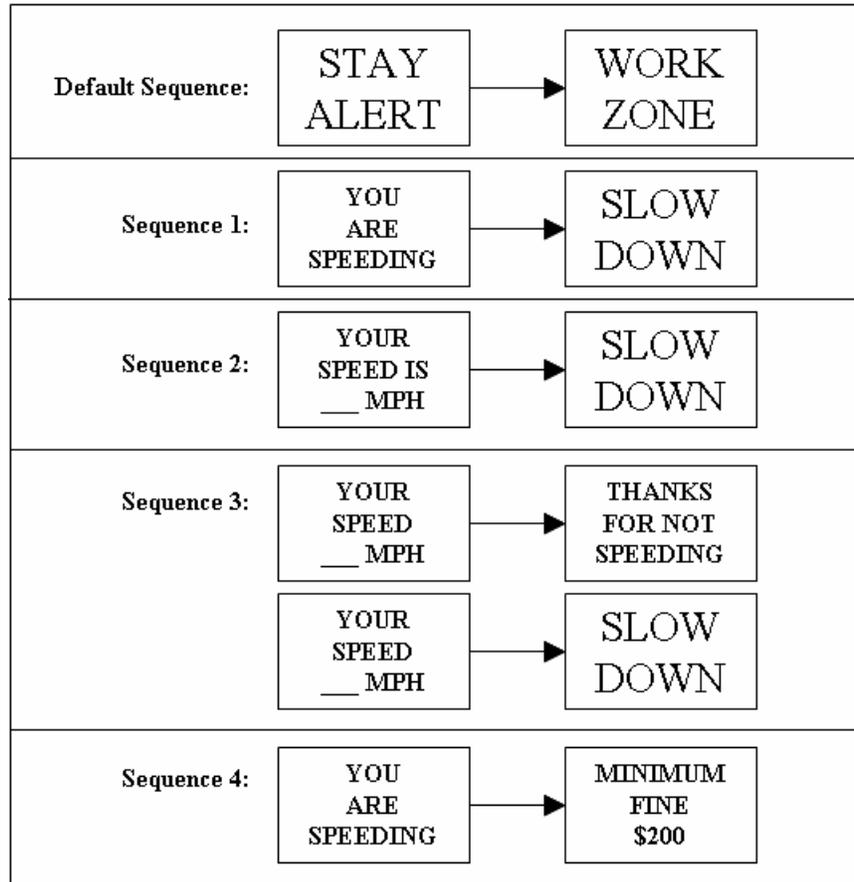


**Figure 4.3 Detecting Radar Detectors in the Field**

### ***Changeable Message Sign with Radar Methodology***

Evaluation of the CMR began in February of 2006 after selecting messages to be used in the study. Four sequences were selected based on the opinions of SCDOT representatives and the Clemson Researchers. The data collection process was divided into two phases. The four selected message sequences, shown as they appeared on the CMR in Figure 4.4, were examined during Phase 1 of the study. The default message played continuously unless it was pre-empted by the radar activated sequence. Sequences 1 and 4 repeated twice per triggering event. Sequences 2 and 3 ran only once per triggering event, but a speeding vehicle could trigger the message more than once while within the radar's range. Each message was displayed for a one-hour period during morning peak hours and was compared to the corresponding one-hour period of baseline data. After a statistical comparison was performed, two of the messages were

selected for further study during Phase 2. Phase 2 was conducted during morning peak hours using the same data collection methods as for Phase 1.



**Figure 4.4 Default and Radar Activated Sequences**

Data collection for the CMR followed the before-mentioned method, using the Autoscope unit for video detection of vehicle speeds and types at Stations 2 and 3. For video collection at Station 2, the camera was located no less than 500 feet, and no more than 1000 feet, away from the detection zone, with attempts made to conceal the support vehicle from drivers. In most cases, the support vehicle was hidden along the shoulder or at a minor turnoff, as illustrated in Figure 4.5. Efforts were made to hide the 35-foot boom and camera assembly by locating it near trees, telephone poles, or other such objects that could either hide it from view or allow it to blend into the background. Video data for Station 3 was collected using a second camera focused on an area about 1200 feet away from the location of the CMR. The video feed was recorded to DVD, and a computer and Autoscope Machine Vision Processor (MVP) were used to determine speeds, volumes, and vehicle classifications.



**Figure 4.5 Camera Setup and Support Vehicle**

### ***Speed Activated Sign Methodology***

For the initial data collection efforts, speed data was collected approximately 150 feet after the sign location using a handheld radar or laser gun. The research team found that this procedure produced limited results as it did not provide any insight into the conditions upstream and downstream of the speed-activated sign. As a result, the procedure was altered to include data collection at three locations for each site, as previously described.

### ***Speed Monitoring Display with CMS Methodology***

A V12C-2M alphanumeric sign manufactured by Ingram Technologies was the speed monitoring display (SMD) with CMS evaluated on the project. The compact size of the message panel limited the types of messages that could be displayed. After consulting with the project steering committee, Clemson researchers decided to use the following message sequences:

- STAY ALERT – WORK ZONE
- WATCH SPEED
- YOU ARE SPEEDING

The first message sequence was programmed for continuous display, while the latter two were triggered whenever a vehicle exceeded a preset threshold. Figure 4.6 shows the typical setup with examples of both types of message sequences.



**Figure 4.6 Setup Showing Speed Triggered Message and Continuous Message**

During the data collection process, the VMS was used in conjunction with law enforcement. In such cases, an alternative message that apprised drivers of the presence of law enforcement was used:

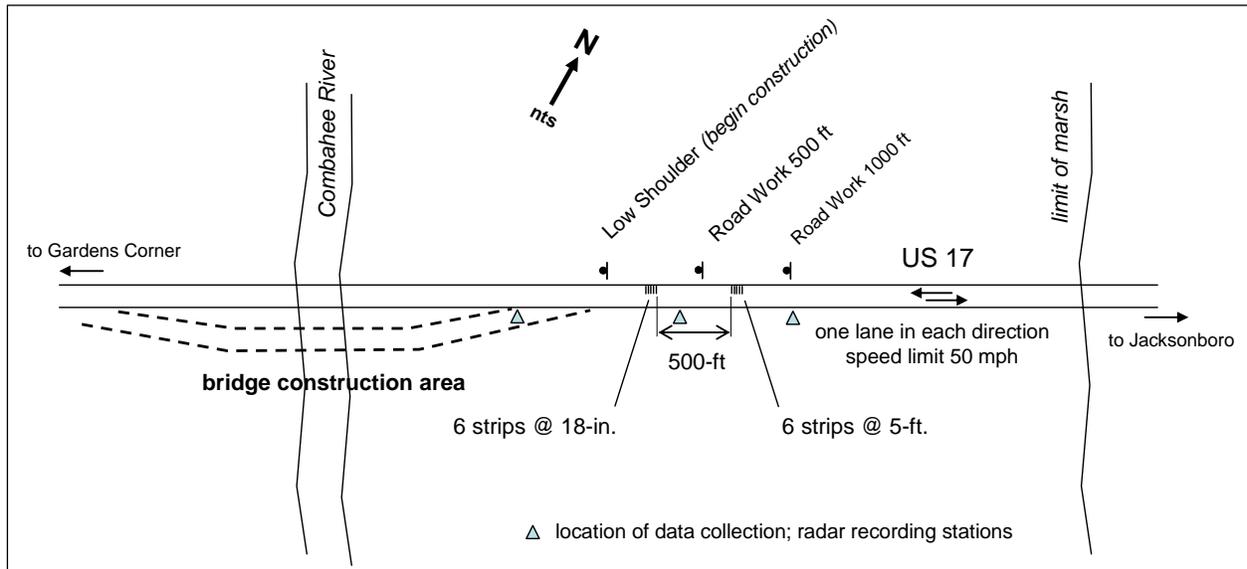
- STAY ALERT – WORK ZONE
- WATCH SPEED
- FINES AHEAD

The sign was mounted on the back of the research van using a simple hitch and was positioned at least 10 feet away from the edge of the travel lane. An external generator providing 12 volt DC continuous was used to provide the necessary power source for the sign. In some cases, the research van's on-board batteries were used to power the sign. Although the SMD with CMS used in this study has the capability of collecting and storing data, the collection range would have been limited to one station. Researchers chose instead to collect data at the three stations manually, as previously described.

### ***Portable Rumble Strips Methodology***

Preformed removable polymer tape rumble strips were placed at the end of the advanced warning sign sequence at the site of a long term construction work zone involving a bridge replacement project on US-17 in Colleton County at the Cumbahee River. Due to site conditions and visibility considerations, rumble strips were placed for the southbound direction only. As per MUTCD and manufacturer requirements, preformed thermoplastic rumble strips were placed as shown in Figure 4.7. No special equipment was necessary for installation. Locations were measured and pre-marked with spray paint. 50-ft. rolls of Strips were pre-cut to 11.5 ft lengths, the backing was removed on-site and after initial adherence, traffic rolled-in the strips for final installation. With regard to durability, in subsequent visits to the site and through discussions with the construction site project manager, it was confirmed that the rumble strips remained firmly in place as per initial installation. This is under a traffic load of approximately 10,000 vehicles per day (two-way ADT) with a relatively high percentage of truck volume. Furthermore, the construction site manager stated the rumble strips were noticeably effective in

lowering speeds through the work zone and requested that they remain in place after the data collection work was completed.



**Figure 4.7 Setup Showing Rumble Strip Installation and data collection stations**

## ***Police Enforcement Methodology***

### ***Marked Enforcement***

A marked law enforcement vehicle was positioned in a visible location along the edge of the work zone. A law enforcement officer was present in the vehicle, but was not issuing speeding tickets. When studied in combination with the SMD, the marked vehicle remained stationary throughout the data collection period at a distance of 500 feet from the sign. Figure 4.8 shows a typical position of a stationary marked law enforcement vehicle.



**Figure 4.8 Marked Enforcement Present in the Work Zone**

### Unmarked Enforcement

Unmarked police enforcement was also examined as a speed reduction measure. An unmarked police vehicle stationed within the work zone monitored vehicle speeds and actively ticketed speeding vehicles. Unmarked enforcement was studied in conjunction with the SMD with CMS. The SMD with CMS displayed a warning message informing drivers of the presence of law enforcement in the work zone.

## CHAPTER 5

### DATA ANALYSIS

Statistical tests were used to analyze the data collected for this study. Specifically, the data collected were examined:

- To test for significant differences in the change in mean speed and change in percent of vehicles exceeding the speed limit (for 5+ and 10+ mph) for each of the three data collection stations under the control (speed reduction device absent) and treatment (speed reduction device present) conditions; and
- To determine the change in 85<sup>th</sup> percentile speeds between the control and treatment conditions.

In some cases, station 1 was used as the control condition and compared with stations 2 and 3

#### *Statistical Testing*

The speed data for this study was collected from a moving traffic stream in stable flow; therefore the data can be assumed to follow the normal distribution [41]. Based on this assumption, parametric hypothesis testing was performed to test for equal means and the percentage of vehicles exceeding the speed limit.

#### Testing for Equal Means: The Two-Sample *t*-Test

Testing for equal means requires a *t*-test, which assesses whether two independent samples are statistically different from each other. This type of test is appropriate for making a comparison between two samples, such as in the analysis of a before-and-after spot speed study, and can therefore be used to accurately analyze data obtained in this study [42]. For this particular study, the effect of the speed reduction measure on mean speeds at each of the three stations is of concern to the research team. The mean speeds for the control condition (speed reduction measure absent) were compared with the mean speeds for the treatment conditions (speed reduction measure present) at the 95 percent confidence level assuming unequal variances. The first step in the analysis is to establish the null ( $H_0$ ) and alternative hypothesis ( $H_a$ ). The null hypothesis is that the mean speeds at each station are equal, while the alternative hypothesis is that there is a statistically significant difference between the mean speeds. The *t*-statistic value is computed as follows [43]:

$$t = \frac{Y_1 - Y_2}{\sqrt{\frac{s_1^2}{N_1} + \frac{s_2^2}{N_2}}} \quad (2)$$

where

$Y_1, Y_2$  = Mean speed for the control and treatment conditions,

$s_1, s_2$  = Sample variance for control and treatment conditions, and  
 $N_1, N_2$  = Sample size for control and treatment conditions

Based on the computed  $t$ -statistic, the  $t$  distribution critical values table is used to determine the probability value ( $p$  value) which indicates the probability that the data obtained may be significant when the null hypothesis is assumed true. As a result, if this  $p$  value is less than 0.05, then the null hypothesis (the mean speeds at each station are equal) is probably false based on a 95 percent confidence level. In comparison, if the resulting  $p$  value is larger than 0.05, the null hypothesis is not rejected and is, instead, assumed true. Significant differences in means have  $p$  values less than 0.01. The final result of the  $t$ -test indicates whether there is a statistical difference in mean speeds for both an increase and decrease with the speed reduction measure present.

### Change in Percent of Vehicles Exceeding the Speed Limit

A statistical analysis was also conducted in order to determine the effectiveness of each speed reduction measure in reducing the percent of vehicles speeding. The sites included in this study contained a variety of posted speed limits ranging from 35 to 65 mph. This statistical test measured the speeds of vehicles exceeding the speed limit by 5 mph and 10 mph. Exception was made for the speed activated sign which examined the percent of vehicles exceeding the speed limit by 3 mph, rather than by 5 mph, because a speed threshold of 3 mph above the posted speed limit was used to activate the flashing beacons. To determine if the reduction in the proportions exceeding the speed limit for both thresholds at each station was significant, hypothesis testing was conducted. The null hypothesis is that the percentage of traffic exceeding the speed limit by 5 mph or 10 mph between the control condition (countermeasure absent) and the treatment condition (countermeasure present) is equal. The  $z$ -statistic for comparing proportions taken from two independent samples is calculated using the following equation:

$$Z = \frac{(P_1 - P_2)}{\left\{ \frac{P_1 \times (1 - P_1) + P_2 \times (1 - P_2)}{N} \right\}^{0.5}} \quad (3)$$

where

$P_1$  = Proportion of traffic exceeding speed limit with no countermeasure

$P_2$  = Proportion of traffic exceeding speed limit with countermeasure, and

$n$  = Sample size.

Based on the calculated  $z$ -statistic, the standard normal distribution probability table was used to determine the corresponding  $p$  value. For resulting  $p$  values less than 0.05, the null hypothesis (that the proportion of traffic exceeding the speed limit by the set threshold is equal) is rejected. In comparison, if the resulting  $p$  value is larger than 0.05, the null hypothesis is assumed true and is not rejected. As in the  $t$ -test for equal means,  $p$  values less than 0.01 correspond to a highly significant difference in means.

### *Changes in 85th Percentile Speeds*

The 85<sup>th</sup> percentile speed represents the speed at which 85 percent of all drivers travel at or below and, as indicated from previous research, should demonstrate the largest speed reductions. The top 15 percent of the population, which represents the fastest drivers, is often used as a general rule for establishing an appropriate speed limit. Because the main objective of this study is to improve the compliance of drivers with the posted speed limit in work zones, determining the change in the 85<sup>th</sup> percentile group should provide a good indicator of effectiveness; however, under a normal distribution, these speeds are more than one standard deviation from the mean speed. Since the 85<sup>th</sup> percentile speed is not a parameter that defines the normal distribution, a parametric hypothesis test can not be conducted. Nonparametric tests can be performed when a value other than the mean is of interest; however, additional assumptions must be made about the distribution, thereby decreasing the accuracy of the test.

### ***Drone Radar Data Analysis***

The data collected for the drone radar were divided into three groups for analysis: passenger cars, tractor trailers, and radar detector users. Statistical tests on mean speeds for the groups representing either tractor trailers or individual vehicles with radar detectors were limited due to their small sample size; however, two interstate locations contained enough samples for tractor trailers to be statistically analyzed over a three-hour period.

During a few hours of data collection in this research, work zone conditions changed, causing speeds to decrease. As a result, these hours of data collection were eliminated from the statistical analysis. Specifically, during the I-585 study for both day and evening periods, Station 1 data was affected by construction causing a lane closure, allowing only one hour of data to be recorded, meaning the following hours were not considered in the analysis. Since Stations 2 and 3 were not affected by this construction, these data were included.

In general, results from this study show a 2 mph decrease in mean speeds of all highway vehicles and a 6 mph decrease in those equipped with radar detectors, as indicated in Table 5.1. This table combines all the sites' mean speed reductions for both secondary and interstate roadways for the entire traffic stream. As expected, tractor trailers have a higher reduction in mean speeds on interstates because secondary roads have lower design speeds than interstate facilities.

**Table 5.1 Comparison of Mean Speed Reductions by Road and Vehicle Type**

<b>Roadway Type</b>	<b>Speed Limit Range (mph)</b>	<b>Passenger Car (mph)</b>	<b>Tractor Trailers (mph)</b>	<b>Radar Detector Users (mph)</b>
Secondary Roads	35 to 55	1.86	1.42	6.1
Interstates	45 to 65	1.34	2.06	5.4

Table 5.2 displays ranges of speed reduction, with the results, in many cases, indicating that the drone radar caused minor reductions in the mean speed, the 85<sup>th</sup> percentile speed, and the percentage of vehicles exceeding the speed limit in the overall traffic stream. Individual vehicles equipped with radar detectors exhibited larger reductions in mean speed. Although the sample size for this vehicle category was insufficient to run a statistical test, observation in the field and the consistency in their speed reduction indicates the likelihood of a significant change. This study also separately analyzed both passenger cars and tractor trailers, finding that passenger cars with radar detectors show greater reductions in speed. The research tested only the short term impact of drone radar, not its long-term effects. The data indicates that drone radar can result in significant reductions in vehicle speed in radar-equipped vehicles over a three-hour period.

Table 5.3 presents the results for the entire traffic stream at each of the five drone radar sites, illustrating how speeds varied by site and time of day. This table indicates that on average, the presence of drone radar caused mean speeds to decrease as much as 3.5 mph. The 85<sup>th</sup> percentile speed had reductions that reached a maximum of 5.2 mph. As a whole, the results of this investigation show relatively minor decreases in speed for all categories of the statistical analysis.

**Table 5.2 Summary of Overall Speed Reductions**

<b>Measure of Effectiveness</b>	<b>Speed Reduction Range for Entire Traffic Stream</b>	<b>Speed Reduction Range for Passenger Cars</b>	<b>Speed Reduction Range for Tractor Trailers</b>
Mean Speed	0.3 – 3.5 mph	0.2 – 3.4 mph	1.2 - 2.7 mph
Mean Speed of Radar Detector Users	4.6 -7.9 mph	4.6 -7.9 mph	4.6 -7.9 mph
85th Percentile Speed	1.0 – 5.2 mph	0.4 – 6.0 mph	1.0 - 3.0 mph
% of Vehicles Exceeding Speed Limit by 5 mph	0.0 – 20.7%	2.8 – 23.0%	5.3 – 5.5%
% of Vehicles Exceeding Speed Limit by 10 mph	0.7 – 6.0%	0.5 – 6.3%	0.0%

**Table 5.3 Summary of Entire Traffic Stream by Site**

Location (County)	% Tractor Trailer	% Radar Detector	Mean Speed Reduction (mph)	85th Percentile Reduction (mph)	% Exceeding Speed Limit by 5 mph	% Exceeding Speed Limit by 10 mph
Laurens SC -72	6.0-16.0	2.0-8.0	0.30-0.90	No Reduction	0.0-0.5	No Reduction
Greenville I-385 AM & PM	10.0-15.0	3.0	0.90-1.50	1.0-2.0	5.3-16.3	2.5-3.1
	11.0	2.0-5.0	1.1-2.5	3.3-5.2	14.9-20.7	4.6-5.4
Spartanburg I-85	16.0-27.0	2.0-4.0	1.1-1.9	1.0-2.0	2.1-13.4	1.4-2.4
Oconee S-488	2.0-5.0	1.0-4.0	1.4-3.5	2.0-3.0	6.4-11.9	0.7-1.3
Spartanburg I-585 AM & PM	7.0-9.0	4.0-8.0	2.2-2.3	2.0	11.6-14.2	3.7-6.6
	2.0-6.0	2.0-8.0	No Reduction	No Reduction	No Reduction	No Reduction

The ranges in percentage of radar detector use for the various types of roadways and vehicles included in this research are, on average, slightly higher than the findings of the Georgia Tech study of 2000, as indicated in Table 5.4. It should be noted, however, that the RDD used in the Georgia Tech Study has been found to be less reliable than the RDD used in this study [14]. The low radar detector use in South Carolina verifies the results shown in mean speed reductions for the various types of work zones. Overall, the drone radar is significantly effective only when looking at the mean speeds of those equipped with radar detectors, with speed reductions ranging from 4.6 to 7.9 mph.

**Table 5.4 Comparison of Radar Detector Use in SC and GA**

Roadway Type	Passenger Cars Radar Detector %			Tractor Trailers Radar Detector %		
	South Carolina		Georgia	South Carolina		Georgia
	Range	Mean		Range	Mean	
Rural Route Site	1.0-4.0%	2.2%	1.5%	0.0-25.0%	7.1%	2.0%
State Route Site	2.0-6.0%	5.0%	1.6%	N/A	N/A	0.0%
Interstate Site	1.0-8.0%	3.1%	2.7%	3.0-18.0%	7.5%	5.4%

A comparison, shown in Table 5.5, between mean speeds of the entire traffic stream and those equipped with radar detectors demonstrates a major difference between the two groups

with the drone radar off. Radar detector users are traveling much faster; however, when the drone is activated, the opposite trend occurs.

**Table 5.5 Comparison of Mean Speeds Between Entire Traffic Stream and Radar Detector Users with Drone Radar Off and On**

Location (County)	Time of Day	Speed Limit (mph)	Mean Speed with Drone Off (mph)		Mean Speed with Drone On (mph)	
			Entire Traffic Stream	Radar Detector Users	Entire Traffic Stream	Radar Detector Users
Laurens SC -72	AM	55	56.1	N/A	54.7	N/A
Greenville I-385	AM	65	68.6	N/A	68.3	N/A
	PM	65	65.8	71.0	65.8	63.1
Spartanburg I-85	AM	60	62.3	64.3	63.3	59.9
Oconee S-488	AM	35	34.8	39.3	36.7	33.2
Spartanburg I-585	AM	45	54.9	55.6	49.8	50.4
	PM	45	45.5	54.8	47.3	48.8

### ***Changeable Message Sign with Radar Data Analysis***

The data collected for the two phases of the changeable message sign with radar (CMR) evaluation was examined to determine the changes in the 85<sup>th</sup> percentile speed, mean speed, frequency of speeds, and number of observed vehicles speeding.

Results from a two-sample *t*-test show a significant reduction in mean speeds at Station 2 for all of the message sequences at all of the sites with only one exception. The results from the two-sample *z* test conducted on the percentage of vehicles exceeding the speed limit indicate that all of the message sequences displayed on the CMR produced a significant reduction in vehicles exceeding the speed limit by more than 5 mph at all sites and by more than 10 mph at almost all sites. The message 2 sequence used in Phase 1 on SC-72 westbound was the only exception because there were very few vehicles speeding by more than 10 mph at all three data collection stations. A general discussion of the results is given in the following sections for both data collection phases.

#### ***Phase One: Evaluation of CMR Message Sequences***

All four messages exhibited a decrease in mean speeds between the three data collection stations. For the two sites studied in Phase 1, the mean speeds observed at Station 1 were relatively close to the posted speed limits. For each successive station, a decrease in the mean speed was

observed through the study area. For the I-585 site, the mean speed was reduced 7 to 9 mph between the first two stations, but remained the same, or nearly the same, between the second and third stations. Speed reductions differed at the SC-72 site, where the drop in mean speeds ranged from 5 to 7 mph between the first two stations, and dropped again at the third station. The continued deceleration may be attributable to the 55 mph speed limit along SC-72. Because traffic was traveling faster at this site, vehicles may not have had enough distance to decelerate to a lower sustained speed before reaching Station 2. Despite this difference between the two sites, the total mean speed reductions between the first and last stations were 7 to 10 mph for I-585 and 9 to 14 mph for SC-72. The mean speeds observed at Station 1 and the speed reductions between the stations are provided for the I-585 site in Table 5.6 and for the SC-72 site in Table 5.7.

**Table 5.6 I-585 Observed Mean Speeds and Speed Reductions**

<b>I-585, speed limit 45 mph</b>				
<b>Message</b>	<b>Observed Mean Speeds at Station 1</b>	<b>Reduction in Mean Speeds</b>		
		<b>Station 1 to 2</b>	<b>Station 2 to 3</b>	<b>Station 1 to 3</b>
	<b>mph</b>	<b>mph</b>	<b>mph</b>	<b>mph</b>
<b>1</b>	47	9	1	10
<b>2</b>	46	9	0	9
<b>3</b>	43	7	0	7
<b>4</b>	44	7	0	7

**Table 5.7 SC-72 Observed Mean Speeds and Speed Reductions**

<b>SC-72, speed limit 55 mph</b>				
<b>Message</b>	<b>Observed Mean Speeds at Station 1</b>	<b>Reduction in Mean Speeds</b>		
		<b>Station 1 to 2</b>	<b>Station 2 to 3</b>	<b>Station 1 to 3</b>
	<b>mph</b>	<b>mph</b>	<b>mph</b>	<b>mph</b>
<b>1</b>	54	5	9	14
<b>2</b>	55	5	4	9
<b>3</b>	54	7	3	10
<b>4</b>	54	6	4	10

All messages demonstrated a decrease in the 85<sup>th</sup> percentile speed between the three stations. The largest decreases occurred at the I-585 site and ranged from 6 to 9 mph. SC-72 showed a reduction in the 85<sup>th</sup> percentile speed ranging from 2 to 4 mph. Table 5.8 lists the observed 85<sup>th</sup> percentile speeds and speed reductions between stations for I-585, while Table 5.9 presents the 85<sup>th</sup> percentile speeds and speed reductions between stations for SC-72.

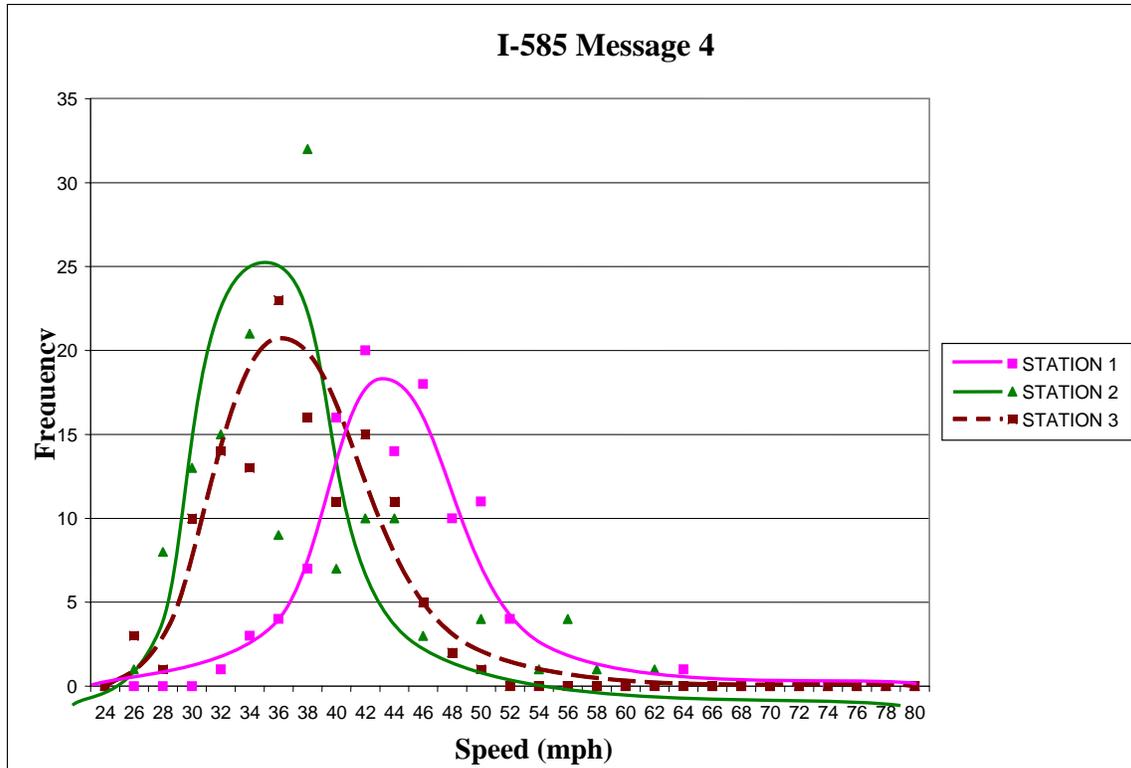
**Table 5.8 I-585 Observed 85th Percentile Speeds and Speed Reductions**

<b>I-585, speed limit 45 mph</b>				
<b>Message</b>	<b>85th Percentile Speed at Station 1 mph</b>	<b>Reduction in 85th Percentile Speeds</b>		
		<b>Station 1 to 2 mph</b>	<b>Station 2 to 3 mph</b>	<b>Station 1 to 3 mph</b>
<b>1</b>	53	9	1	10
<b>2</b>	51	8	0	8
<b>3</b>	48	6	2	8
<b>4</b>	50	7	1	7

**Table 5.9 SC-72 85th Percentile Speeds and Speed Reductions**

<b>SC-72, speed limit 55 mph</b>				
<b>Message</b>	<b>85th Percentile Speed at Station 1 mph</b>	<b>Reduction in 85th Percentile Speeds</b>		
		<b>Station 1 to 2 mph</b>	<b>Station 2 to 3 mph</b>	<b>Station 1 to 3 mph</b>
<b>1</b>	58	3	8	11
<b>2</b>	59	4	0	4
<b>3</b>	58	4	3	7
<b>4</b>	57	2	3	5

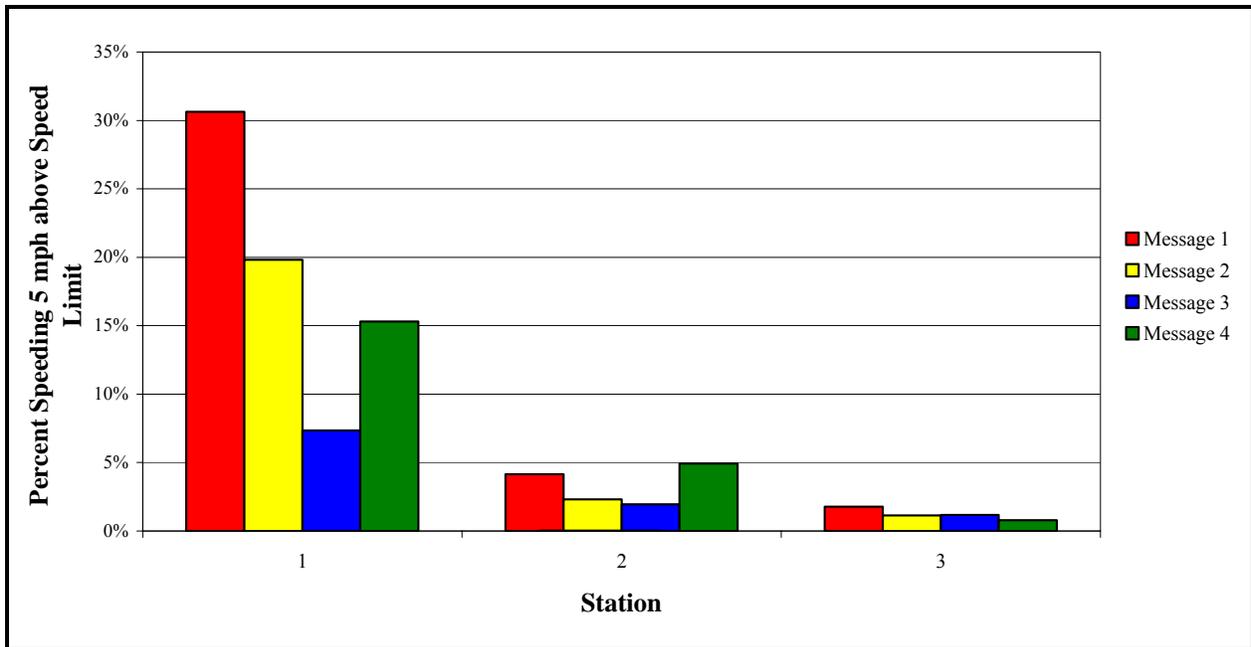
The frequency and cumulative frequency of observed speeds were determined by stratifying vehicle speed data into 2 mph increments. Frequency tables and graphs were created to provide a representation of motorist behavior across data collection stations within the study area limits. Figure 5.1 depicts the frequency distribution of speeds for message sequence 4 observed at each of the three data collection stations. The figure clearly indicates that the presence of the CMR produced a beneficial shift in the speed characteristics of vehicles. The rightmost curve, representing Station 1, exhibits a speed distribution where the mode speed (speed of highest occurrence) on the fitted curves is nearly 10 mph greater than the mode speeds for the other two curves. The speed distribution curves for Stations 2 and 3 are relatively similar indicating that drivers are maintaining their speed reduction.



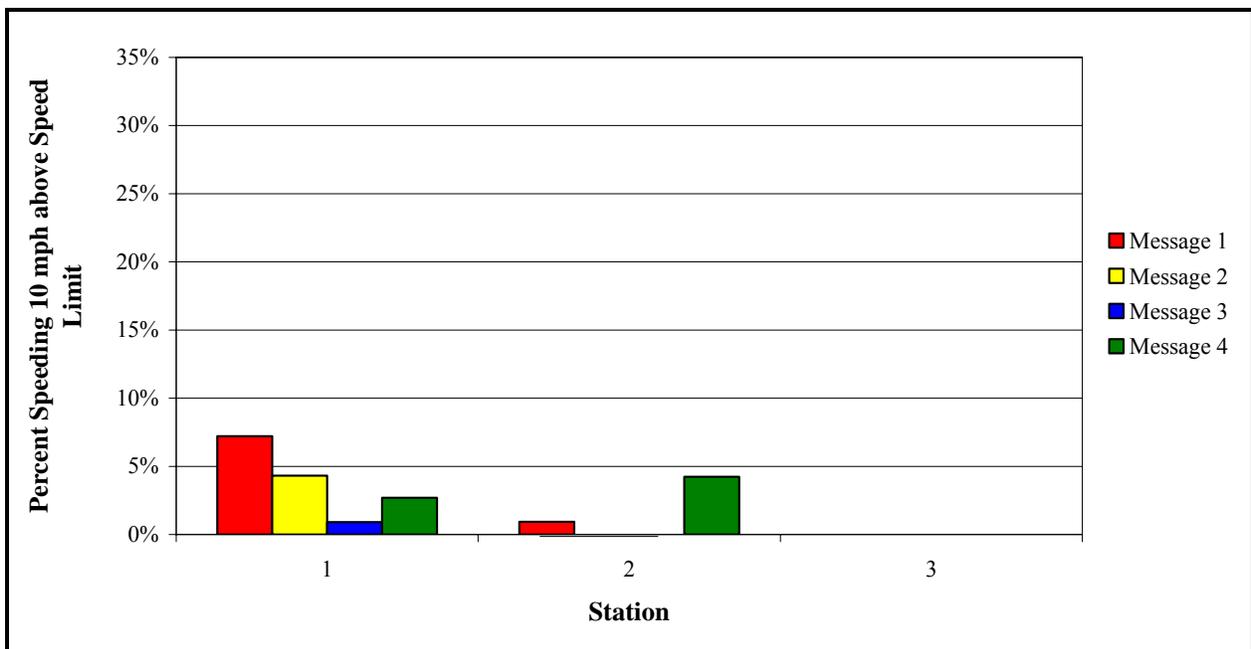
**Figure 5.1 Speed Frequency Graph for I-585 Message 4**

The percentage of drivers speeding in excess of 5 or 10 mph decreased for all messages at both sites, with one exception. Message 2 at SC-72 produced a small decrease in the percentage of drivers speeding in excess of 5 mph between the first and second stations, but nearly a half-percent increase from the first to the last station. In the same population, the percentage of drivers speeding by more than 10 mph increased from 0 percent at Station 1 to 1.1 percent at Station 2.

The I-585 data collection site experienced a decrease in the number of vehicles speeding in excess of 5 mph between stations 1 and 2, and 1 and 3 for all CMR message sequences. The site experienced a decrease in the number of vehicles speeding in excess of 10 mph between stations 1 and 3 for all CMR message sequences and for all but one message sequence between stations 1 and 2. Figure 5.2 and Figure 5.3 summarize percent drivers in both speeding categories for all four CMR message sequences throughout data collection stations on I-585. It should be noted that CMR message sequence 1 caused the highest observed reductions in the percent of drivers speeding. This was due to the unusually high number of vehicles traveling at speeds greater than 5 mph over the speed limit when message sequence 1 was deployed. Even though message sequence 1 performed well, it was not studied in the second phase of this study because the sequence has been used extensively by other researchers who had similar findings. Message Sequence 1 was primarily used to verify the validity of data collection methods and analysis procedures used in Phase 1, and essentially served as a baseline for further study.



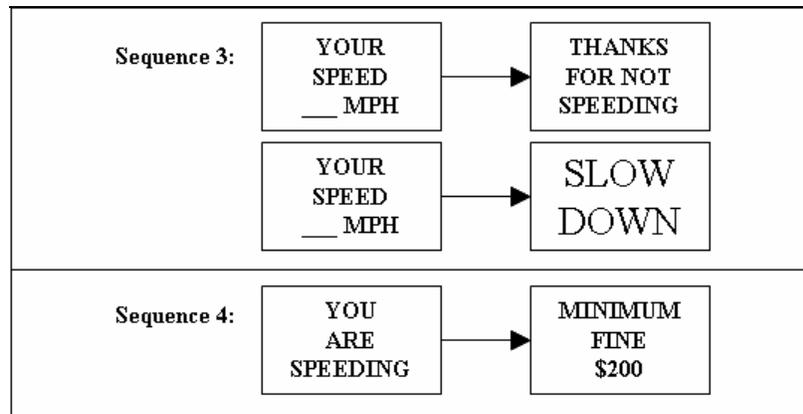
**Figure 5.2 I-585 Drivers Speeding 5 mph or more above the Speed Limit**



**Figure 5.3 I-585 Drivers Speeding 10 mph or more above the Speed Limit**

Message sequences 2 and 3 performed similarly in the study, and were not significantly different from each other. The comparable performance of these two messages was likely due to the fact that the same message was displayed to speeders, with the only difference being the message displayed to non-speeders. Message 3 was chosen for further study because it involved a more novel approach to driver feedback and exhibited a slightly better performance, albeit not supported through statistically proven data results. Message Sequence 4 performed very well between stations 1 and 3. With elimination of Messages 1 and 2, the forth message sequence

was chosen because the literature review indicated that, like message 3, it has not been studied on other projects.



**Figure 5.4 Messages Sequences Selected for Study in Phase 2**

*Phase Two: Evaluation of CMR Message Sequences 3 and 4*

CMR message sequences 3 and 4 (Figure 5.4) were evaluated in greater detail at four work zone locations in a similar manner as described for Phase 1. A summary of 85<sup>th</sup> percentile speed reductions for each site is provided in Table 5.10. The average 85<sup>th</sup> percentile speed observed at Station 1 for each of the three 45 mph work zone locations (I-585, SC-101 and SC-290) was determined as 53 mph for both message sequences. In the 55 mph work zone (SC-72), the 85<sup>th</sup> percentile speed at station 1 was 60 mph. Reductions in the 85<sup>th</sup> percentile speeds differed significantly between the three 45 mph work zones and the one 55 mph work zone. SC-101 and SC-290 exhibited reductions in average 85<sup>th</sup> percentile speed of approximately 10 mph for both message sequences between the first two stations, and reductions of 4 to 5 mph between stations 1 and 3. The SC-72 location exhibited the greatest speed reduction between stations 1 and 3. This indicates that drivers were still decelerating after station 2.

**Table 5.10 Observed Reductions in 85th Percentile Speeds**

Site	Characteristics	Station 1 to 2		Station 1 to 3	
		Message 3	Message 4	Message 3	Message 4
<b>SC-101</b>	45 mph 2-lane	10	8	3	3
<b>SC-290</b>	45 mph 2-lane	10	13	4	7
	<b>Mean</b>	10	10.5	3.5	5
<b>I-585</b>	45 mph 4-lane	5	-6	2	2
<b>SC-72</b>	55 mph 2 lane	8	4	10	10

A summary of the Phase 2 mean speed data for message sequences 3 and 4 is shown in Table 5.11. In comparing mean speeds for the three stations, the observed trends were similar to those noted for the 85<sup>th</sup> percentile speeds. The greatest reduction in speeds occurred between the first

two stations, and nearly half of the reduced speed was regained by Station 3. Generally, mean speeds dropped from approximately 3 mph above the posted speed limit at the first station to between 5 and 8 mph below the speed limit at the second station. At the last station, most mean speeds were measured to be at, or slightly below, the posted speed limit. This fluctuation in speed may be due to an over-reaction by drivers to the CMR. The accelerating back to the speed limit by the last station may suggest drivers realized they had overcompensated. Additional data collection at a fourth data station located further downstream would be useful in helping to confirm this hypothesis.

**Table 5.11 Observed Reduction in Mean Speeds**

Site	Characteristics	Station 1 to 2		Station 1 to 3	
		Message 3	Message 4	Message 3	Message 4
SC-101	45 mph 2-lane	10	10	3	6
SC-290	45 mph 2-lane	12	12	6	7
	<b>Mean</b>	11	11	4.5	6.5
I-585	45 mph 4-lane	7	0	2	1
SC-72	55 mph 2 lane	8	6	14	11

In general, the frequency of measured speeds was determined to be similar to that observed in the Phase 1 data collection. Aggregated data for the Station 1 frequency curve produced a higher distribution of speeds than stations 2 and 3. Station 2 realized a wider disbursement of driver speeds, demonstrated by a wider bell curve and higher standard deviation of 7.4 mph. The second station also typically exhibited the lowest mean speed of the three data collection stations. Station 3 generally peaked between the first two curves and its distribution was varied. In some cases, more drivers were near the mean speed at Station 3 than any other station, but other cases showed a wider distribution of speeds and a considerably flatter curve, as demonstrated by the frequency curve for message sequence 4 at SC-290, shown in Figure 5.5. Furthermore, the percentage of drivers speeding 5 mph or more over the speed limit behaved differently in Phase 2 than in Phase 1. In the first phase, a continued reduction was observed throughout the work zone for all CMR message sequences. In the second phase, only message sequence 4 exhibited this trend. CMR message sequence 3 had a percentage at Station 3 that was more than twice that of Station 2, but still less than half of Station 1. Figure 5.6 summarizes the magnitude of speeders for this speed category.

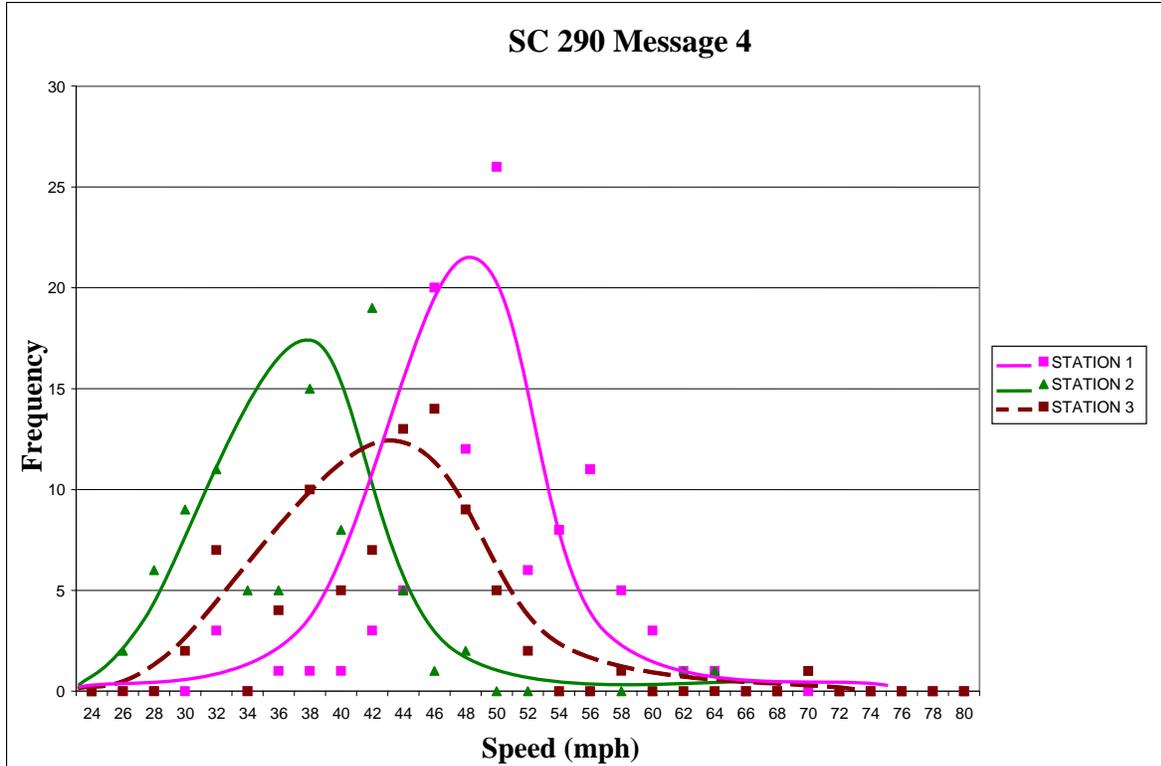
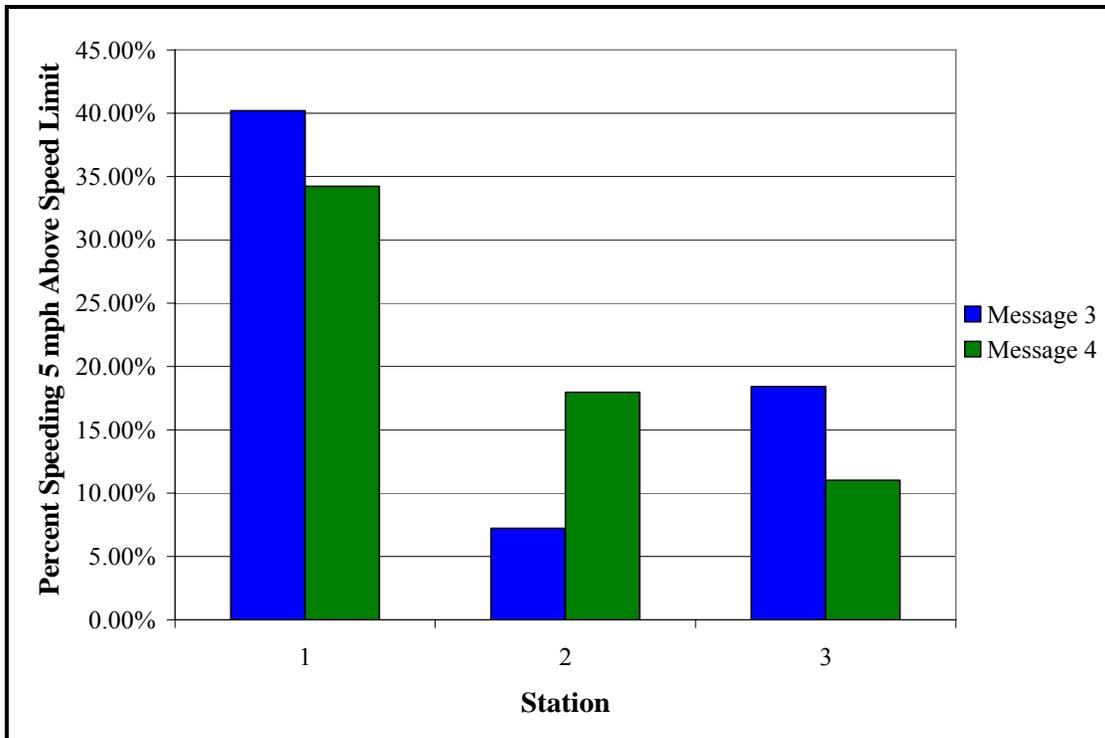
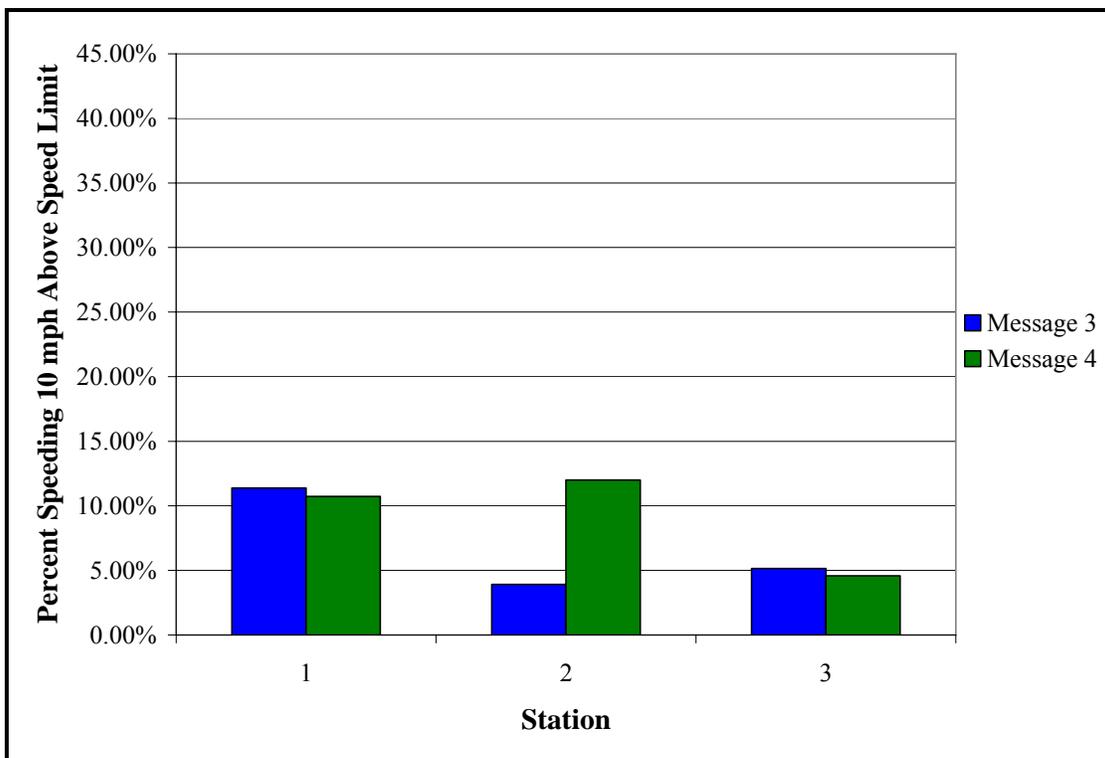


Figure 5.5 Frequency Curve for SC-290 Message 4

The same relationship was observed for drivers speeding by 10 mph or more over the speed limit, with the exception of the decrease in response to message sequence 4. For the first category, the majority of the decrease occurred between the first and second stations. For those speeding 10 mph and above, the largest drop occurred between stations 2 and 3. This difference may be due to increased deceleration time required for higher speeds and could account for the small decrease between the first two stations. These results are summarized in Figure 5.7.



**Figure 5.6 Percent Speeding 5 mph or more above the Speed Limit**



**Figure 5.7 Speeding 10 mph or more above the Speed Limit**

In general, CMR Message Sequences were observed to reduce mean speed, 85<sup>th</sup> percentile speed, and percentage of drivers exceeding the speed limit. The mean speed decreased between stations 1 and 3 from speeds as high as 6 mph above the speed limit to speeds typically within a 2 mph range of the speed limit. The 85<sup>th</sup> percentile speeds were observed as high as 10 mph above the speed limit before the sign, but dropped to about 5 mph above the speed limit at the last station. The percent of drivers speeding also improved for all messages, varying among the messages.

### ***Speed Activated Sign Data Analysis***

The two-sample *t*-test showed a significant reduction in the mean speeds at Station 2 (150 to 200 feet past the sign) for nearly all of the data sets when the speed-activated sign was on. Results from Station 1 (more than 500 feet before the sign) indicated that in most cases there was not a significant reduction in speed for the two conditions before drivers encountered the sign location. The lack of speed reduction was expected at this station because the station was located at such a distance away that the speed-activated sign could not be seen. Results from Station 3 (more than 800 feet past the sign) showed a significant reduction in the means for the majority of the treatment data sets. The test was not conducted for Stations 1 and 3 for the initial projects because researchers identified the need for Station 1 and 3 after these locations were already collected.

The results from the two-sample *z*-test conducted on the percentage of vehicles exceeding the speed limit indicates that the sign produced a significant reduction in vehicles exceeding the speed limit by more than 3 mph and more than 10 mph. For Station 2, all data sets indicated a significant reduction in the percentage of vehicles exceeding the speed limit by more than 3 mph. A significant reduction in vehicles speeding by 10 mph or more was present in all but two treatment sets of data; however, these two sets indicated that less than 8 percent of all vehicles were speeding by more than 10 mph for the control condition (speed-activated sign off).

Combining all treatment and control data, the histogram in Figure 5.8 shows that, when the speed-activated sign was on, far more people obeyed the speed limit, and approximately 50 percent fewer vehicles traveled at speeds in excess of 55 mph, or 10 mph over the posted speed limit. Also, a greater number of vehicles traveled at or less than the posted speed limit with the speed-activated sign on.

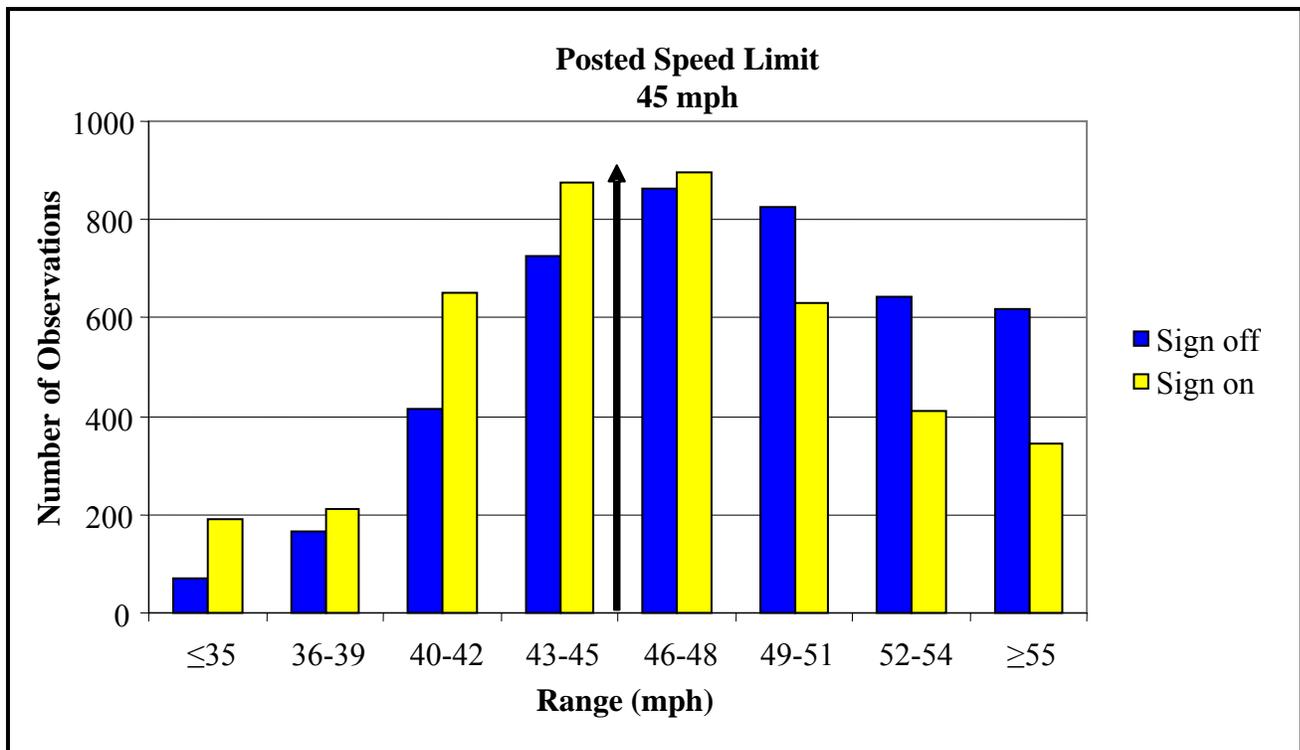


Figure 5.8 Histogram of Speed Data

Table 5.12 summarizes the results for all data collection sites and indicates that the speed-activated sign caused reductions in mean speed, 85<sup>th</sup> percentile speed, and percentage of vehicles exceeding the speed limit.

Table 5.12 Summary of Overall Speed Reductions

Measure of Effectiveness	Overall Speed Reductions		Overall Speed Reductions during Periods of Excessive Speeding	
	Average Speed Reduction	Speed Reduction Range	Average Speed Reduction	Speed Reduction Range
Mean Speed	3.29 mph	2.0 - 6.0 mph	4.12 mph	2.5 - 6.0 mph
85th Percentile Speed	3.22 mph	1.0 - 6.5 mph	3.67 mph	1.0 - 6.5 mph
% of Vehicles Exceeding Speed Limit by 3mph+	23.42 %	15.0 - 41.5 %	31.71 %	18.5 - 41.5 %
% of Vehicles Exceeding Speed Limit by 10 mph+	5.75 %	0.5 - 20.0 %	9.98 %	2.5 - 18.0 %

The large variation in the ranges of reductions for the measures of effectiveness can be attributed to the variation of the number of vehicles traveling over the posted speed limit for each period. The rightmost columns of the table show a summary of speed reduction averages and ranges for the periods when at least 50 percent or more of the volume was exceeding the speed limit by

three mph or more. Through this comparison, it has become evident that the speed-activated sign is most effective during periods of excessive speeding.

### ***Modified Speed Activated Sign Data Analysis***

Based on the results obtained from the initial study, an additional phase of research was developed. First, the speed-activated sign was redesigned to use a single modular power supply that could power both the radar unit and the flasher. The benefit of having a solar flasher in the first phase was negated because the radar unit could not be powered by the flasher's small three-volt solar cell thus a battery system was still required. Further, the solar flasher used initially was not designed to be charged by an alternative electrical source, thus, it was inconvenient to use, as it had to be left in sunlight to charge. This was not always practical. The battery packs chosen for the second phase were standard 12-volt flashing beacon battery packs that contain two six-volt lantern batteries. Rechargeable lantern batteries were purchased and fitted in the battery packs. The benefit of these battery packs is that they are quite common in work zone use and are easily interchangeable making them more practical in widespread field application.

Second, another data collection phase was added to the study to identify the effectiveness of using the speed-activated sign on multi-lane highways and freeways. A second sign was constructed so that two signs placed on either side of the same direction of highway could be studied. Initial field-testing was done in one direction of a divided highway near the Clemson University campus and researchers found that regardless of the orientation of the signs, the radar units could not be focused on a single lane. Some radar spillover was inevitable, but most could be minimized through trial and error adjustment.

Third, additional data collection was done to study the effectiveness of using the speed-activated sign at maintenance sites.

### ***Study of Two-Sign Configuration***

The researchers tested the two-sign configuration on Interstate 585 in Spartanburg, South Carolina and different directions of a multi-lane highway (SR-278) in Hilton Head, South Carolina. Histograms showing the performance of the signs are provided for the I-585 site in Figure 5.9 and for the Hilton Head site in Figure 5.10. Station 1 was used as the control condition for each of the sites. The histograms clearly indicated that there was a beneficial shift in the speed characteristics of vehicles due to the signs. It is noteworthy that Station 3 on both of the histograms shows the lowest speeds suggesting that vehicles continued decelerating and maintained lower speeds well after the signs.

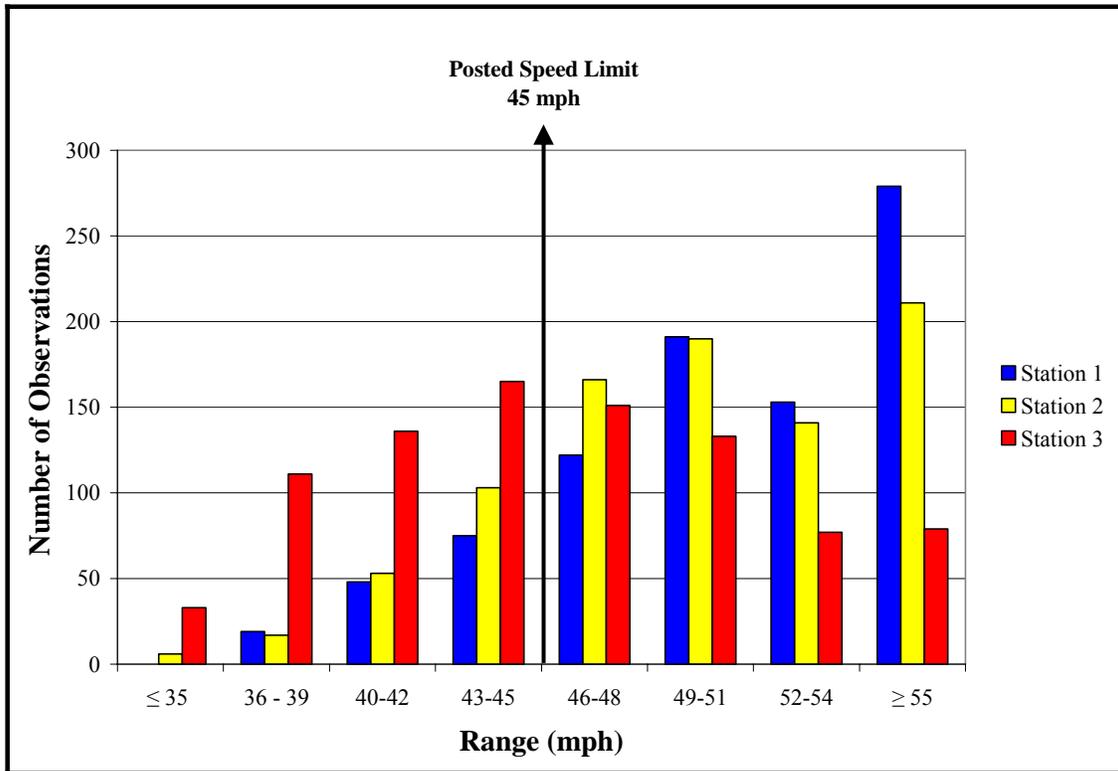


Figure 5.9 Histogram of Speed Data for Two Sign Configuration at I-585

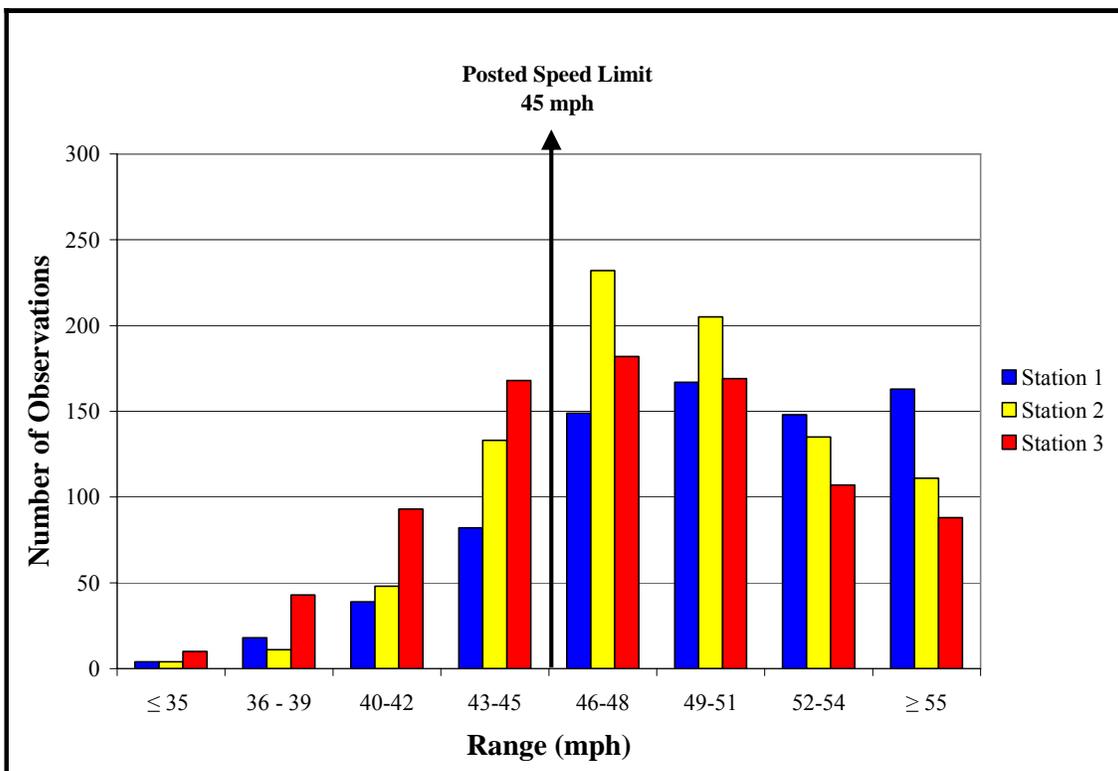


Figure 5.10 Histogram of Speed Data for Two Sign Configuration at Hilton Head (SR-278)

Table 5.13 summarizes the results for the multi-lane data collection sites and indicates that the speed-activated sign caused reductions in mean speed, 85<sup>th</sup>-percentile speed, and percentage of vehicles exceeding the speed limit for freeways and multi-lane highways. Statistical tests on the multi-lane and interstate freeway data indicated that the reductions for each project were significant at the 95-percent confidence level.

**Table 5.13 Summary of Speed Reductions for Multi-lane Sites**

Measure of Effectiveness	Average Speed Reduction		Speed Reduction Range	
	US Highway	Interstate	US Highway	Interstate
Roadway Type				
Mean Speed	2.6 mph	6 mph	0.9-3.3 mph	2.9-10.3 mph
85th Percentile	2.5 mph	4.7 mph	1.6-4.7 mph	3.0-11.2 mph
% of Vehicles Exceeding Speed Limit by 3 mph	19%	37%	10.5-28.8 %	7.6-67.2 %
% of Vehicles Exceeding Speed Limit by 10 mph	7.8%	20.6%	3.7-20 %	9.5-32.7 %

*Study of Speed Activated Sign at Maintenance Sites*

The speed activated sign was tested at 2 maintenance site locations. The analysis indicated that the sign was very effective in lowering speeds, reducing the 85th percentile speed, and reducing the proportion of vehicles exceeding the speed limit by 5 mph and 10 mph. The summary of speed reductions at the two maintenance sites is shown in Table 5.14.

**Table 5.14 Summary of Speed Reductions for Maintenance Sites**

Measure of Effectiveness	Average Speed Reduction	Speed Reduction Range
Mean speed	6.4 mph	3.7 - 9.0 mph
85th Percentile speed	5.5 mph	3.0 - 8.0 mph
% of Vehicles exceeding speed limit by 10mph	4.7 %	0.0 - 9.5 %

***Speed Monitoring Display with CMS Data Analysis***

*Study of Speed Monitoring Display with CMS at Construction Sites*

Results from the *t*-test show a significant change in mean speeds between stations 1 and 3 signifying that the speed monitoring display (SMD) with CMS is effective in reducing mean speeds through work zone construction sites.

Table 5.15 provides a summary of speed reductions for all the construction work zones. The speed reduction for vehicles exceeding the speed limit by 5 mph is prominent. An average 30% reduction in vehicles exceeding the speed limit by 5 mph was experienced as a result of the SMD with CMS. A 57% reduction occurred at one site. The same comparison for vehicles exceeding by 10mph showed an average 12.6% reduction.

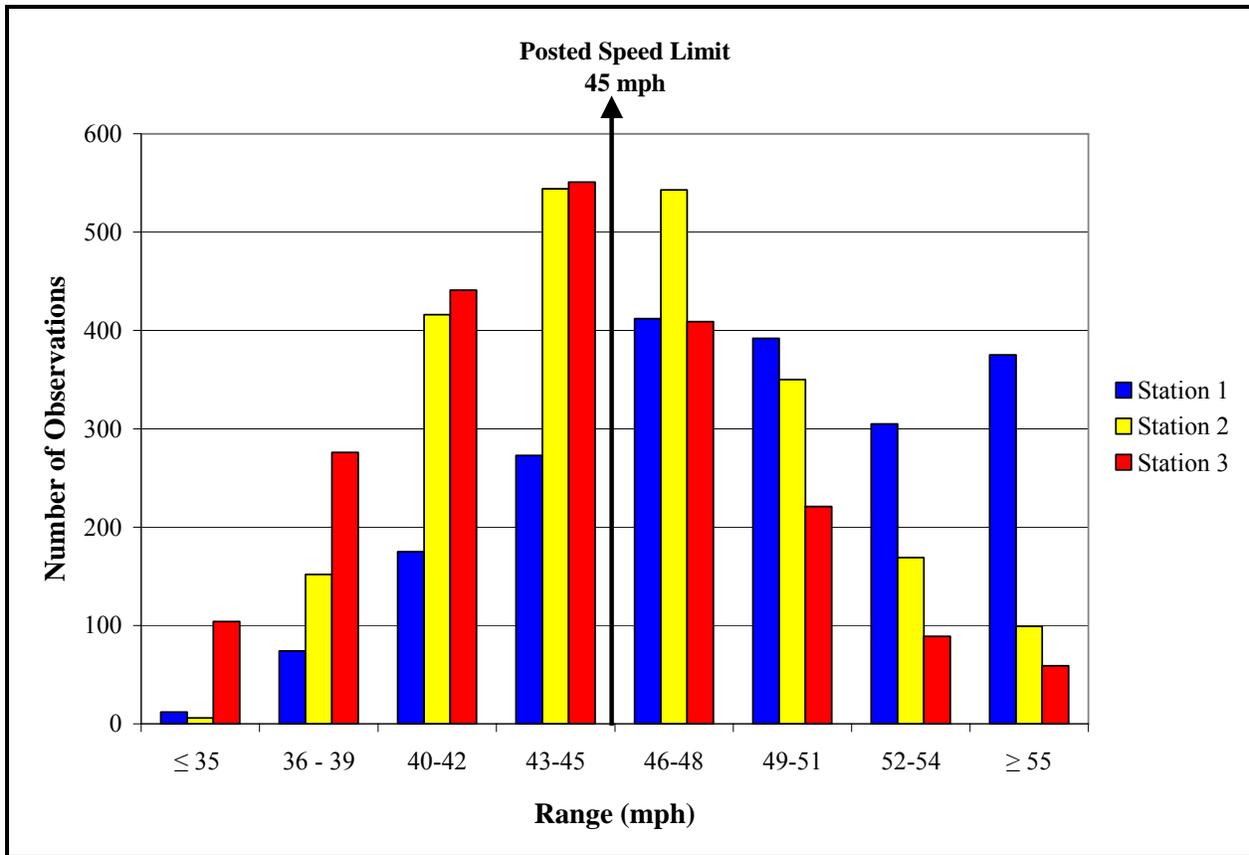
**Table 5.15 Summary of Overall Speed Reductions in Construction Work Zones**

Measure of effectiveness	Average Speed reduction	Speed reduction range
Mean speed	5.1 mph	1.1 mph – 9.8 mph
85 <sup>th</sup> Percentile speed	6.6 mph	2 mph-11.5 mph
% of Vehicles exceeding speed limit by 5mph	30%	5.9% – 57%
% of Vehicles exceeding speed limit by 10mph	12.6%	1.1% - 21.6%

As shown in Table 5.15, mean speed reductions ranged from 1.1 to 9.8 mph with an average reduction of 5.1 mph. The large range in mean speed reductions can be attributed to the disparate mean speeds determined for Station 1 for each of the study locations. Some sites were noted as having initial mean speeds almost equal to the posted speed limit, so mean speed reductions due to additional devices would be expected to be low. The correlation between the initial mean speed and the posted speed limit for a certain site indicates how the SMD with CMS may have functioned within that particular work zone. Drivers traveling at or below the posted speed limit were shown a basic "STAY ALERT" message, whereas drivers traveling above the speed limit were specifically warned by a "WATCH SPEED" message. At sites where the mean speed was comparable to the posted limit more drivers may have seen the generic alert message and reacted by maintaining the same speed. Conversely, at sites where the initial mean speed greatly exceeded the speed limit, drivers may have reacted to the warning message by reducing their speeds. This is evident from Table 5.16 that shows the passenger car mean speed at Station 1 as well as the change in the mean speeds from station to station. All three locations shown had posted speed limits of 45 mph. The table shows that for higher mean speeds the total reduction from Station 1 to 3 is around 6 mph, indicating that the sign is effective for higher speeds. Figure 5.11 clearly shows a reduction in the distribution of speeds from station 1 to stations 2 and 3.

**Table 5.16 Mean Speed Reductions for Passenger Cars by Site and Station**

Site Location	Date	Observed Mean Speeds At Station 1 (mph)	Difference from 45 mph Posted Limit (mph)	Reduction in Mean Speeds		
				Station 1 to 2 (mph)	Station 2 to 3 (mph)	Station 1 to 3 (mph)
SC 101	20 Apr	50.67	+ 5.67	5.93	0.10	5.90
	9 May	46.50	+ 1.5	1.00	7.40	8.37
US 278	1 Jun	45.60	+ 0.6	0.18	1.77	2.00
	2 Jun	53.77	+ 8.77	5.27	1.47	6.73
SC 121	22 May	50.93	+ 5.93	5.80	0.43	5.40
	23 May	46.67	+ 1.67	1.93	0.13	2.00



**Figure 5.11 Histogram of Speed Data for SMD with CMS in Construction Work Zones**

Table 5.17 shows 85<sup>th</sup> percentile speeds for the sites at station 1 along with the reduction in 85<sup>th</sup> percentile speed between the stations. When comparing the 85<sup>th</sup> percentile speeds, reductions range from 1.6 to 6.4 mph between stations 1 and 2 and from 2.9 to over 10 mph between stations 1 and 3.

**Table 5.17 Observed Reductions in 85th Percentile Speeds by Construction Site and Station**

Site Location	Date	Observed 85th Percentile Speeds at Station 1 (mph)	85th Percentile Reduction		
			Station 1 to 2 (mph)	Station 2 to 3 (mph)	Station 1 to 3 (mph)
SC-101	20 Apr.	55.90	5.66	1.00	6.60
	9 May	52.16	2.33	8.00	10.33
US-278	1 Jun.	50.17	1.66	1.27	2.93
	2 Jun.	58.50	5.30	1.47	6.77
SC-121	22 May	56.20	6.40	0.47	6.93
	23 May	52.30	3.10	0.00	3.10

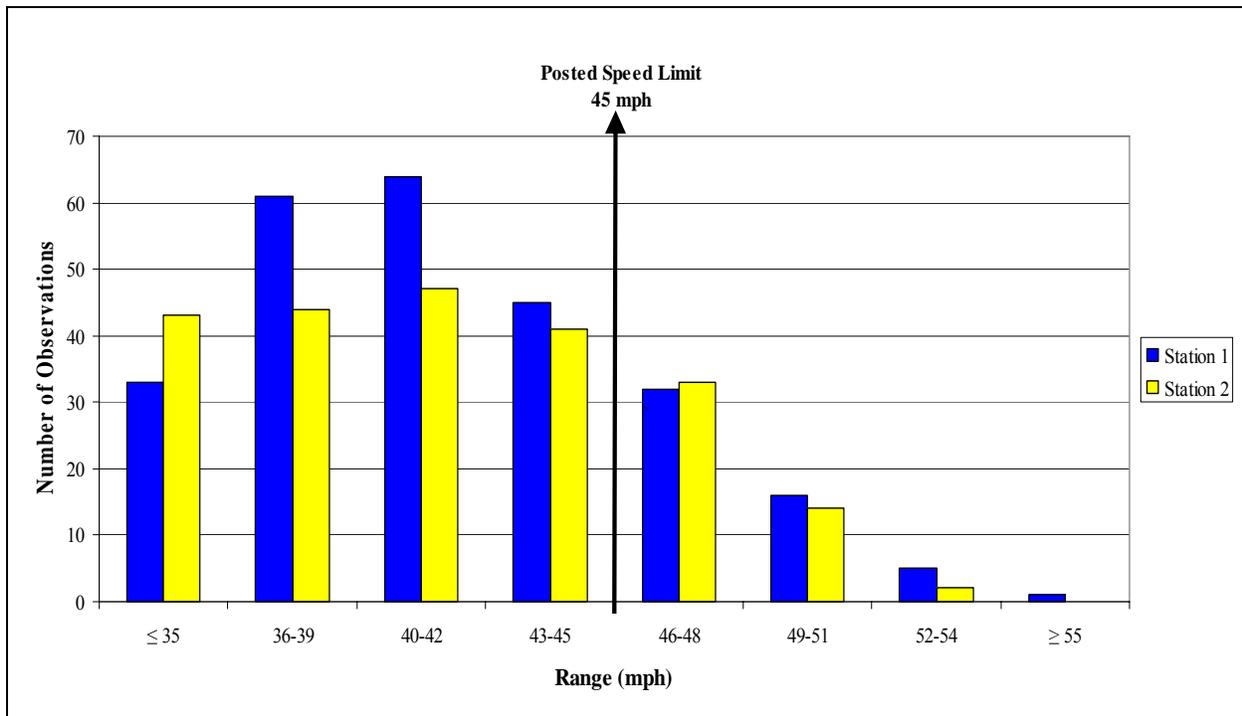
The results from the z-test show a significant reduction in the percent of vehicles exceeding the speed limit by 5 mph between all stations. The reduction is most significant between stations 1 and 3, demonstrating that the SMD with CMS is effective in reducing speeds through the work zone. For vehicles exceeding 10 mph over the speed limit the reduction in the proportion of speeders is greatest between stations 1 and 2. Considering that Station 2 speeds were recorded at the location of the sign, the reduced proportion of vehicles speeding in excess of 10 mph indicates that the SMD with CMS is successful in attracting the attention of motorists and influencing them to slow down.

*Study of Speed Monitoring Display with CMS at Maintenance Sites*

The maintenance site data showed a small reduction in the mean speed due to the SMD with CMS (Table 5.18). A primary reason for this is the inability of the vehicles to speed in the maintenance sites studied due to lane closures, shifting of traffic, and the maintenance activity. The speed reduction range, shown in Table 5.18, was from 0.20mph to 3.7 mph. In many cases, the actual speeds of vehicles traveling through the maintenance work zone were not high enough to trigger the warning message and thus the vehicles tend to travel at their original speed. The statistical testing also shows that there was not a significant difference in the mean speeds between the stations. The smaller number of data collection sites compared to the construction sites may also be a reason that no statistically significant reductions were found in mean speed. Figure 5.12 shows a histogram of the maintenance site speed data.

**Table 5.18 Maintenance Sites Summary**

Measure of Effectiveness	Average Speed Reduction	Speed Reduction Range
Mean speed	1.8 mph	0.2 mph – 3.7 mph
85 <sup>th</sup> Percentile speed	1.3 mph	1.0 mph-2.9 mph
% of Vehicles exceeding speed limit by 5mph	13.4%	2.3% – 25.1%
% of Vehicles exceeding speed limit by 10mph	6.5%	3.5% - 9.5%



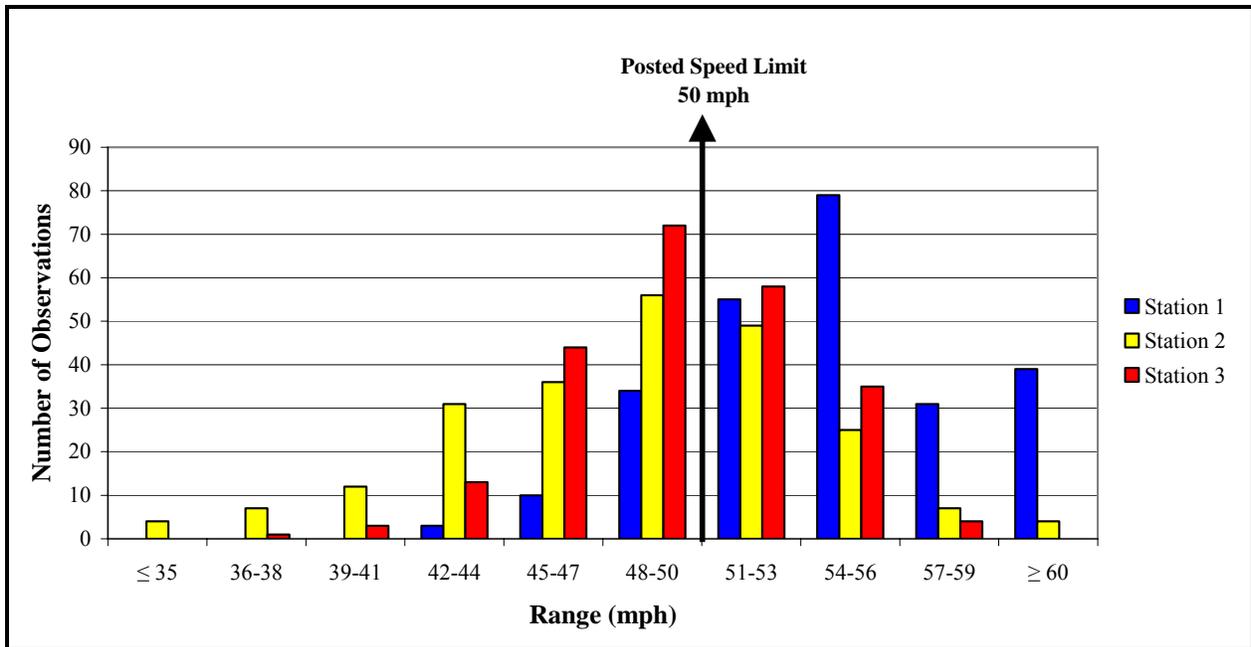
**Figure 5.12 Histogram of Speed Data for SMD with CMS in Maintenance Work Zones**

### *Portable Rumble Strips Data Analysis*

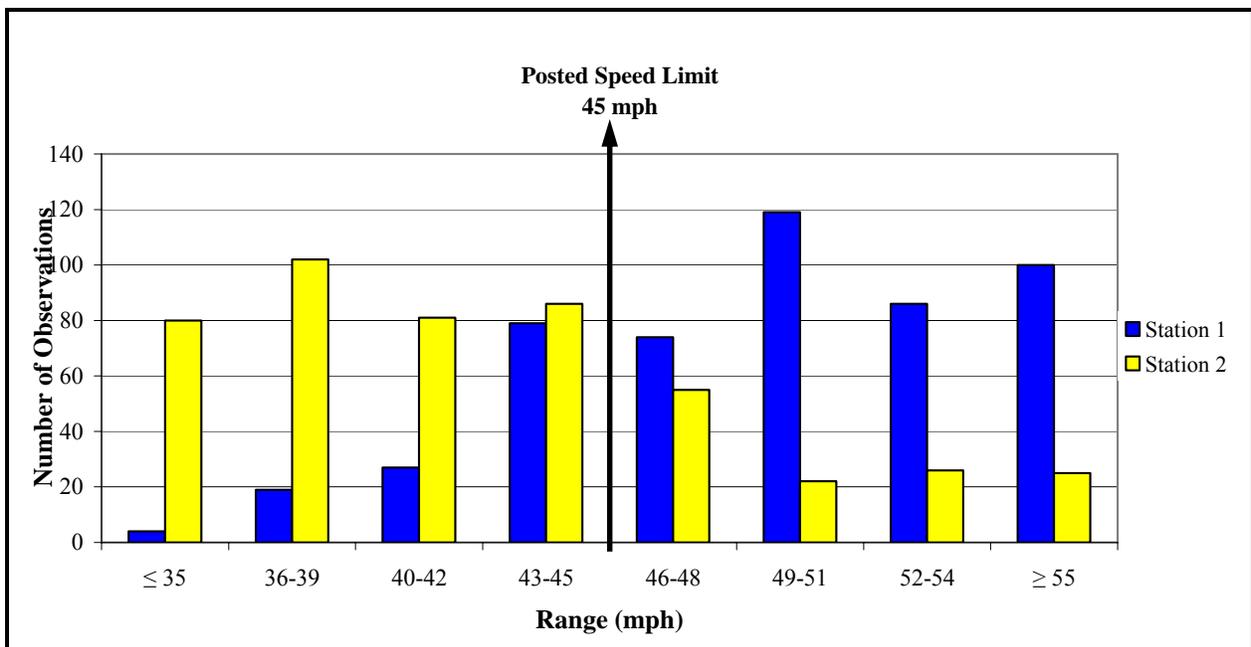
Table 5.19 summarizes the speed reduction results for the data collected September 20, 2006 and indicates that the rumble strips were effective in reducing mean speeds, 85<sup>th</sup> percentile speeds, and the percent of vehicles exceeding the speed limit. A histogram demonstrating the performance of the rumble strips is provided in Figure 5.13.

**Table 5.19 Summary of Overall Speed Reductions**

Measure of Effectiveness	Average Speed Reduction	Speed Reduction Range
Mean Speed	4.9 mph	4.4-5.4 mph
85th Percentile Speed	5.5 mph	5.0-6.0 mph
% of Vehicles Exceeding Speed Limit by 5 mph	30%	21.4-38.2 %
% of Vehicles Exceeding Speed Limit by 10 mph	12.4%	12.1-12.6 %



**Figure 5.13 Histogram of Speed Data for Initial Rumble Strips Testing (Sept. 20, 2006)**



**Figure 5.14 Histogram of Speed Data for Rumble Strips (Oct. 24, 2006)**

Researchers returned to the Charleston work zone to collect more data on October 24, 2006, one month after the initial data collection session. Figure 5.14 presents a histogram of the second set of speed data collected for the rumble strips. By the time of the second data collection, the work zone site contained many additional factors that likely affected speeds. The speed limit of the site had been reduced from 50 mph during the first collection of data to 35 mph during the second. Since the work zone was considered a more active work site in comparison to the first data collection, a flagman was stationed near the beginning of the bridge construction to control

traffic while any machinery or workers were in the roadway. At the same location of the flagman, the travel lane widths were reduced by two feet, which individually can be a cause for decreased speed. Another difference in the site was the amount of warning signs located on the shoulder of the roadways. The extensive signing along with the frequent stopping of traffic at the work zone may have influenced vehicle speeds more than the rumble strips.

### ***Police Enforcement***

The 2005 Work Zone Safety High Visibility Enforcement Campaign was a joint initiative of SCDOT, SCDPS, FHWA, local law enforcement agencies, the SC Law Enforcement Networks, Carolinas Associated General Contractors (AGC), and the SC Municipal Association. The campaign ran from April 8 - October 31, 2005, with four specific enforcement blitz periods. On October 10, 2005, researchers traveled to Laurens County to collect data in the work zone on SC-72, which was part of the work zone blitz campaign. On this particular day, the police enforcement consisted of mobile units that traversed the 8-mile section of SC-72 with a posted speed limit of 45 mph. The officer that was assigned to this area informed the researchers that he would patrol the work zone for his entire shift (7am-5pm) but was unaware of any other units that would be in the area. Throughout the 2 hour data collection period from 9:00 am-11:00 am for the northbound and southbound directions, the mobile unit passed the point of data collection only once and no other units were seen in the area.

On October 20, 2005, the research team re-visited the SC-72 site to collect data in the same location for the condition without police enforcement. Data was collected for the same time period (9:00-11:00) for both directions. Researchers noted an increased amount of work zone activity affecting the northbound traffic, but the southbound traffic conditions were virtually the same for both data collections. Table 5.20 summarizes the results.

**Table 5.20 SC-72 Police Enforcement Data**

<b>Direction</b>	<b>Time Period</b>	<b>Mean Speed with Police Enforcement</b>	<b>Mean Speed without Police Enforcement</b>	<b>Change</b>
<b>Southbound</b>	9:00-10:00	52.7	52.1	0.6
	10:00-11:00	52.9	52.9	0
<b>Northbound</b>	9:00-10:00	50	53.9	-3.9
	10:00-11:00	49.5	50.9	-1.4

On October 13, 2005, researchers traveled to Spartanburg County to collect data in the work zone on I-585, which was also part of the work zone blitz campaign. On this particular day, the police enforcement consisted of mobile units that traversed the 1-mile section of I-585 with a posted speed limit of 55 mph. Throughout the 2 hour data collection period, which lasted from 9:00 am-11:00 am for the northbound and southbound directions, the mobile unit passed the point of data collection only twice and no other units were seen in the area.

On December 1, 2005, the research team re-visited the I-585 site to collect data in the same location for the condition without police enforcement. Data was collected for the same time

period (9:00-11:00) for both directions. As indicated in Table 5.21, vehicles traveled much slower during the “Blitz Period.”

**Table 5.21 I-585 Police Enforcement Data**

<b>Direction</b>	<b>Time Period</b>	<b>Mean Speed with Police Enforcement</b>	<b>Mean Speed without Police Enforcement</b>	<b>Change</b>
<b>Southbound</b>	9:00-10:00	60.3	61.3	-1.0
	10:00-11:00	57.6	60.3	-2.7
<b>Northbound</b>	9:00-10:00	55.9	61.3	-5.4
	10:00-11:00	54.8	61.1	-6.3

***Combined Speed Monitoring Display with CMS and Police Enforcement Data Analysis***

The use of SMD with CMS in conjunction with police enforcement was evaluated at the SC-292 and SC-295 construction sites. The research team collected data for four conditions: no countermeasure, SMD with CMS only, police enforcement only, and the combination of SMD and police enforcement present in the work zone. Table 5.22 provides a summary of the speed reduction ranges for mean speed, 85<sup>th</sup> percentile speed, and the percent of vehicles exceeding the speed limit by 5 and 10 mph.

**Table 5.22 Speed Reduction Ranges for SMD and Police Enforcement**

<b>Measure of Effectiveness</b>	<b>Speed Reduction Range</b>		
	<b>SMD only</b>	<b>Police only</b>	<b>SMD + Police Enforcement</b>
Mean Speed	2.9 - 4.6 mph	9.2 mph	3.3 - 4.0 mph
85th Percentile	2.0 - 4.0 mph	8.0 mph	2.0 - 3.0 mph
% of Vehicles Exceeding Speed Limit by 5 mph	1.8 - 13.7%	14.6%	4.3 - 5.2%
% of Vehicles Exceeding Speed Limit by 10 mph	1.7 - 2.4%	2.4%	0 - 1.7%

The greatest reduction in mean speed occurred when stationary police enforcement was clearly visible to motorists. The reduction in the mean speeds when only SMD with CMS was used ranges from 2.9 to 4.6 mph, while the combination of both the SMD and the enforcement ranged from 3.3 to 4.0 mph. The baseline mean speeds determined at the sites under consideration were close to the posted speed limit of 45 mph; therefore lower mean speed reductions would be expected. Results from *t*-tests conducted for the different conditions reveal that the difference in mean speeds is significant only for the condition where police enforcement alone was present in the work zone. While it seems that SMD combined with police enforcement is less effective than enforcement alone, the results are deceiving. Drivers may not have been aware of the speed limit with police enforcement only. Thus drivers slowed down to a mean speed of 36 mph with enforcement even though the speed limit was 45 mph. The SMD with CMS setup includes a

speed limit sign so the feedback seemed to reduce the driver's tendency to overreact to the enforcement. Still, the average speed with SMD and CMS combined with enforcement was 39 mph to 6 mph below the posted speed limit. A histogram of the speed data for each of the 4 conditions is shown in Figure 5.15. The figure clearly indicates how many drivers overreact in the police enforcement only condition.

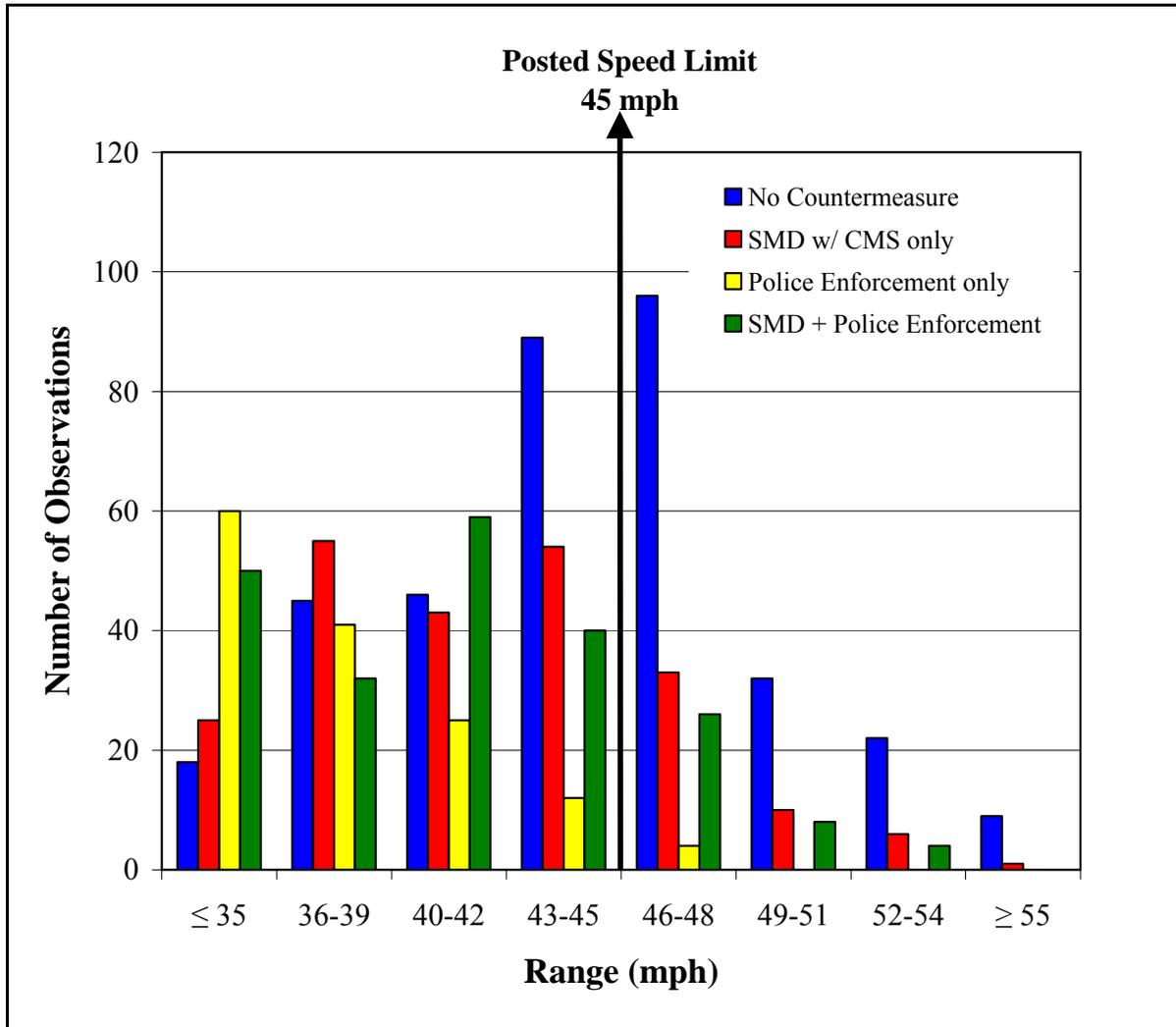


Figure 5.15 Histogram of Speed Data for SMD with CMS and Speed Enforcement

# CHAPTER 6

## SURVEY OF STATES

Aside from the literature review and the testing of multiple speed reduction strategies, the research team also conducted a survey of State Departments of Transportation to determine usage levels and characteristics of use for a number of the speed reduction strategies. The survey was developed and implemented using an Internet application provided by SurveyMonkey.com. SurveyMonkey offers user-friendly interfaces for both survey designers and survey participants. Survey designers can include pictures, files, raised buttons, and other features. Additionally, the Internet application allows designers to program skips so that respondents need not view questions that are not applicable. A sample survey page is shown in Figure 6.1.

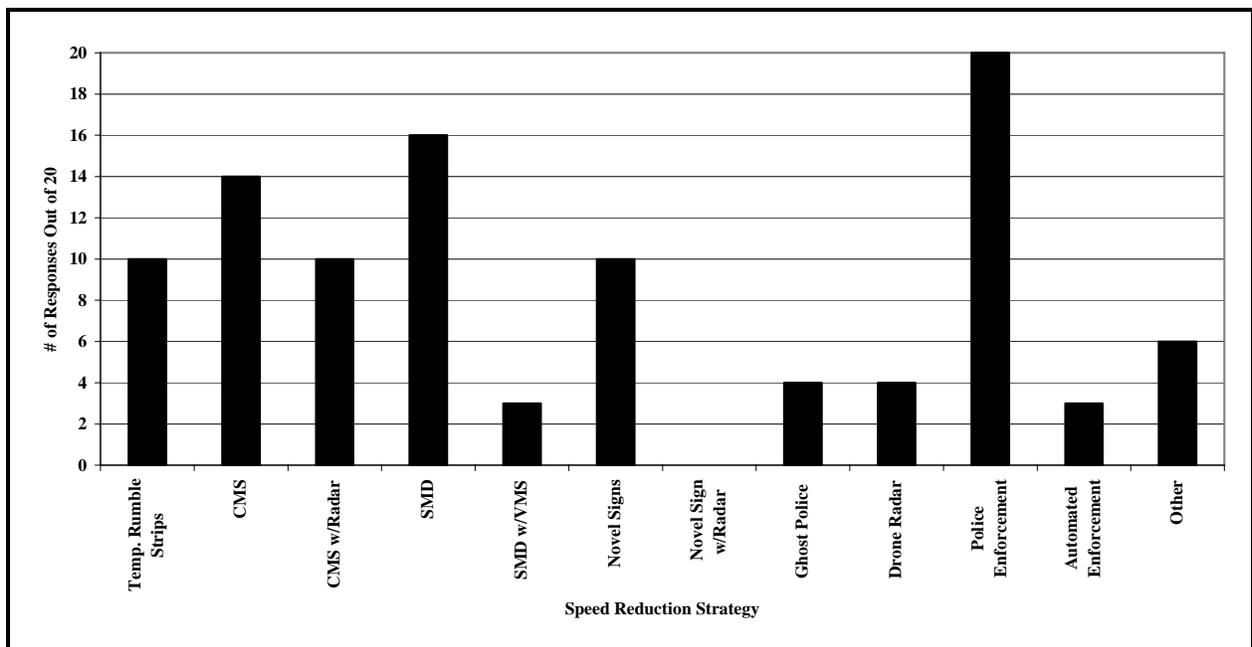


Figure 6.1 Sample Web Survey Page Content

After designing the survey with SurveyMonkey, the survey can be posted for open public view or for specific user groups by adding password protections. The Work Zone Speed Reduction Strategy Survey was password protected to ensure that only authorized users would respond. SCDOT staff assisted the research team by sending out an email asking members of other state

DOTs (50 in total) to complete the survey. The email included a link to the survey web site and a password. In total, 20 surveys were returned. Of those 20, New York and New Jersey each had two separate responses – both with important information. Therefore, 18 of 50 states responded to the survey. Two additional attempts were made to contact the remaining states. One reminder was emailed directly from SCDOT staff, and an additional reminder was sent from the research team. The survey site was maintained for an extended period of time beyond the two-week window in which reminders were sent to allow sufficient time for responses.

The intent of the survey was to determine how many other states were either testing or using the work zone speed reduction strategies identified by the research team. The survey included questions regarding 11 different strategies. As shown in Figure 6.1, the survey was designed to first ask the respondent if they used a particular strategy in their state. If a state indicated that they had used/tested one of the technologies or strategies, additional questions were displayed. Figure 6.2 provides the total number of responses out of 20 completed surveys for each strategy.



**Figure 6.2 Total Survey Responses Indicating Use of Particular Speed Reduction Strategies (Out of 20 Completed Surveys)**

From Figure 6.2, researchers found that the most popular speed reduction strategy is active police enforcement followed by speed monitoring displays and changeable message signs. As a follow-up to the question of whether the state uses a particular strategy, researchers also inquired on the level of use (widespread, moderate, limited, test application only). The responses are shown in Table 6.1.

**Table 6.1 Speed Reduction Strategy Usage Level by State**

State	Temporary Rumble Strips	Changeable Message Signs	Changeable Message Sign w/Radar	Speed Monitoring Displays	Speed Monitoring Displays w/VMS	Novel Signs	Radar Activated Novel Sign	Ghost Police Cars	Drone Radar	Police Enforcement	Automated Speed Enforcement	Other
Arkansas	--	L	--	L	--	--	--	--	--	L	--	--
Colorado	M	W	M	--	--	M	--	W	--	W	--	X
Florida	L	W	--	M	--	--	--	--	--	M	--	--
Georgia	--	M	L	L	L	--	--	--	--	M	L	--
Idaho	--	M	L	M	--	--	--	--	--	L	--	--
Illinois	M	W	--	L	L	W	--	M	L	W	L	--
Iowa	T	--	--	L	--	--	--	--	--	L	--	X
Maryland	L	L	L	L	--	--	--	--	T	M	--	X
Mississippi	--	W	M	--	--	L	--	--	--	L	--	--
Missouri	T	--	--	L	--	W	--	--	--	M	--	--
Montana	--	--	T	--	--	--	--	--	--	M	--	--
New Hampshire	L	M	--	--	--	--	--	L	--	M	--	--
New Jersey	--	M	--	M	--	M	--	--	--	W	--	--
New Jersey	--	L	L	L	--	W	--	--	--	M	--	X
New York	--	--	--	L	--	L	--	--	--	W	--	--
New York	M	W	W	W	--	W	--	--	L	M	--	--
North Dakota	--	--	--	L	--	L	--	--	--	M	--	--
Oregon	L	W	L	M	M	--	--	T	--	M	T	X
Texas	L	M	T	M	--	W	--	--	L	W	--	X
Wyoming	--	--	--	L	--	--	--	--	--	M	--	--
<b>Total</b>	10	14	10	16	3	10	0	4	4	20	3	6

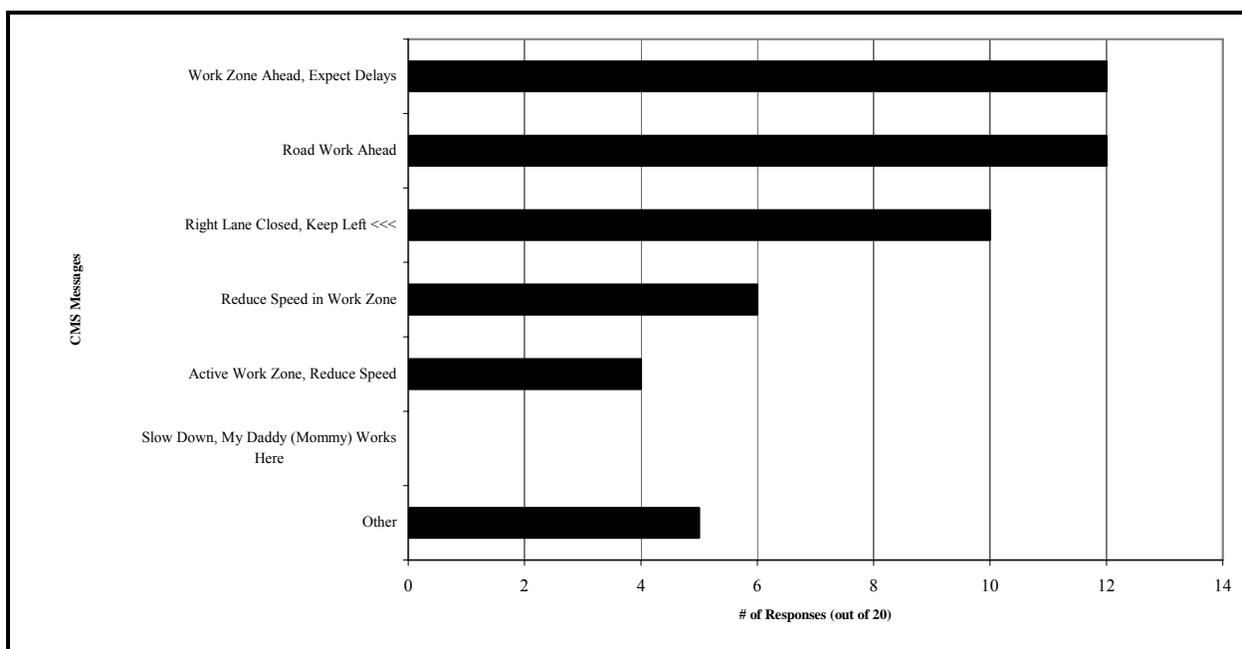
- W Widespread Use
- M Moderate Use
- L Limited Use
- T Test Application Only
- None

***Temporary Rumble Strips***

Half of the survey respondents indicated using or testing temporary rumble strips as a speed reduction strategy in work zones. Mostly the use was limited, and the strips were placed predominantly on 2-lane highways with some on highways and arterials. The effectiveness of the temporary rumble strips was rated between poor and good. Four respondents had conducted evaluations of the rumble strips. Maryland found a maximum speed reduction of 1.9 mph. They also stated that the rumble strips were relatively easy to implement, but a variety of factors seemed to contribute to the speed reduction, such as proximity to the work zone and expected fluctuations in the daily traffic. New York indicated that they used the rumble strips primarily to wake drivers up and did not focus evaluations on speed reductions.

## ***Changeable Message Sign***

Almost two-thirds of those surveyed responded positively to using changeable message signs as a speed reduction technique in work zones. Almost all respondents that indicated using CMS also noted that they were used on numerous road types including Interstates, multi-lane highways, and two-lane highways. Most states rated CMS as average or good for effectiveness in reducing speeds. As shown in Figure 6.3, the two most popular messages include ‘ROAD WORK AHEAD’ and ‘WORK ZONE AHEAD, EXPECT DELAYS’. Directional messages such as, ‘RIGHT LANE CLOSED, KEEP LEFT’ were also popular. Despite their popularity, only four evaluations of the changeable message signs were indicated in the survey responses.



**Figure 6.3 Frequency of CMS Messages Used by Respondents**

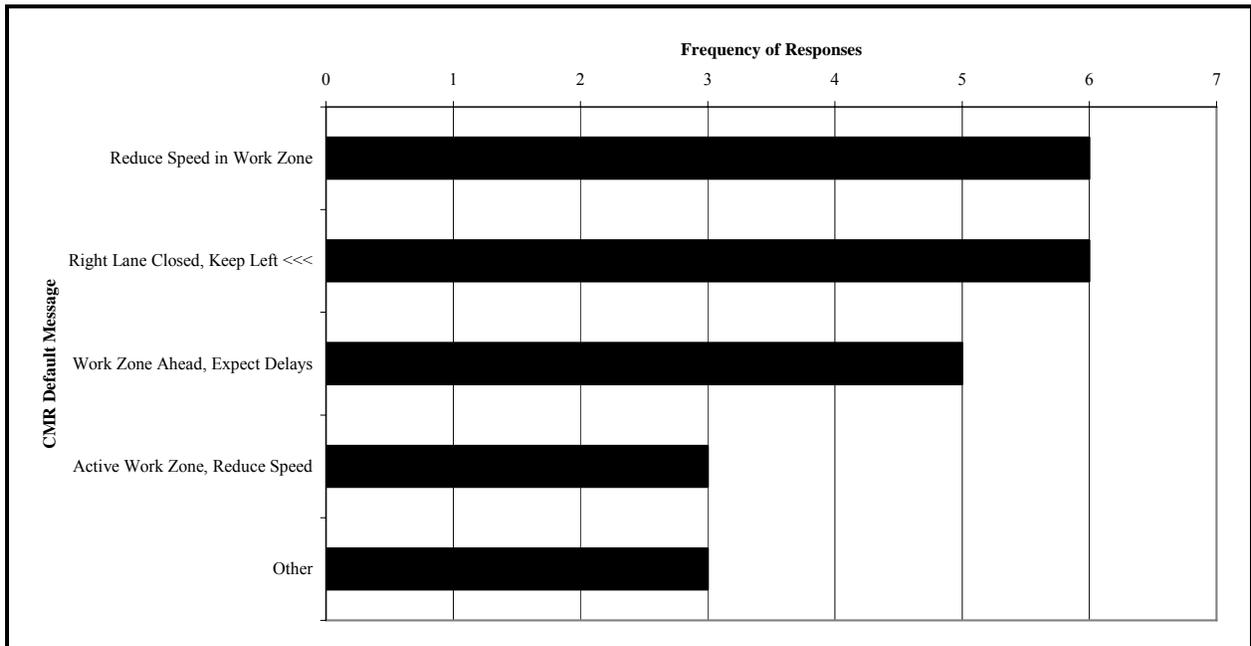
Also noted in Figure 6.3, five respondents noted using other messages that were not in the list. The other messages include:

- Police Ahead (but only during active enforcement – no false threats)
- Entering Work Area, Stay Alert
- Reduced Speed Ahead, Speed Limit XX
- Right Lane Closed, Merge Left
- Fines Doubled in Work Zones
- Slow Down, Use Caution.

## ***Changeable Message Sign with Radar***

Slightly fewer states indicated using changeable message signs with radar – 10 out of 20. The majority of CMR usage by the states was limited to moderate use with application primarily on Interstates followed by multi-lane highways and two-lane highways. The survey respondents rated the effectiveness of CMR as average to good. Three-quarters of the respondents that use CMR, use only a single speed threshold instead of multiple speed thresholds. Further, the speed

thresholds most commonly used ranged between 3-5 mph to 5-10 mph over the work zone speed limit. Changeable message signs with radar require a minimum of two messages – one default message shown to drivers within posted speed limits, and a second shown to drivers over the threshold speed. Survey respondents indicated most often using ‘REDUCE SPEED IN WORK ZONE’ and ‘RIGHT LANE CLOSED, KEEP LEFT <<<’ as default messages. Figure 6.4 shows the frequency of use for each of the CMR default messages.



**Figure 6.4 CMR Default Messages**

Additional messages were also provided by respondents that indicated other including:

- Police Ahead
- Your Speed is XX
- Slow Down, Use Caution.

Respondents were also asked to indicate what messages were typically used after thresholds had been exceeded. One message received 6 out of 10 responses – ‘YOUR SPEED IS XX, POSTED SPEED IS XX’. Four other responses indicated four different messages including:

- Slow Down Now
- Your Speed XX mph, Obey Speed Limit 50 mph
- You Are Speeding.

These findings are interesting considering that research has shown that the message ‘YOU ARE SPEEDING, SLOW DOWN’ is highly effective in reducing speeds.

A Maryland evaluation found that speeds were reduced more than five miles per hour immediately after the deployment of the CMR. However, the longer the CMR remained, fewer instances of speed reduction were observed. Researchers believe that the lack of enforcement was a key factor in this drop. They suggested CMR in conjunction with active enforcement to provide a consistent speed reduction throughout the duration of a project.

### ***Speed Monitoring Devices***

80% (16 of 20) of the survey respondents indicated using or testing speed monitoring devices on all types of Interstates and highways, making them one of the more popular work zone speed reduction strategies. However, the use of these devices was mostly limited to moderate use with only one respondent claiming widespread use. For the most part, respondents ranked the effectiveness as a speed reduction strategy as good to average, with only one evaluation being completed.

### ***Speed Monitoring Devices with Variable Message Sign***

3 of the 16 respondents who indicated using speed monitoring displays also indicated using speed monitoring displays with variable message signs. Respondents stated that the use of these signs was limited with average effectiveness as a work zone speed reduction strategy.

### ***Novel Signs***

Half of the survey respondents stated that they have used or tested novel signs as a speed reduction strategy in work zones. The novelty messages in order of most frequently used include:

- Working for You, Give Us a Brake – 8 responses
- My Mommy (Daddy) Works Here – 3 responses
- Let ‘em Work, Let ‘em Live – 2 responses

Respondents stated that these signs were used on all types of Interstates and highways. As well, their use was widespread to moderate due to the low cost. The effectiveness of the novel signs was ranked as average to poor. No evaluations of the novel signs were indicated by survey respondents.

### ***Novel Signs with Radar***

As expected, no respondents had used or tested the application of novel signs with radar. This is a unique development of this research and its initial speed reductions indicate that it could be a positive development for work zone safety enhancements.

### ***Ghost Police Car***

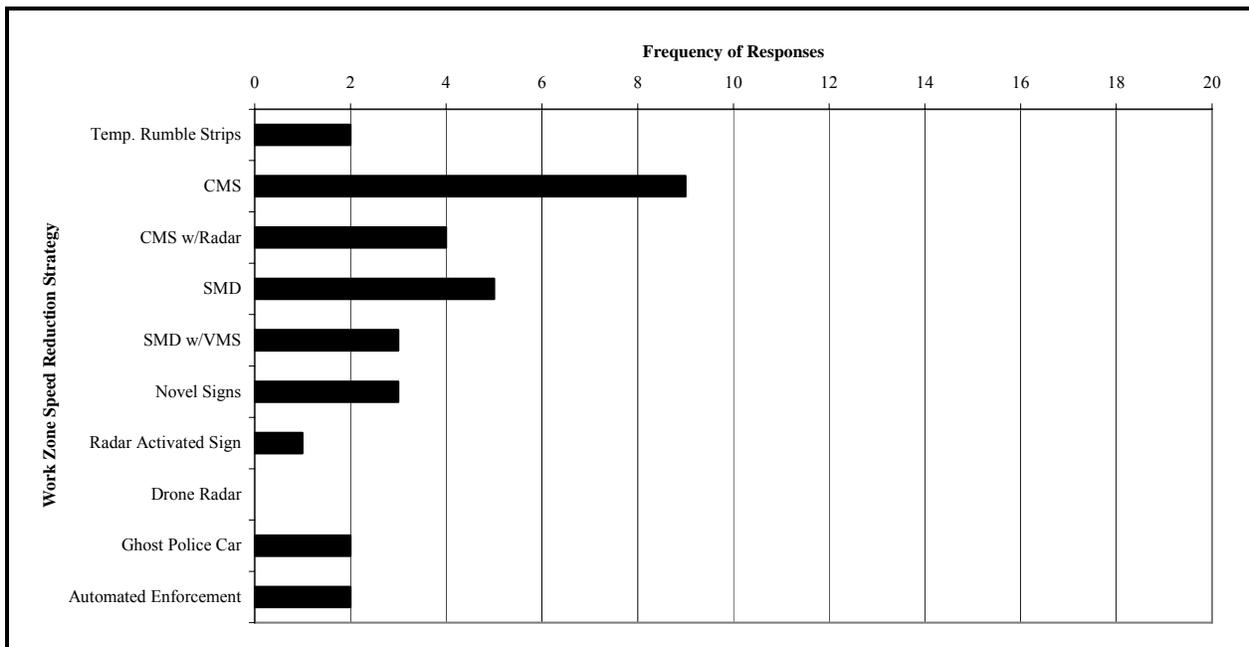
4 out of 20 survey respondents indicated using or testing applications of ghost police cars in work zones as a speed reduction strategy ranking it as excellent to average for effectiveness. The application level varies from widespread to limited use, and none of the survey participants had conducted an evaluation. Oregon tested the application but abandoned it due to driver expectation that there is actually a law enforcement officer present.

## *Drone Radar*

4 out of 20 respondents indicated limited or test use of drone radar applications in work zones to reduce speeds. The drone radar devices were primarily installed on DOT construction vehicles and contractor vehicles. All of the 4 respondents stated that the drone radar had fair effectiveness for controlling speed in work zones. However, none of the respondents had used radar detector detectors to determine the number of radar detectors in the traffic stream. Two evaluations were cited with mixed results.

## *Police Enforcement*

All respondent indicated that they used police enforcement in work zones as a speed reduction strategy. The majority of the respondents stated that they use police on Interstates with fewer indicating use on multi-lane and two-lane highways. The method of enforcement varied greatly and included stationary police car at the beginning of the active work zone, stationary police car before the active work zone area, mobile police cars circulating through the work zone, and combinations of all of the above. Police enforcement has moderate to widespread use and is ranked as a good to excellent strategy for reducing speeds in work zones. Survey respondents also indicated using a number of other strategies in combination with police enforcement as shown in Figure 6.5.



**Figure 6.5 Speed Reduction Strategies Used in Combination with Police Enforcement**

Missouri stated that police enforcement was, by far, the most effective means of controlling speed, that is until someone is pulled over and the apparent threat to getting stopped is gone. Missouri also noted that problems with this option include the availability of law enforcement, and their location within work zone. New York noted a cost concern with using police enforcement. They pay for off-duty troopers (overtime) out of their capital program budget.

However, they are shifting from passive enforcement (trooper parked upstream of work zone with lights flashing) to active enforcement (more aggressive ticketing)

### ***Automated Speed Enforcement***

Three respondents indicated either using or testing automatic speed enforcement including Illinois, Oregon, and Georgia. These states are applying automated speed enforcement in limited or test applications and tests are still ongoing. Oregon stated that one limitation is that photo radar is only allowed in certain cities in the state and must be conducted by the related police jurisdiction. Oregon state police does not use photo radar, so their ability to test photo radar on state highway work zones is very limited at this time.

### ***Other***

Finally, survey participants were asked if there were any other strategies in use in their states that had not been covered by the survey. Respondents offered a number of other methods for reducing speed in work zones:

- Wider Lane Lines
- ITS Technologies
- Flagging
- Lane narrowing
- Transverse striping
- Speed limit signs with orange border
- Reduced regulatory speeds only when workers are present, with traffic control designed for normal operating speeds for other times.
- Lane closure to reduce capacity and therefore speed
- Public information and education campaigns.
- Police 'Slow Downs'
- Lane closure to reduce capacity and therefore speed
- Public information and education campaigns.
- Police 'Slow Downs'

### ***Survey Summary***

The survey of work zone speed reduction strategies indicates that there are a wide variety of strategies being employed across the U.S. Researchers found that the most popular speed reduction strategy is active police enforcement followed by speed monitoring displays and changeable message signs. These three strategies are also those that had the most effective speed reductions as found in the literature review. However, several states indicated issues of cost as a real limitation in choice of speed reduction measures, and thus low cost solutions are greatly needed. Novel signs are also widely used, yet no indications of novel signs with radar exist. This is one of the areas where this research project can be of great value. Additionally, many respondents indicated using changeable message signs with radar, but none indicated using the most effective message identified in previous research, 'YOU ARE SPEEDING, SLOW DOWN'. Thus, it is important to ensure transfer of research findings to ensure that the most effective measures are being implemented.

## CHAPTER 7

### CONCLUSIONS AND RECOMMENDATIONS

This project has focused on researching ways to better manage speed control in work zones. Motorists' disregard for speed limits in work zones is a significant problem, not only in South Carolina but nationwide. The project began with a number of objectives. Specifically, SCDOT intended this project to:

- Develop methods for reducing speed violations by identifying traffic control devices such as signing and pavement markings, use of radar activated speed signs, changeable message signs, drone radar units, Lidar units which are infrared laser speed detection devices, and any other technological developments that may assist to reduce speeding;
- Determine the current role of law enforcement in work zones and the effectiveness of current methods in enforcing speed limits;
- Determine new methods to better integrate law enforcement and traffic control devices and technology to reduce speed violations; and
- Identify methods for reducing speed violations in other states and the effectiveness of these methods.

All of these objectives were addressed, and key findings on all of the project tasks are presented in the following sections.

#### *Literature Review*

The available literature related to this project is very extensive. Many of the speed reduction measures included in this research have been studied in other states. CMS with radar, drone radar, and temporary rumble strips have been studied extensively. Very limited research has been done with novel speed activated signs. Speed monitoring signs have been studied but not in combination with a CMS. While extensive research has been done with drone radar, most of this research was conducted over 5 years ago. The literature review also indicated that there is a need to combine the analysis of drone radar effectiveness with a study of radar detector usage. This finding made it pivotal that an effective radar detector detector was acquired for this project.

Though the conclusions by previous researchers for various speed reduction strategies are diverse, depending on various factors, it appears that in no case did the deployment of these strategies worsen the existing operational conditions. As a result, it was apparent that the findings of devices tested as part of this research would be promising.

***Results of the analysis***

Table 7.1 summarizes the results of the speed reduction devices study in this research. The table indicates that all of the devices have beneficial effects on the speed. These benefits also have a positive influence on 85<sup>th</sup> percentile speeds. The cost for the SMD with CMS indicates a range depending on how the device is mounted (e.g. hitch mounted or trailer mounted). Conclusions and recommendations for individual devices are discussed in the following sections.

**Table 7.1 Comparison of Speed Reduction Strategies**

<b>Speed Control Technique</b>	<b>Change in Mean Speed</b>	<b>Approximate Cost</b>
Speed Monitoring Display with CMS	1.1 -9.8 mph	\$3100-\$5000
Changeable Message Signs with Radar	4.0 -13.0 mph	\$20,000
Speed Activated Sign	1.74 – 6.12 mph	\$1,500
Drone Radar with Mounting Structure	0.3 – 3.5 mph *4.6 -7.9 mph *vehicles with radar detectors	\$250

***Drone Radar***

This research determined the optimal deployment conditions for drone radar and evaluated its effectiveness as a speed control device in five South Carolina work zones. Overall, the drone radar caused minor reductions in mean speeds, 85<sup>th</sup> percentile speeds, and percentage of vehicles exceeding the speed limit; however, this technology caused significant decreases in the mean speed of isolated vehicles equipped with radar detectors which indicates the effectiveness of drone radar is dependant on the number of radar detectors in the traffic stream. South Carolina’s radar detector statistics were comparable to the ranges noted by the research in Georgia, both being too low to show large significant changes in mean speed for an entire traffic stream. One of the findings when developing specifications for the drone radar was the discovery of a radar detector that failed to detect the signal of the drone. This inexpensive radar detector model purchased at a large department store may be one of many models that fail to detect drone radar.

If the SCDOT does decide to install drone radars in their vehicles, it is important that the drones are oriented properly for maximum detection by radar detectors. In addition, research needs to be conducted to determine what percentage of vehicles will possess radar detectors in the future before the SCDOT adopts this new change in work zone setup. The drone radar studied in this research satisfied the objective provided by SCDOT for an affordable and easy-to-implement technology to reduce speeds in work zones. The < \$250 cost of drone radar is much more affordable than other traffic control devices ranging from \$10,000 to \$20,000. One side benefit of the drone radar includes is the possibility of alerting fatigued drivers as they drive through work zones

The drone radar should not be limited to work zone conditions because the low cost of this technology potentially allows their use for non-work zone applications. The long-term effects of

drone radar as a speed reduction measure were not evaluated in this study. Previous research suggests that its effectiveness decreases with time; however, this conclusion could not be verified in this research. Radar detector user's means speeds are significantly higher than those without these devices. The drone radar also decreases speeds of vehicle platoons if a radar detector user is at the front.

The following recommendations can be made to improve the effectiveness of drone radar as a speed reduction measure in work zones:

- The highest consideration for the use of the drone radar should be given to short-term evening work zones on interstate highways with an on-site inspector. It is much more difficult to detect the presence of a drone or lack of law enforcement at night. Further, previous research has shown that drones lose their effectiveness in long-term use.
- A single drone should not be used for work zones longer than a mile because drivers may speed up after the detection no longer exists.
- The drone radar should be elevated to avoid lower obstructions and faced in the proper direction to optimize transmission distance.
- Multiple drones should be placed in work zones consisting of rolling terrain to maintain a longer detection period.
- The drone radar should be placed in advance of the work zone activity to slow vehicles prior to entering a heavy work area.
- The drone radar should be turned off during non-operation hours of the work zone to maintain effectiveness for those using the road daily.

### ***Changeable Message Sign with Radar***

Results from this study support the finding that radar equipped Changeable Message Signs are effective in reducing mean speed, 85<sup>th</sup> percentile speed, and percentage of vehicles exceeding the speed limit. Specific findings from of the CMR evaluation include:

- Previous research from other sources has proven radar equipped changeable message signs are an effective means of reducing speeds in work zones.
- Message Sequence 1, "YOU ARE SPEEDING" followed by "SLOW DOWN", was used as a baseline for comparison in this study to other more novel message variations. However, based on data collected in Phase 1, and as reflected extensively in previous studies, this message has been proven effective in reducing speeds in work zone areas.
- Message Sequence 2, "YOUR SPEED IS \_\_\_\_" followed by "SLOW DOWN", was determined to be effective in reducing work zone speeds through Phase 1 data collection, however, was primarily included to serve as a basis for comparison to Message 3 that included positive feedback for compliant drivers.
- Message Sequence 3, "YOUR SPEED IS \_\_\_\_" followed by either "THANKS FOR NOT SPEEDING" or "SLOW DOWN", performed similarly in the study and did not significantly differ from Message 2, despite the belief that positive feedback for compliant drivers would be useful in addressing the tendency of drivers to increase their speeds at station 3, downstream from the CMR.

- Message Sequence 4, “YOU ARE SPEEDING” followed by “MINIMUM FINE \$200”, showed comparable speed reductions to the other messages and incorporated a novel approach for displaying possible consequences for speeding.

In the past, standard changeable message signs have been used by the SCDOT and numerous contractors in South Carolina work zones to convey road conditions, construction activities, and other general information. As shown in this and previous studies, equipping these signs with radar and allowing them to aid in speed control measures will decrease speeds. While some messages exhibit greater speed reductions, any of the studied messages would improve driver compliance to the posted speed limits. Message Sequence 3 is especially recommended based on its performance and its credibility in that it indicates actual speed to the driver rather than a general statement that they are speeding. Improving speed limit compliance will help increase the safety of work zones for not only the motorists who travel through them, but also the dedicated and hardworking people who work in them

### *Speed Activated Sign*

Research results demonstrated that the speed -activated sign reduced mean speed, 85<sup>th</sup>-percentile speeds, and percentages of vehicles exceeding the speed limit. Even though the impact of the novelty of this technique and its long-term effects could not be determined from this study, the data revealed that significant reductions in vehicle speed can be achieved at least in the short-term.

In addition, the speed-activated sign developed through this research fulfilled the objectives set forth by the SCDOT of developing an affordable and easy-to-implement technology to reduce speeds in work zones. The total cost of the fabrication of this type sign (approximately \$1,500) was substantially lower than the other technologies identified by the research team, including changeable message signs and speed monitoring displays. The cost of the speed -activated sign would be significantly reduced if the radar assembly were produced in quantity. Typically, one person could set up the speed -activated sign in less than 15 minutes, including calibration of the radar. Unlike most other technologies, the speed -activated sign did not require the use of a trailer for transport. Instead, it could be transported in the bed of a truck or back of a van or sports utility vehicle.

As a result of this study and past research, the following recommendations can be made regarding the use of a speed-activated sign as a speed reduction measure in work zones.

- Highest consideration for the use of the speed-activated sign should be given to short-term work zones on two-lane primary and secondary highways. The novelty of the sign might not be as effective in long-term use.
- Similar speed reduction benefits can be experienced on multi-lane divided roads where a two sign configuration is recommended.
- Use of a two-sign configuration is not recommended when traffic is congested because excessive spillover between lanes can cause false indications. These unwarranted indications can reduce the sign’s credibility, which in turn will decrease its effectiveness.
- The MUTCD (may define) requires that a sign be mounted at least one foot above

the ground (Section 6F.04) [45]; however, the speed-activated sign should be mounted at least 5-feet above the ground (measured from the bottom of the sign) to avoid interference with other traffic control devices.

- The speed-activated sign should be placed in the advance-warning area of the work zones to slow vehicles prior to entering activity areas.
- The speed-activated sign should be removed from the stand and the radar turned off during non-operation hours of the work zone.
- The radar on the speed-activated sign should be calibrated based on each unique location and its respective terrain.
- The speed-activated sign should be properly maintained for cleanliness and visibility.

An important safety concern of the speed-activated sign is whether the device is crash worthy per NCHRP 350 Report [44]. The research team contacted representatives from the Federal Highway Administration (FHWA) and they indicated that the flashing beacon mounted atop the temporary sign support would potentially need to be crash tested, but that the radar box would not be of worry as long as it was mounted at or below 24 inches, which is 6 inches greater than bumper height for the smallest required test vehicle. The manufacturer of the temporary sign stand indicated that the stand was designed with a frangible coupling system that would cause the sign stand to fly over a vehicle if impacted. The small flashing beacon that was used during the additional research phase weighs 1.5 lbs and is roughly half the weight of the original solar beacon. The sign stand manufacturer indicated that a 1.5 lb beacon mounted on top of the sign would not adversely affect the trajectory of the stand if struck by a vehicle. However, they stated that the 4.0 lb radar box could cancel or slow down the breakaway effect and cause the stand to impale the vehicle's windshield upon impact. Due to these findings, the research team recommends the speed-activated sign be re-designed removing the radar box from the sign support and mounting it on the battery box with a ballast and placing it in front of the sign support at a height no greater than 24 inches.

Further testing of this sign is recommended to obtain a more comprehensive evaluation of its long-term effectiveness. The research team acknowledges a novelty effect because most drivers during the experimental sessions were seeing this particular sign for the first time. Future evaluation should focus on long-term effects and include data collection over periods of weeks or months. Other potential applications of the speed-activated sign include its use in school zones or in residential areas where speeding is a problem. Researchers observed reduction in speeds during preliminary testing of the speed-activated sign around Clemson University's campus, which suggested its potential benefits in settings other than work zones. Minor alterations of the sign would be required by the MUTCD such as changing the sign's color to yellow or fluorescent yellow-green [45].

### ***Speed Activated Display with CMS***

The speed activated display with CMS, developed through this research was unique in its use and implementation. The sign is much smaller when compared with the large 3-line CMS. The unique sign studied in the research is also cost effective when mounted with the use of a hitch on the back of a van or car. This type of sign has never been used for traffic control in work zones. Thus, the research team found that further research is necessary on the visibility of the sign and use of various messages to be displayed to the drivers. Many speed display signs were effective in their use in the past, whereas this unique sign not only provides feedback to the drivers based

on their speeds, but also helps in reducing those speeds. The message sequence and the speed thresholds are programmable, which gives versatility in the use of the sign at various work zone locations. With little training, anyone should be in a position to program the sign. The ease of use of the SMD is also a commendable factor. With its small size, the SMD can be easily transported in a van or truck without the use of a separate trailer. One more benefit of the SMD is its use as an advance warning for speeding vehicles about the presence of enforcement ahead. The sign proved to be effective on two lane roads with a maximum observed speed reduction of 9 mph at some locations. This sign can also be used as an advisory sign for diverting traffic, lane closure etc.

The sign reduced the mean speeds of the vehicles between stations 1 and 2. The sign was also effective in reducing the number of vehicles exceeding the speed limit. The message sequence proved to be useful in warning drivers to slow down as well as informing them of the presence of law enforcement. The following recommendations need to be considered when implementing the sign:

- The sign should be placed at a distance of at least 10 feet from the edge of the road.
- The sign can be mounted on the back of a van with the help of simple hitch.
- As the sign is being powered by an external source, it should be turned off when not in use.
- It is recommended that the user manual be referred to when programming the sign. Preliminary tests are also necessary to test the speed thresholds.
- The sign should be placed in advance of the work area in the work zone.
- The sign needs to be orientated in an appropriate direction to optimize the use of the radar.
- A survey of drivers should be conducted to determine appropriate message content
- Sufficient time and distance should be provided for the drivers to see and react to the message displayed on the sign.

The sign being unique in its use, further research of this sign is recommended to evaluate the long-term effects. SMD can be of good use in maintenance work zones as well as in school zones. Cost effective and easy to handle, the research team recommends the use of SMD with CMS for reduction of speeds in work zone.

### ***Portable Rumble Strips***

For comparative purposes a data collection site was included in the research analysis using portable rumble strips. Results demonstrated that these countermeasures were effective in reducing mean speeds, 85<sup>th</sup> percentile speeds and the percent of vehicles exceeding the speed limit. The success of the portable rumble strips compared favorability with other speed reduction devices used in the study. The results were noticeable and the project manager of the construction site requested that the devices be left in place after the data collection was completed. Because of their expense and time to install/remove, it is recommended that use of portable rumble strips be concentrated for application in long-term work zones. Furthermore the rumble strips used on this project were found to be very durable, as the installation was on a major roadway (US 17 south) with an ADT of approximately 10,000 vehicles per day and a large

percentage of truck traffic. There was very little visible deterioration more than a month after the rumble strips were initially installed. Other issues pertaining to portable rumble strips installation and use are summarized as follows:

- The strips used in the study were from Advance Traffic Markings and are available in 4" x 50' rolls. Furthermore the strips were 4" wide, 150 mil thick and in addition to orange, other colors include bright green, white, black, or custom colors. The strips used in the study were orange.
- As per the manufacturer's specifications rumble strips should be applied in three sets of ten. The strips in set one should be 10' apart followed by 500'; in set two the strips should be 5' apart followed by 500'; in set three the strips should be 18" apart. Due to material constraints, this was slightly different that what was used at the US 17 site which included 6 strips at 5' spacing followed 500-ft. downstream by 6 strips at 18" spacing.
- As per the manufacturer's described benefits of rumble strips include vibration of the wheel in conjunction with the rumble sound increases work zone awareness, and rumble strips alert motorists to a change in traffic pattern and draw attention to road construction. Furthermore rumble strips create a visual, audible, and physical alert to drivers of a change in traffic patterns and draw attention to caution signs or road construction. The highly visible, orange rumble strips focus drivers' attention on the road and surroundings, while a repeating "rumble" sound and physical vibration increases drivers' awareness.
- As per the manufacturer's application instructions, strips should be firmly tamped longitudinally in the same direction as tape was applied on the initial pass. A minimum of three passes total are required. A tamping device with a minimum 200 lb. (90kg) load and a tamping surface a minimum 2" wider than the width of tape should be used for application. Due to the high traffic volume and complications in traffic control along the US 17 causeway extending through the flood plain of the Combahee River, strips were tamped into place by traffic and this method was effective.
- According to the manufacturer's directions the vibration can be intensified by double-stacking the 150 mil strips for a total thickness of 300 mils
- High tack, user friendly, polymeric adhesive, which provides a temporary bond to the road surface is removable when the Rumble Strip is no longer required. Rumble strips can be removed from asphalt or concrete intact or in large pieces without the use of heat, solvent, grinding, or blasting at temperatures above 40°F.

### ***Survey of States***

The survey of work zone speed reduction strategies indicates that there are a wide variety of strategies being employed across the U.S. Researchers found that the most popular speed reduction strategy is active police enforcement followed by speed monitoring displays and changeable message signs. These three strategies are also those that had the most effective speed reductions as found in the literature review. However, several states indicated issues of cost as a

real limitation in choice of speed reduction measures, and thus low cost solutions are greatly needed. Novel signs are also widely used, yet no indications of novel signs with radar exist. This is one of the areas where this research project can be of great value. Additionally, many respondents indicated using changeable message signs with radar, but none indicated using the most effective message identified in previous research, 'YOU ARE SPEEDING, SLOW DOWN'. Thus, it is important to ensure transfer of research findings to ensure that the most effective measures are being implemented.

### ***Summary of Recommendations***

The results of the analysis show that all of the speed control devices studied during this project have the capability of lowering speeds. The researchers recommend that each of the devices be considered for routine use in future work zones. It is understandable that the deployment of the devices can only be accomplished based on available resources. Consideration should be based on cost, manpower, and the characteristics of the work zones. Here are some general recommendations based on the findings of the research.

- All of the devices show varying levels of effectiveness in the short term. More research should be done studying the devices over several weeks. It is anticipated that some level of enforcement would improve long term usage of the devices
- Widespread use of radar drone will be beneficial but has limited effectiveness. Regardless, widespread deployment in SCDOT vehicles is recommended due to the cost, ease of installation, and minimal manpower necessary to use the devices.
- This research found that CMS with Radar is very effective and should be considered on primary roads where speeding is a concern. Message 3 is recommended because of its effectiveness.
- The speed monitoring display with CMS is effective on 2-lane and 4-lane roads and is more cost effective than the CMS with Radar. It can be portable if it is used in a tow hitch mount. Trailer mounted application is also suitable but adds considerably to the cost. Power should be supplied via a generator or deep cycle battery.
- The novel speed activated signs are effective on both 2-lane and 4-lane roads and are very portable and extremely cost effective.
- Devices should be turned off if work zones are not active. Otherwise, the device may lose its effectiveness over time if drivers feel that the devices are unwarranted.

One of the objectives of the project was to determine the role of law enforcement in the management of speeds in work zones. The literature review and data collection on this project indicates that visible enforcement is effective and is highly recommended. Some of the studies show that there is an increase in speed between station 2 and 3. This was somewhat expected as drivers speed up if they feel they overreacted to the speed reduction device. Enforcement is one way to help ensure that drivers take the speed reduction devices seriously. Our sites that involved studying the combined effect of enforcement with speed reduction devices showed that the SMD with CMS is effective when it includes a feedback message that there is active enforcement. The speed-activated sign can be used in combination with enforcement if it is placed after the presence of visible enforcement to remind drivers not to speed.

If implemented, the results of the research will have significant benefits for SCDOT, its contractors, and users of the State's highways. The primary benefits relate to the safety of work zones. Researchers generally agree that crash frequency is higher in work zones than in other highway locations. Recent experience in South Carolina supports this contention. Further, speed is related to accident severity. Thus, encouraging vehicles to adhere to work zone speed limits will have a positive effect on safety, both for motorists and for workers. Increased safety can result in reducing the number of crashes in work zones, reducing the severity of crashes that do occur, and reducing the number of fatalities in work zones. Other benefits include:

- Better informed traveling public where CMSs are used;
- A lower 85th percentile speed which will reduce the speed differential between vehicles; and
- Reduced speeding violations.

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