SPR 681 AUGUST 2014

Reduction of Speed in Work Zones Using ITS DMS Instant Feedback to Drivers

Arizona Department of Transportation Research Center

ADOT

Reduction of Speed in Work Zones Using ITS DMS Instant Feedback to Drivers: Vehicle Speed Versus Traffic Fine

SPR-681
August 2014

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206 South 17th Avenue
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In cooperation with
U.S. Department of Transportation
Federal Highway Administration

Technical Report Documentation Page

1. Report No.	2. Government Accession No.	3. Recipient's Catalog No.
FHWA-AZ-14-681		

4. Title and Subtitle	5. Report Date / 6. Performing Organization Code
Reduction of Speed in Work Zones Using ITS DMS Instant Feedback to Drivers: Vehicle Speed Versus Traffic Fine	5. Report Date: August 2014 6. Performing Organization Code:
7. Author Craig A. Roberts and Edward J. Smaglik	8. Performing Organization Report No.
9. Performing Organization Name and Address AZTrans: The Arizona Laboratory for Applied Transportation Research Northern Arizona University Department of Civil and Environmental Engineering Flagstaff, AZ 86004-5600	10. Work Unit No. 11. Contract or Grant No. SPR-PL1 (175) 681
12. Sponsoring Agency Name and Address Arizona Department of Transportation 206 S. 17th Avenue Phoenix, Arizona 85007	13.Type of Report & Period Covered FINAL (08/09-12/12) 14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration..

16. Abstract

Accidents in work zones produced 17 fatalities in Arizona and 840 fatalities and over 40,000 injuries nationally in 2009. Motorists nationwide can expect to drive through one active work zone for every 100 miles driven on the National Highway System, and the number of work zones should increase as roadways age. Research has shown that speeds exceeding those posted at work zones are the primary cause of work-zone crashes and account for potentially up to 25 percent of the fatalities.

A literature review revealed five types of technology-driven, work-zone speed-control devices performed comparably to police presence and can supplement the Temporary Traffic Control Plans for work zones in the Manual of Uniform Traffic Control Devices (MUTCD) that the Arizona Department of Transportation (ADOT) uses along with its supplemental policies. Changeable message signs with radar (CMSR) affected speed reductions across various studies, including a South Carolina study in which a monetary fine message alternated with the speed message.

This study examined results of using a similar CMSR alternating a speed message with a monetary fine message on State Route 89 in Prescott, Arizona. This sign produced smaller mean speed reductions, but reduced by half the number of speeders driving 15 mph or more over the posted speed limit.

This research indicated that displaying a monetary fine message alternating with a vehicle speed message was effective in reducing higher speeds in the tested work zone. Based on these findings and the results of the South Carolina study, the researchers recommend that ADOT deploy mobile CMSR with alternating speed feedback and monetary fine messages in work zones wherever practicable.

17. Key Words	18. Distribution Statement	23. Registrant's Seal
variable message signs; radar vehicle detectors; work zones; work zone traffic control; work zone safety; traffic safety; highway safety; construction safety; speeding; traffic accidents; highway factors in accidents; human factors in accidents; fatalities; crash injuries	Document is available to the U.S. Public through the National Technical Information Service, Springfield, Virginia, 22161	

19. Security Classification	20. Security Classification	21. No. of Pages	22. Price
Unclassified	Unclassified	68	

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
		TEMPERATURE (exact degrees)		
^oF	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	^oC
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
		TEMPERATURE (exact degrees)		
^oC	Celsius	1.8C+32	Fahrenheit	^oF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380.
(Revised March 2003)

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LIST OF ACRONYMS AND ABBREVIATIONS

ADOT	Arizona Department of Transportation
ANS	After: No Sign
BNS	Before: No Sign
cdf	Cumulative Distribution Function
CI	Confidence Interval
CMS	Changeable Message Sign
CMSR	Changeable Message Sign with Radar
DMS	Dynamic Message Sign
DOT	Department of Transportation
FHWA	Federal Highway Administration
GTE	Greater Than or Equal To
I-585	Interstate 585
LTE	Less Than or Equal To
MUTCD	Manual of Uniform Traffic Control Devices
NB	Northbound
NHS	National Highway System
NWZSICH	National Work Zone Safety Information Clearinghouse
PCMS	Portable Changeable Message Sign
R2-1	Speed limit sign provided in MUTCD
RA	Research Assistant
SB	Southbound
SC	South Carolina
SF	Speed and Fine
SO	Speed Only
SR	State Route
TTC	Temporary Traffic Control
VMS	Variable Message Sign
W20-1	Warning sign provided in MUTCD
W20-5L	Warning sign provided in MUTCD
W3-5aAZ	Warning sign provided in Arizona Manual of Traffic Signs
W4-2L	Warning sign provided in MUTCD

EXECUTIVE SUMMARY

According to the National Work Zone Safety Information Clearinghouse (NWZSICH), Arizona roadways saw 806 fatalities in 2009, of which 17 were in construction or maintenance work zones (NWZSICH 2009)[1]. Nationally, one work-zone fatality occurs every 10 hours (about 2.3 each day) and one injury every 13 minutes (110 each day) (FHWA 2009a). Motorists nationwide can expect to drive through an active work zone for every 100 miles driven on the National Highway System (NHS) (FHWA 2009a). As the roadways age, the frequency of drivers encountering work zones should only increase.

Transportation agencies have been concerned for years about speed limit compliance in and around work zones because excessive speeds (which vary according to conditions but may be at least 10 mph over the posted limit) are a primary cause of work-zone crashes (Wasson et al. 2011; Pigman and Agent 1990). Potentially up to 25 percent of fatal crashes in work zones involved speeds higher than posted limits. Large speed differentials (high variance) occur at work zones where speed limits have been considerably reduced from normal speed limits (Hou et al. 2011).

The Arizona Department of Transportation (ADOT) develops and follows Temporary Traffic Control (TTC) Plans for work zones, as described by the *Manual of Uniform Traffic Control Devices*, or *MUTCD* (FHWA 2009b), as well as supplemental policies adopted by ADOT. In recent years, experiments have been conducted nationally using supplemental devices, loosely described as technology-driven practices. This report focuses on this category of supplemental work-zone control devices, specifically those aimed at reducing speeding. The report reviews research done using these devices and discusses its applicability for use by ADOT.

This report also presents the original research conducted using a changeable message sign with radar (CMSR) at one work-zone location in Prescott, Arizona, on State Route 89. In addition, findings from a previous extensive study of CMSR use conducted by the South Carolina DOT (Sarasua et al. 2006) are reported in detail to compare and contrast its results with the original research in this study. The primary objective here was to investigate whether providing potential traffic fine feedback (in U.S. dollars) to drivers of speeding vehicles in a work zone changes their speeding behavior.

In the literature search, researchers investigated five supplemental devices: automated speed enforcement, drone radar, speed trailers, changeable message signs (CMS), and CMSR. Various

[1] Methods of counting fatalities differ. Arizona reported 806 fatalities in 2009: 443 drivers, 216 passengers, 122 pedestrians, and 25 pedal cyclists. The number of crashes that resulted in one or more fatalities was 709. Of these, 320 were single-vehicle crashes and 389 were multivehicle crashes. Rear-end collision was the most common type of collision, and speed too fast for conditions was the most common driver violation (ADOT 2010).

researchers found all of these devices were effective in reducing speeding in work zones. Automated speed enforcement has been very effective in reducing the average speed and increasing compliance with the work-zone speed limit of all vehicles. Speeds dropped to or below the speed limit, and the percentage of vehicles exceeding the speed limit dropped to the 6 percent to 8 percent range. Researchers found that automated speed enforcement methods were comparable to active police presence in the work zone, which is the most effective of any supplemental method. Downstream effects were also positive (Benekohal et al. 2009; Medina et al. 2009; Hajbabaie et al. 2009). Arizona has a long history of using automated speed enforcement (also called automated speed photo enforcement) dating from about 1987. It was deployed on the Arizona highway system for approximately two years and deemed effective (Washington et al. 2007), but no studies have been done in Arizona work zones.

Researchers studied other supplemental devices, which are discussed in detail in this report. Drone radar emits active radar frequencies that trigger radar detectors in vehicles equipped with them. Overall mean speed reductions of 2 mph were observed for the entire traffic stream, while vehicles equipped with radar detectors reduced mean speeds from 5 mph to 8 mph (Eckenrode et al. 2007).

Many researchers studied speed trailers; some reported mean speed reductions from 2 mph to 9 mph (Fontaine and Carlson 2001), which was representative. Also much research has been done on CMS with highly varied results, perhaps due to the wide variety of messages tested. Overall reductions in mean speeds ranged from about 2 mph to 5 mph.

In studies of CMSR effectiveness, typically (but not always) the CMSR provided speed feedback to the drivers via messages such as “YOUR SPEED XX MPH.” Additionally, the speed message was alternated with another message such as “SLOW DOWN,” “YOU ARE SPEEDING SLOW DOWN,” “HIGH SPEED SLOW DOWN,” “REDUCE SPEED IN WORK ZONE,” and “EXCESSIVE SPEED SLOW DOWN.” Overall results of reductions in mean speeds varied, but the greatest reductions were 7 to 8 mph for traffic immediately adjacent to the CMSR.

The research conducted for this study extended the work of prior CMSR research by adding the dollar amount of the speeding fine to the feedback message. The South Carolina DOT study also explored a feedback message relating to the speeding fine (Sarasua et al. 2006). In the South Carolina DOT study, researchers used a static message alternating with the speed of the approaching vehicle: “MINIMUM FINE $200.” This ADOT study alternated the speed feedback with the message “POSSIBLE FINE $XXX,” where the dollar amount varied depending on the speed of the vehicle. As the vehicle slowed (or accelerated), the sign message changed to reflect the new speed and any resulting change in the amount of the fine.

The South Carolina DOT study showed greater reductions in mean speeds. However, this ADOT study’s data documented marked reductions in vehicles driven 10 mph or more above the posted limit.

The speed limit prior to the work zone was 50 mph, decreasing to 35 mph at the beginning of the work zone, with a 45 mph intermediate step. Before the CMSR was placed in the work zone, counting 2900 vehicles traveling through the work zone per day, percentages of the vehicles traveling over the 35 mph speed limit were 83 percent at more than 5 mph over, 51 percent at more than 10 mph over, 20 percent at more than 15 mph over, 5 percent at more than 20 mph over, and 0.6 percent at more than 25 mph over the speed limit. When the CMSR was deployed with its alternating speed and fine feedback messages, these percentages dropped to 63 percent, 31 percent, 10 percent, 2 percent, and 0.3 percent, respectively. In practical terms, that third figure of 10 percent means that for the free flow volume of vehicles at the site (2900 vehicles per day), the number of speeders traveling at or greater than 50 mph (15 mph over the work-zone speed limit) was reduced from about 580 vehicles to 291 vehicles—a reduction of one-half. The number of vehicles traveling at the extreme speed of 25 mph above the speed limit was reduced from about 18 vehicles to nine, again a reduction of one-half.

In summary, this research indicates that, in the tested Arizona work zone, messages coupling the speeding fine feedback with alternating vehicle speed provided a slight reduction in mean speeds and greater reductions in vehicles that, without the feedback, traveled at least 10 mph more than the posted limit. Based on these findings and the results of the South Carolina DOT study, the researchers recommend that ADOT deploy in its work zones mobile CMSR with alternating speed feedback and fine feedback messages wherever practicable.

CHAPTER 1. INTRODUCTION

MOTIVATION FOR THE RESEARCH

In 2009, the Federal Highway Administration (FHWA) reported 667 fatalities nationally resulting from vehicle crashes in work zones, which represented a decrease of 37 percent from 2005 (1058 fatalities) (FHWA 2011). According to the National Work Zone Safety Information Clearinghouse (NWZSICH), Arizona experienced 806 total fatalities in 2009, of which 17 were in construction or maintenance work zones (NWZSICH 2009).[2] The downward national trends are encouraging and can be attributed to many factors, but nationally the numbers are still alarming: one work-zone fatality every 10 hours (about 2.3 each day) and one injury every 13 minutes (110 each day) (FHWA 2009a).

While the four-year 37 percent decrease is significant, it follows an opposite trend. Previously, a 45 percent increase was experienced for the 10 years ending in 2006. More than 41,000 people were injured in 2003 as a result of vehicle crashes in work zones, which was an approximate increase of 40 percent from 1996 (36,000 people injured). According to estimates, more than 20 percent of the National Highway System (NHS) is under construction during the peak construction season, which will have more than 3,000 work zones. An estimated 12 billion vehicle miles of travel each year will be through active work zones. Motorists can expect to drive through an active work zone for every 100 miles driven on the NHS (FHWA 2009a). As the roadways age, the frequency of drivers encountering work zones should only increase.

Transportation agencies have long been concerned about speed limit compliance in and around work zones because excessive speeds (which vary according to conditions but usually are at least 10 mph over the posted limit) are a primary cause of work-zone crashes (Wasson et al. 2011; Pigman and Agent 1990). Potentially up to 25 percent of fatal crashes in work zones involved speeds over the posted limits. Additionally, a large speed variance coupled with hazardous work zone conditions (such as the presence of workers, lane closures, and narrow lanes) can lead to higher crash rates at work zones. Crash rates have been found to increase as speed variance increases. Large speed differentials (high variance) occur at work zones where speed limits have been considerably reduced from normal speed limits (Hou et al. 2011).

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[2] Methods of counting fatalities differ. Arizona reported 806 fatalities in 2009: 443 drivers, 216 passengers, 122 pedestrians, and 25 pedal cyclists. The number of crashes that resulted in one or more fatalities was 709. Of these, 320 were single-vehicle crashes and 389 were multivehicle crashes. Rear-end collision was the most common type of collision, and speed too fast for conditions was the most common driver violation (ADOT 2010).

SCOPE OF THIS RESEARCH

The Arizona Department of Transportation (ADOT) develops and follows Temporary Traffic Control Plans (TTC Plans) for work zones, as described by the *Manual of Uniform Traffic Control Devices*, or *MUTCD* (FHWA 2009b), as well as supplemental policies adopted by ADOT. In recent years, researchers have conducted experiments nationally using supplemental devices, loosely described as technology-driven practices. This report focuses on this category of supplemental work-zone control devices, specifically those aimed at reducing speeding. The report provides an extensive review of research done to date using these devices and discusses its applicability for use by ADOT. The report also includes the original research conducted using a changeable message sign with radar (CMSR) at one work-zone location in Arizona, and detailed results of an earlier, extensive study done by the South Carolina DOT to compare and contrast its results with the findings in this study.

Arizona has extensive experience using one technology-driven method: portable automated speed enforcement (also known as automated speed photo enforcement). While this practice is capable of supplementing standard *MUTCD* methods, its use in Arizona is problematic. First, it is a limited resource and is probably not feasible to deploy at all ADOT work zones at any given time. Second, the ADOT Division of Motor Vehicles has currently curtailed its use. Another technology-driven device available to ADOT is the dynamic message sign (DMS) equipped with radar, which is alternately referred to as a variable message sign (VMS) or CMSR, which is how it is referred to in this report.

Using a CMSR is currently available to most ADOT districts. Often, however, the radar feature is not used. If the device is used, it is limited to only giving vehicle speed feedback to the approaching vehicles. This is an effective way to use the device and has been shown to measurably reduce driver speeds. However, the device has far more capabilities. By accessing a built-in menu, ADOT can program the radar unit to change the displayed message based on the speed of the approaching vehicle, a feature used in this research.

The primary objective of this project was to investigate whether providing potential traffic fine feedback (in U.S. dollars) to drivers of speeding vehicles in a work zone changes their speeding behavior. Ideally, researchers would track the behavior of individual vehicles to collect data for this study. However, this approach is difficult, and researchers instead gathered data on all vehicles traveling through a work zone.

Researchers evaluated the change in mean speeds using speed feedback only and using both speed and traffic fine feedback. Equally important was the study of the distributions of speeds. Specifically, changes in the proportions of the speed distributions above the speed limit were investigated.

PROJECT APPROACH

To gather information for this project, researchers initially conducted a literature review in the area of speed reduction using a DMS that gives actual vehicle speed feedback. In addition, they worked with the manufacturer of ADOT's VMS radar-capable trailer and ADOT Equipment Services to confirm capability, program the VMS display, and shop-test the trailer and display. Algorithms developed for this project allowed for two separate displays: vehicle speed only and an alternating display of vehicle speed and traffic fine amount.

Working with ADOT personnel, researchers then identified potential construction work-zone sites that could serve as a test site, selected the final site for gathering data, and installed the equipment at the test site. Once the study was under way, researchers collected data from the test site while using no DMS (hence, no feedback), DMS with vehicle speed feedback, and DMS with alternating vehicle speed/traffic fine feedback.

CHAPTER 2. GENERAL LITERATURE REVIEW

Substantial research has been conducted on improving the safety of the work-zone environment. Previous research has cited driver inattention, speed differential, failure to yield, unsafe speed, and following too closely as leading work-zone hazards (McAvoy et al. 2011; Akepati and Dissanayake 2011). One study (Hou et al. 2011) found that speed in general has been identified as a significant contributor to unsafe conditions affecting drivers and roadway workers in the roadway right of way. Specifically, they found up to 25 percent of fatal crashes in work zones involved high speeds. Additionally, a large speed variance coupled with hazardous conditions in work zones (for example, workers' presence, lane closure, and narrow lanes) can also lead to higher crash rates at work zones. Finally, one study they reviewed specifically found that crash rates increase as speed variance increases while another found large speed differentials (high variance) occur at work zones where speed limits have been considerably reduced from normal speed limits. An additional literature search (Wasson et al. 2011) documented that speed limit compliance in and around work zones has been of concern to transportation agencies for many years because excessive speeds are a primary cause of work-zone crashes.

The methods used to control speed in work zones can be split into two broad groups: standard practices and technology-driven practices. Standard practices can loosely be defined as those described in the *MUTCD* (FHWA 2009b) and involve a TTC Plan, usually with static signs and markings. (Note: ADOT (2009) has supplemental policies regarding work-zone TTC Plans that also apply.) Technology-driven practices cover a host of devices that have and are being developed using various technologies. Typically these new devices, often dynamic in nature, supplement the TTC Plan.

It is important to note that TTC Plans where the work zone speed limit is reduced do effectively reduce driving speeds. Researchers conducted field studies in Missouri on three rural Interstate 70 short-term work zones, all of which had normal speed limits of 70 mph (Hou et al. 2011). Only free-flow vehicles were used in the analysis. The authors found that the differences in 85th percentile speeds and their associated variances were significant for the three cases studied of no posted speed reduction, 10 mph limit reduction, and 20 mph limit reduction. Results for each case were 81 mph and 10 mph variance, 62 mph and 8 mph variance, and 48 mph and 6 mph variance, respectively. The authors reported that their study results were counter to those of previous studies.

The previous studies cited by Hou et al. (2011) had generally found that drivers were more likely to exceed the speed limit in a work zone with a greater speed limit reduction. The Hou et al. study was for a short-term work zone on four-lane rural, divided Interstates with one lane closed to traffic; therefore their results cannot be generalized for other conditions. However, for their study conditions, and by defining aggressive drivers as those exceeding the speed limit by more than 10 mph, they found that, in the no-speed-limit reduction case, about one driver in seven was an aggressive driver; in the 10 mph speed reduction case, about one driver in 21 was an aggressive driver; and in the 20 mph speed reduction case, aggressive drivers were almost nonexistent. Another important result noted was that the lower speed limits in the work zones did not lead to greater variation in vehicle speeds; in fact, they led to less.

Researchers conducted an extensive study of work-zone speed reduction practices for the Iowa DOT (Maze et al. 2000). They concluded from their literature review that:

> . . . flagging and police enforcement speed reduction strategies have had very positive impacts in reducing work zone speeds. They are, however, labor intensive and can become costly with long-term use. Flagging by its nature is physically tiring, boring work. Moreover, due to limited resources, the use of police officers at work zones is infrequent by many agencies. The impracticality of the extensive use of law enforcement at work zones may result in a short-term impact on motorists. Replacing these strategies with innovative technologies … may be practical, more cost-effective solutions (Maze et al. 2000, 1).

The research reviewed here first examines the main characteristics of crashes in work zones and then focuses mainly on five types of innovative technology devices:

- Automated speed enforcement.
- Drone radar.
- Speed trailers.
- CMS.
- CMSR.

CHARACTERISTICS OF CRASHES IN WORK ZONES

Work-zone crashes have accounted for 9,900 fatalities in the United States in the last 10 years (Akepati and Dissanayake 2011). Akepati and Dissanayake used data from the five-state Smart Work Zone Deployment Initiative taken between 2002 and 2006 to characterize the nature of work-zone crashes:

> Results showed that most of the work zone crashes occurred under clear environmental conditions [such] as during daylight, no adverse weather, etc. Multiple-vehicle crashes were more predominant than single-vehicle crashes in work zone crashes. Primary driver-contributing factors of work zone crashes were inattentive driving, following too close for conditions, failure to yield right of way, driving too fast for conditions, and exceeding posted speed limits within work zones.. . . Passenger cars were more involved in work zone crashes when

> compared to light-duty and heavy-duty vehicles. Rear-end was the most predominant type of collision in work zone areas when compared to other collisions (Akepati and Dissanayake 2011, 2).
> . . . Results showed that nearly 50 percent of work zone crashes occurred in the activity area of the work zone where the actual work goes on. The safest zone within work zones was before the work zone warning sign, i.e., advance warning area which warns the traffic what to expect ahead. The lane-closure work zone type was the one where the highest percentages of crashes occurred, followed by work on the shoulder or median type of work zone. . . .Drivers aged between 25 to 64 years were more involved in work zone crashes when compared to young and old age drivers (15).

In a different type of study, Mohammadi and Bham (2011) examined quantitatively and qualitatively the speed characteristics and driver compliance with the posted speed limits. The authors studied the effects of lane closure, lane-width reduction, and construction activity on speeds of vehicles. Twenty-seven states responded to their survey, and this feedback was used to determine the most common work-zone practices related to posted speed limits. The dominant factors in determining the reduced speed limit were presence of workers, lane width, roadway alignment, and type of activity. Seventy percent of respondents indicated a maximum speed limit reduction of 10 mph in work zones. Respondents also listed static speed limit signs as the most commonly used traffic control devices. Results indicated that using police enforcement was the best strategy to increase compliance with speed limits in work zones. Only 25 percent of the respondents said regulatory signs were effective.

In addition, Mohammadi and Bham surveyed drivers and found that they preferred to be informed more than a mile from the work zone where workers were present. Most drivers indicated that they experienced delays in the work zone, and more than 90 percent of drivers agreed that construction activity reduced their speeds, a result that agreed with the state DOTs surveyed. An important finding of the driver survey related to the posted speed limit; specifically, an overwhelming majority of drivers suggested reducing the speed limit in work zones that consistently had congested conditions. Conversely, an overwhelming number of participants suggested increasing the posted speed limit in work zones that did not experience congested conditions consistently.

AUTOMATED SPEED ENFORCEMENT

Arizona has used automated speed enforcement (also called automated speed photo enforcement) in municipalities since approximately 1987. This technology was also deployed on the Arizona state highway system for approximately two years, from 2008 to 2010, after a pilot project showed that the system "seems to be an effective deterrent to speeding within the enforcement zone, since removing the deterrent resulted in increased speeding. [The pilot system] reduced the average speed at the enforcement camera sites by about 9 mph and also contributed to reducing the speed dispersion at the enforcement camera sites. In agreement with a substantial body of prior national and international research [the] reduced speeds and speed dispersion improve safety (Washington et al. 2007, 9)."

Arizona did employ its automated speed enforcement system in the form of mobile, unmanned vans within construction zones. For these deployments, either no data were collected or no results were officially reported regarding their efficacy in these work zones. However, specific work-zone studies have been conducted in Illinois. Benekohal et al. (2008) reported in their literature review that their work using automated speed enforcement in Illinois work zones was the first done both in the United States and worldwide. They cited a five-year study of manned mobile radar for general speed enforcement in the Netherlands that showed an estimated 21percent decrease in the number of injury accidents and serious casualties. Four other studies were also cited that showed positive results using general manned radar speed enforcement.

In 2009, various collaborators reported extensively about the effects of using automated speed enforcement in controlled experiments in Illinois (Benekohal et al. 2009; Medina et al. 2009; Hajbabaie et al. 2009). Near the automated speed enforcement vans, speeds dropped to or below the speed limit. In addition, the percentage of vehicles exceeding the speed limit dropped from the 30 percent to 40 percent range to the 6 percent to 8 percent range. The authors summarized their results as being very effective in reducing the average speed and increasing compliance with the work-zone speed limit of all the vehicles recorded, regardless of lane, vehicle type, or traffic flow type (free or platoon). Automated speed enforcement methods were judged to be comparable to active police presence in the work zone. The authors also studied the downstream effect (in long work zones) and found that automated speed enforcement had significant effects, which were appreciably greater than those of a speed trailer alone.

From these studies, researchers concluded that the most effective work-zone speed control method to date is automated speed enforcement or active police presence. However, when police leave a work zone, the speed reduction due to their presence vanishes quickly. In a study of a 12.2-mile work zone on I-65 in Indiana (Wasson et al. 2011), researchers found that when the exceptionally high presence of police enforcement was present, a 5 mph reduction in average speed over the entire work zone could be achieved. But just as significantly, within 30 minutes of suspending the enforcement, the speeds returned to their pre-enforcement levels.

DRONE RADAR

Drone radar simulates the presence of law enforcement by transmitting the same radar frequency that law enforcement uses to check the speeds of passing vehicles. Vehicles with radar detectors perceive this transmitted radar energy and assume it is law enforcement checking their speed. In an extensive study conducted in South Carolina from 2005 to 2006 (Eckenrode et al. 2007), the authors acknowledged that drone radar had been tested for more than 20 years prior to their study. Their analysis included a review of past literature, but since newer equipment that detected radar detectors was now available, it warranted revisiting.

Additionally, the extent of radar detector usage in South Carolina was unknown. The authors studied its use in Interstate work zones and on secondary highways during day and evening conditions for both passenger cars and tractor-trailers. They found that drone radar caused overall mean speed reductions of 2 mph for the entire traffic stream, while vehicles equipped with radar detectors reduced speeds ranging from 5 mph to 8 mph. The 85th percentile speeds decreased from 1 mph to 5 mph, and the percentage of vehicles exceeding the speed limit was reduced by 20 percent.

The authors concluded that while drone radar caused only minor reductions in speeds of the entire traffic flow, it caused significant decreases in speeds of isolated vehicles equipped with radar detectors. More importantly, the authors observed that the effectiveness of drone radar is dependent on the number of radar detectors in the traffic stream: from 2 percent to 5 percent in passenger cars and about 7 percent in tractor-trailers. These percentages were comparable to studies they referenced in Georgia. The authors concluded that these numbers were too low to show large, significant changes in speeds for the entire traffic stream. The motivation for this study was the low cost of drone radar devices compared with all other technology-driven devices, which in 2006 were estimated to cost about $250 each.

SPEED TRAILERS

Speed trailers, also called speed displays or speed monitoring displays, are radar-activated signs that show the speed of approaching vehicles. A regular black-and-white speed limit sign is typically mounted above the display (Figure 1 and Figure 2). In 2001, Fontaine and Carlson theorized that speed trailers reduce speeds in two ways: drivers tend to slow down once they see their speed shown on the display; and the radar in the speed trailer will activate radar detectors far in advance of the trailer, which may influence drivers with these detectors because of the perceived presence of a police officer.

Figure 1. Speed Trailer.
(Photo courtesy of Ver-Mac, Quebec, Canada)

Figure 2. Speed Trailer.
(Photo courtesy of RU2 Systems, Mesa, Ariz.)

The effectiveness of speed trailers reported by Fontaine and Carlson (2001) was fairly typical of the results from similar studies. They studied work zones on two-lane, low-volume roads, and their general findings included the following:

- Speed trailers can be set up quickly, typically in less than 10 minutes.
- Average passenger car speeds were reduced between 2 mph and 9 mph, and the percentage exceeding the speed limit was reduced from 15 percent to 20 percent.
- Average truck speeds were reduced greater than average passenger car speeds. Reductions were from 3 mph to 10 mph. Trucks generally complied with the work-zone speed limits with and without the speed trailers, but their speeds were lower when the trailers were used.
- Only one driver accelerated dramatically as he approached the speed trailer, which represented less than 1 percent of the vehicles evaluated.
- Results varied among sites, causing the researchers to suggest that where speed trailers are positioned in the work zone may be a factor in the magnitude of speed reductions achieved.
- Reductions on the studied two-lane, low-volume roads were slightly greater than those observed in another study performed by the Texas Transportation Institute on a four-lane divided highway.

Pesti and McCoy (2001) reported on the results of a four-state, pooled research project called the Midwest States Smart Work Zone Deployment Initiative regarding the effectiveness of speed trailers on rural Interstate highways. Three speed trailers were placed in a 2.7-mile section of a work zone. The four-lane divided section was abutted on both ends by two-way, two-lane work-zone sections. These constrictions caused speeding in the 2.7-mile section as vehicles that had been traveling at relatively low speeds for several miles in the head-to-head section entered the four-lane divided section of the study area. Vehicle speed tended to increase above the work-zone speed limit in the study section, possibly to allow drivers to pass slower-moving vehicles and position themselves farther ahead before merging again at the far end of the study section into another head-to-head condition.

These findings were consistent with those of Fontaine and Carlson, and were summarized as being effective in lowering speeds and increasing the uniformity of speeds over a five-week period. Overall mean speeds of all vehicles were reduced by 3 mph to 4 mph, 85th percentile speeds were reduced by 2 mph to 7 mph, and the percentage of vehicles over the speed limit (55 mph) and over the speed limit plus 5 mph (60 mph) were reduced from 20 percent to 40 percent. Pesti and McCoy also found that the long-term effectiveness of the trailers was positive (that is, the reductions applied fairly consistently over the five-week study period), and some residual effect was noted. However, they observed that the proportion of commuters would influence the long-term effectiveness (22 percent in their study), so their results may not apply to other sites.

In a related study (Brewer et al. 2006), researchers found that speed trailers reduced the 85th percentile speeds from 2 mph to 4 mph, averaging 3 percent to 15 percent lower than before a speed trailer was installed in the work zone. The study measured speeds at five locations within a three-mile work zone on a four-lane divided highway. Researchers noted that compliance rates decreased at the end of the work zone where there was no sign of active roadwork even though the reduced work-zone speed limit still applied. The authors concluded that drivers tend to travel as fast as they feel comfortable doing without the threat of enforcement.

Cruzado and Donnell (2009) conducted an extensive study of speed trailers at 12 sites along rural high-speed, two-lane highway transition zones. These were not work zones but permanent changes in speed for sections of the highway that pass through rural communities. The results confirmed findings of similar studies that were done in work zones, specifically, free-flow passenger car operating speeds were reduced from 1 mph to 12 mph, while averaging a 6 mph drop. The authors also observed that the positive effect of speed trailers diminished after they were removed from the sites.

A study by Teng et al. (2009) supports this report’s literature review findings regarding speed trailers. The authors added three enhancement factors to the normal speed trailer setup to enhance speed compliance: size of the displayed message, use of flashing, and more than one speed trailer in the work zone. They found that the speed trailers, regardless of enhancement factors, all reduced speeds of vehicles about 8 mph to 9 mph in work zones. They also found some evidence that a larger speed sign performed better than a smaller one, particularly for multi-unit trucks, but had the same performance for other types of vehicles. The results of flashing the speed were mixed but always slightly better, or at least no worse than not flashing it. Finally, they concluded that an additional speed trailer can be very effective in reducing vehicle speeds when the amount of speed reduction at the first location is insufficient.

CHANGEABLE MESSAGE SIGNS

A CMS is a traffic control device that is capable of displaying a variety of messages to inform motorists of unusual driving conditions. Typically housed on a trailer (Figure 3) or on a truck bed, CMS is usually portable and can be deployed quickly for meeting the temporary requirements frequently found in work zones (FHWA 2003).

A South Carolina study (Sarasua et al. 2006) performed an extensive study of devices to manage speed in work zones. A review of the literature regarding CMS messages such as "SPEED LIMIT 45 MPH" and "WORK ZONE AHEAD" found that when a CMS is placed in advance of a work zone, speeds decreased up to 3 mph in one study and up to 7 mph in another study.

Figure 3. Portable CMS.
(Photo courtesy of Ver-Mac, Quebec, Canada)

Benekohal and Shu (1992) performed experiments on a rural Illinois Interstate, with two lanes per direction and one lane closure in each direction. They used CMS that alternated the messages "WORKERS AHEAD" and "SPEED LIMIT 45 MPH" every two or three seconds. They found that using a CMS ahead of the work zone reduced the average speed of cars by 2.8 mph and the average speed of trucks by 1.4 mph at a point near the beginning of the traffic control zone. Placing the CMS in the work activity areas was effective for cars in reducing the average by 1.7 mph about 1000 ft beyond it but was no longer effective two miles from the CMS (but still within the work zone). For trucks, this arrangement produced opposite results—1000 ft beyond the CMS it had no effect, while two miles beyond it reduced truck speeds by 3.7 mph. The data indicated that cars reacted by slowing down near the CMS, but the effect was not sustained at a point far from the CMS. However, trucks did not reduce their speeds immediately near the CMS, but traveled at a reduced speed far from the CMS (but still within the work zone).

Benekohal and Shu also examined the impact of using two CMS in the work-zone activity area. This approach was effective in reducing the average speed of cars as well as trucks. Near the first CMS, car speeds decreased by 4.6 mph and truck speeds by 3.7 mph. Near the second CMS, car speeds decreased by 4.7 mph and truck speeds by 2.6 mph.

One study's literature search (Mattox et al. 2007) found that researchers from an early 1984 study on Texas Interstates using CMS concluded that a greater speed reduction occurred when the CMS was located close to the actual work areas instead of ahead of the work-zone warning sign sequence. Specifically, the CMS reduced speeds from 0 mph to 5 mph, depending on the CMS location.

A research team in New York (Zech et al. 2008) studied the effectiveness of three commonly used CMS messages in reducing vehicular speeds and variances in highway work zones. The study was conducted on Interstate 90 in western New York and included speed measurements of nearly 180,000 vehicles. The three types of CMS messages tested were "RIGHT LANE CLOSED—KEEP LEFT," "WORK ZONE MAX SPEED 45 MPH—BE PREPARED TO STOP," and "LEFT LANE CLOSED—KEEP RIGHT." The most effective CMS message was "WORK ZONE MAX SPEED 45 MPH—BE PREPARED TO STOP," which significantly reduced vehicle speeds by 3.3 mph to 6.7 mph. However, this message increased the standard deviation of the reduced speeds by 1.1 mph to 1.7 mph in the driving lane and 0.2 mph to 2.0 mph in the passing lane.

A study for the Texas DOT (Fontaine et al. 2000) compared several devices. The researchers found that CMS resulted in minimal speed reductions within the work zone. However, they did find a useful benefit in reducing the number of vehicles in the closed lane approaching a work-zone taper. On average, the closed lane held 20 percent fewer vehicles when the CMS was operational, reducing the number of conflicts created by later merges at the work-zone taper.

One study (Finger et al. 2009) directly compared a CMS displaying "SLOW DOWN, DRIVE SAFELY" to a temporary traffic sign (TTS) displaying W20-1 "ROAD WORK AHEAD" in a study on two-way rural highways in Kansas. The W20-1 sign was located downstream from the CMS and was always in place—when the CMS was turned on or off. They found that the TTS in the advance area had as great or sometimes greater impact on speed reduction than did the CMS, either on or off. All speed reductions were in the 2.4 mph to 5 mph range. With the TTS, reductions were from 6 percent to 10 percent, and with the CMS on, the reductions were from 5 percent to 8 percent.

CHANGEABLE MESSAGE SIGNS WITH RADAR

CMSR can be used to display specific warning messages to speeding drivers. The radar unit detects the speed of each vehicle entering the work zone and can be programmed to activate the CMS if the speed of the vehicle exceeds a preset threshold value. Often the CMSR can be programmed to display different messages based on the specific radar speed.

Garber and Patel (1994) studied the short-term effects of four CMSR messages on speeding vehicles in a work zone. All four messages were effective in significantly reducing the average speeds of high-speeding vehicles (vehicles traveling 4 mph or more over the 55 mph speed limit), typically reducing the number of speeding vehicles by 50 percent or more. The four messages, in order of their effectiveness, were “YOU ARE SPEEDING SLOW DOWN,” “HIGH SPEED SLOW DOWN,” “REDUCE SPEED IN WORK ZONE,” and “EXCESSIVE SPEED SLOW DOWN.”

Garber and Srinivasan (1998) continued the work of Garber and Patel using their most effective sign but looking at the long-term effects of CMSR in work zones. They found that the duration of exposure of the CMSR did not have a significant impact on speed characteristics and driver behavior, leading them to conclude that CMSR would be continuously effective in work zones for projects of long duration (at least up to seven weeks). The CMSR reduced the probability of speeding over the entire seven-week study period.

Researchers studied CMSR for a three-week period and found that the CMSR provided significant speed reductions from 7 mph to 8 mph for approaching traffic at locations immediately adjacent to the CMSR (Wang et al. 2003). Speed variances were also reduced, and the speed reductions did not wear off over the three-week study period.

Research by Brewer et al. (2006) included deploying the CMSR at a work zone on a rural Interstate highway that had two lanes in the same direction and then experienced a lane closure. The CMSR displayed a default message until it detected a vehicle traveling at a speed above a preset threshold. Once this threshold was passed, the CMSR display changed to a message urging the driver to slow down to a compliant speed but reverted to its default message if the vehicle slowed sufficiently or passed the CMSR. The default message displayed was “GIVE US A BRAKE,” which then sequenced through three messages for speeders in this order: “SLOW DOWN,” “YOUR SPEED,” and “XX” (which was the actual speed detected). The CMSR reduced 85th percentile speeds for both passenger cars and trucks at the two nearest downstream data collection points (within one-half mile of the CMSR) from 1 mph to 2 mph. The last half-mile of the work zone did not experience any speed reduction when using the CMSR. However, when two CMSR were used, where the second was about one-half mile from the first (in the middle of the work zone), speed reductions were from 1 mph to 3 mph throughout the entire mile downstream.

CHAPTER 3. SOUTH CAROLINA CMSR CASE STUDY

Sarasua et al. (2006) conducted a study for the South Carolina Department of Transportation (DOT) using portable CMSR with four different messages. They investigated many different types of work-zone management devices, and theirs was the only study found in this report's literature search that used a message providing traffic fine feedback. For this reason, the results of the South Carolina DOT study supplement the findings of this ADOT study and are presented here in detail.

The CMSR used in the South Carolina research (Figure 4) conformed to *MUTCD* guidance for a portable CMR: three-line messages with a maximum of eight characters per line (FHWA 2003; FHWA 2009b). The sign display measured 126 inches by 76 inches (the same size as the sign used for gathering data in this ADOT study).

Figure 4. CMSR Used in South Carolina Study. (Sarasua et al. 2006)

Four CMSR messages were studied (Figure 5). The default sequence 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. Data were collected in February and March of 2006 for a one-hour period during morning peak hours.

Data were collected at four work sites that represented both rural and urban locations (Table 1). There was limited activity within each work zone to eliminate any influence that might result from the presence of workers or large machinery. The work sites were long (from 4 to 8 miles), and the CMSR was placed within the work site so the reduced work-zone speed limit was already in effect before a vehicle encountered the CMSR. Three of the sites had posted work-zone speeds of 45 mph, and one site had a 55 mph speed.

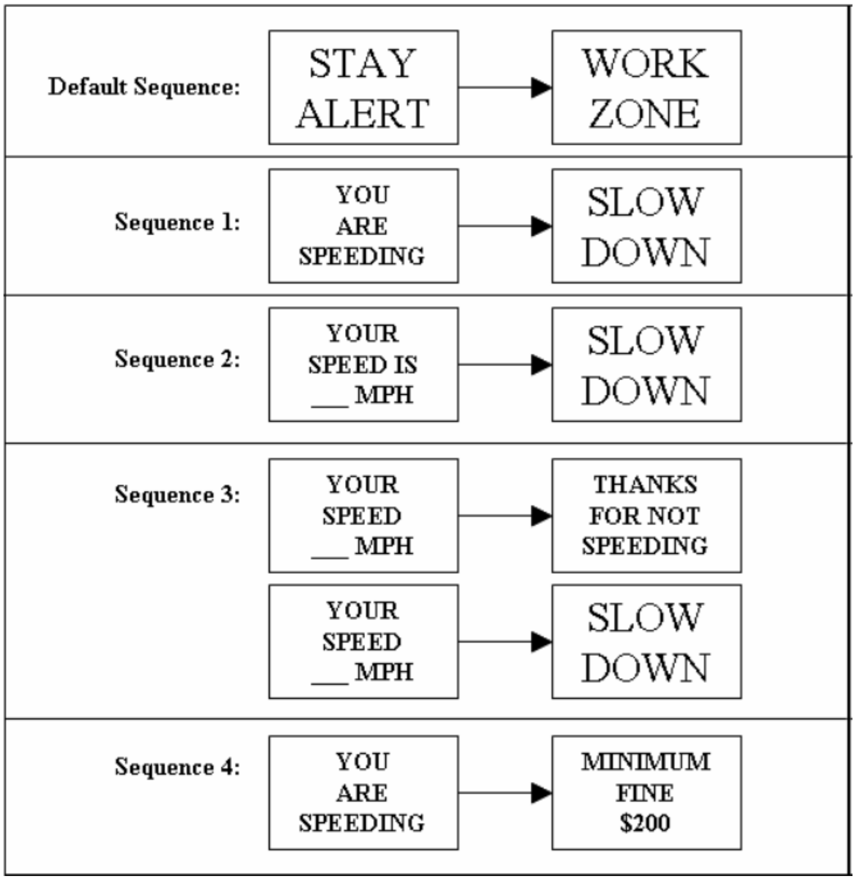


Figure 5. South Carolina Study's Message Sequences. (Sarasua et al. 2006)

Baseline data were collected when the CMSR was not present for a corresponding one-hour period of morning rush hour. While the CMSR was operating, data were collected at three stations: upstream of the CMSR from 1000 ft to one mile, immediately downstream from the CMSR (within 300 ft), and downstream approximately 1200 ft (Figure 6). Data were excluded if vehicles could not travel at their desired speed (that is, if vehicles were queuing).

Table 1. South Carolina Study Work Sites. (Sarasua et al. 2006)

Study Site	Highway Route	Work-Zone Length (miles)	Zone Speed Limit (mph)	Study Lanes Open to Traffic	Type of Work Zone	Study Phases
A	I-585	6.0	45	2	Interchange construction	Phases 1 and 2
B	SC 72	4.0	55	1	Widening	Phases 1 and 2
C	SC 101	8.1	45	1	Widening	Phase 1
D	SC 290	6.0	45	1	Widening	Phase 1

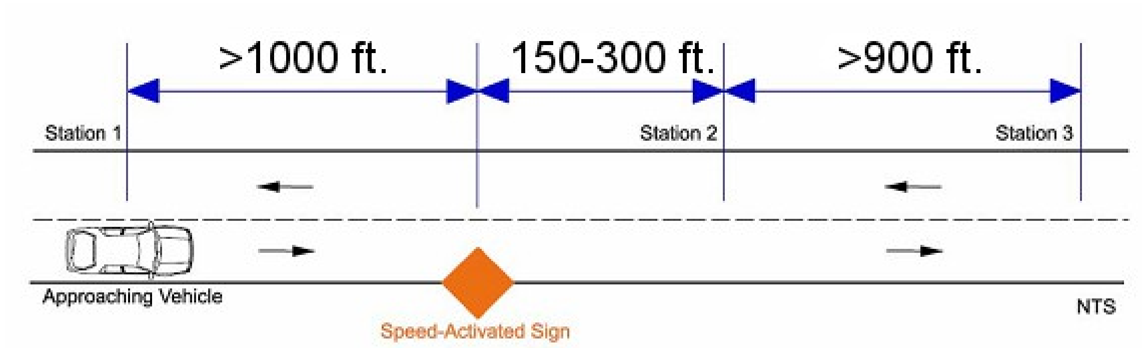


Figure 6. Typical South Carolina Layout for Data Collection. (Sarasua et al. 2006)

PHASE 1 RESULTS: FOUR MESSAGE SEQUENCES COMPARED AT TWO SITES

The South Carolina study was conducted in two phases. In the first phase, researchers studied all four message sequences at Site A on Interstate 585 (I-85) and Site B on South Carolina State Route 72 (SC 72). They found that all four message sequences resulted in decreases in mean speeds and 85th percentile speeds between each of the three data collection stations.

The mean speeds of vehicles at Station 1 were relatively close to the posted work-zone speed limits (Table 2). In general, for each successive station, a decrease in the mean speed was observed through the study area for all four sign message sequences. The total mean speed reductions between Stations 1 and 3 were 7 mph to 10 mph for Site A (I-585, 45 mph, two lanes open in same direction) and 9 mph to 14 mph for Site B (SC 72, 55 mph, one lane open in same direction). At the I-585 site, vehicles achieved their decreased speeds by Station 2 and maintained them at Station 3. However, at the SC 72 site, vehicles didn’t achieve their full speed reduction until Station 3. This difference between sites, the researchers suggested, may have been because the higher speed limit (55 versus 45 mph) required more distance to decelerate to a lower sustained speed.

Table 2. Phase 1: Observed Mean Speeds and Reductions. (Sarasua et al. 2006)

I-585, Speed Limit 45 mph (72.4 km/h)								
Message	**Observed Mean Speeds at Station 1**		**Reduction in Mean Speeds**					
			Station 1 to 2		**Station 1 to 3**		**Station 2 to 3**	
	mph	**km/h**	**mph**	**km/h**	**mph**	**km/h**	**mph**	**km/h**
1	47	75.6	9	14.5	10	16.1	1	1.6
2	46	74.0	9	14.5	9	14.5	0	0
3	43	69.2	7	11.3	7	11.3	0	0
4	44	70.8	7	11.3	7	11.3	0	0
SC 72, Speed Limit 55 mph (88.5 km/h)								
Message	**Speeds at Station 1**		**Station 1 to 2**		**Station 1 to 3**		**Station 2 to 3**	
1	54	86.9	5	8.0	14	22.5	9	14.5
2	55	88.5	5	8.0	9	14.5	4	6.4
3	54	86.9	7	11.3	10	16.1	3	4.8
4	54	86.9	6	9.7	10	16.1	4	6.4

All message sequences resulted in a decrease in the 85th percentile speeds successively between each station (n.

Table 3). The total 85th percentile reductions for Site A (I-585, 45 mph, two lanes open in same direction) between Stations 1 and 2 were 6 mph to 9 mph and reduced by an additional 1 mph to 2 mph by Station 3. For Site B (SC 72, 55 mph, one lane open in same direction), the reductions were from 2 mph to 4 mph between the first two stations and reduced by another 3 mph to 8 mph by the last station.

Table 3. Phase 1: Observed 85th Percentile Speeds and Reductions. (Sarasua et al. 2006)

I-585, Speed Limit 45 mph (72.4 km/h)								
Message	**Observed 85th Percentile**		**Reduction in 85th Percentile Speeds**					
			Station 1 to 2		**Station 1 to 3**		**Station 2 to 3**	
	mph	**km/h**	**mph**	**km/h**	**mph**	**km/h**	**mph**	**km/h**
1	53	85.3	9	14.5	10	16.1	1	1.6
2	51	82.1	8	12.9	8	12.9	0	0
3	48	77.2	6	9.7	8	12.9	2	3.2
4	50	80.5	7	11.3	7	11.3	1	1.6
SC 72, Speed Limit 55 mph (88.5 km/h)								
Message	**Speeds at Station 1**		**Station 1 to 2**		**Station 1 to 3**		**Station 2 to 3**	
1	58	93.3	3	4.8	11	17.7	8	12.9
2	59	95.0	4	6.4	4	6.4	0	0
3	58	93.3	4	6.4	7	11.3	3	4.8
4	57	91.7	2	3.2	5	8.0	3	4.8

Of particular interest was the impact on drivers who were speeding, which was determined in the South Carolina study by measuring the percentage of drivers who were speeding above the work-zone speed limit; both 5 mph and 10 mph over the speed limit were calculated. In the first phase of the study, these percentages decreased for all four messages at both sites, with one minor exception.

When researchers graphed the percentages of speeders at the I-585 site (Figure 7 and Figure 8), they noted that the highest observed reductions for Message 1 were due to the unusually high number of vehicles traveling at speeds greater than 5 mph over the speed limit when this message sequence was deployed.

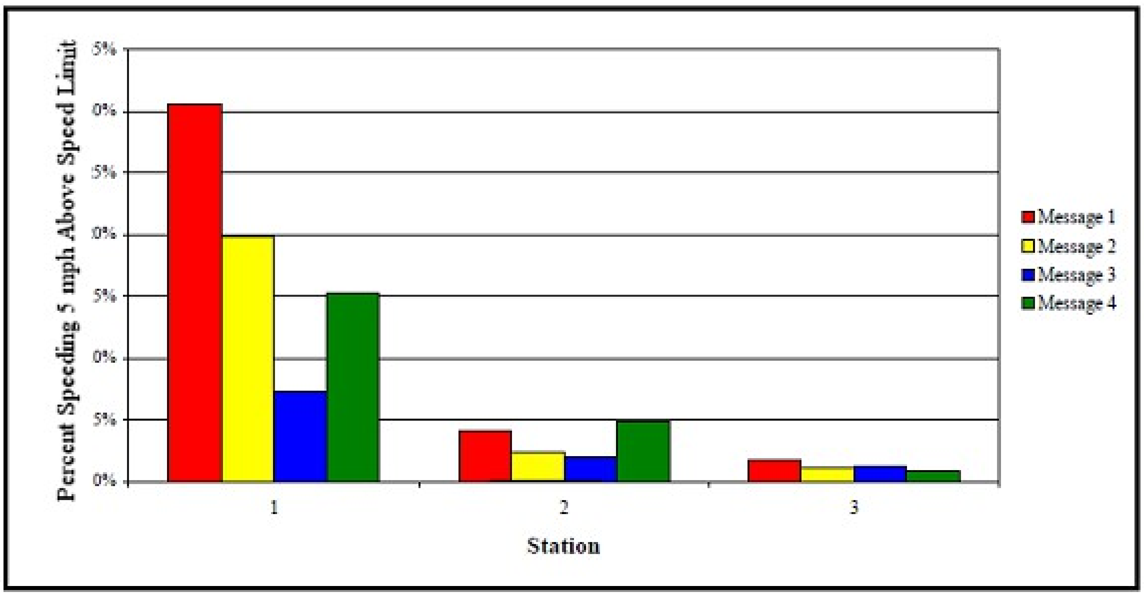


Figure 7. Phase 1: I-585 Drivers Speeding 5 mph or More Above Speed Limit. (Sarasua et al. 2006)

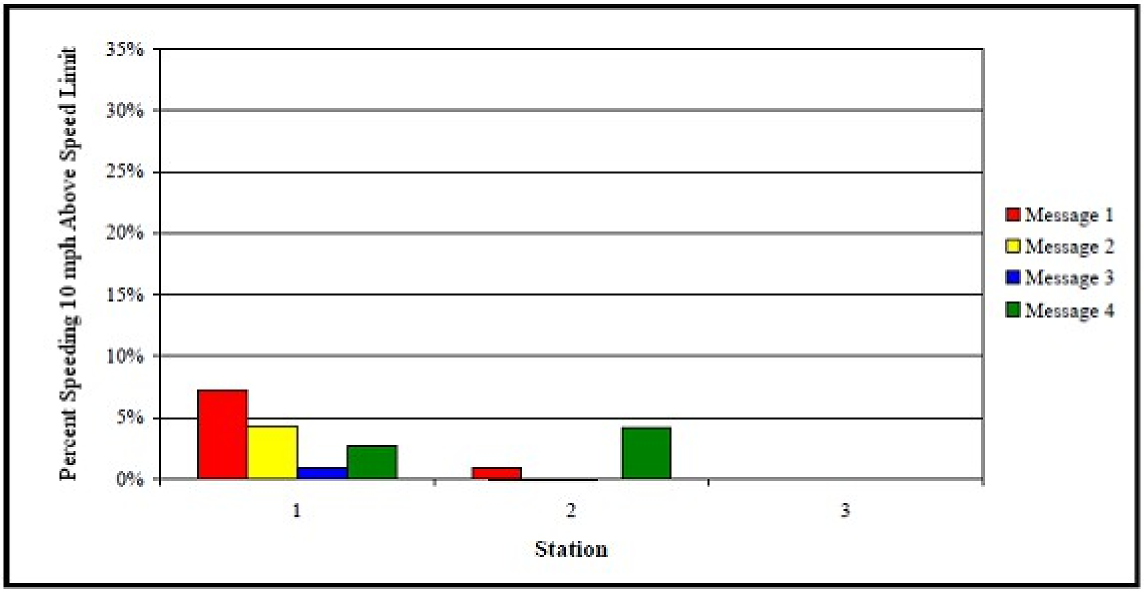


Figure 8. Phase 1: I-585 Drivers Speeding 10 mph or More Above Speed Limit. (Sarasua et al. 2006)

Researchers developed speed-frequency graphs for Message 4 showing the differences in distributions of speeds at the three data collection stations (Figure 9). The graphs indicate that Message 4 produced a beneficial shift downward in the speed characteristics of the vehicles.

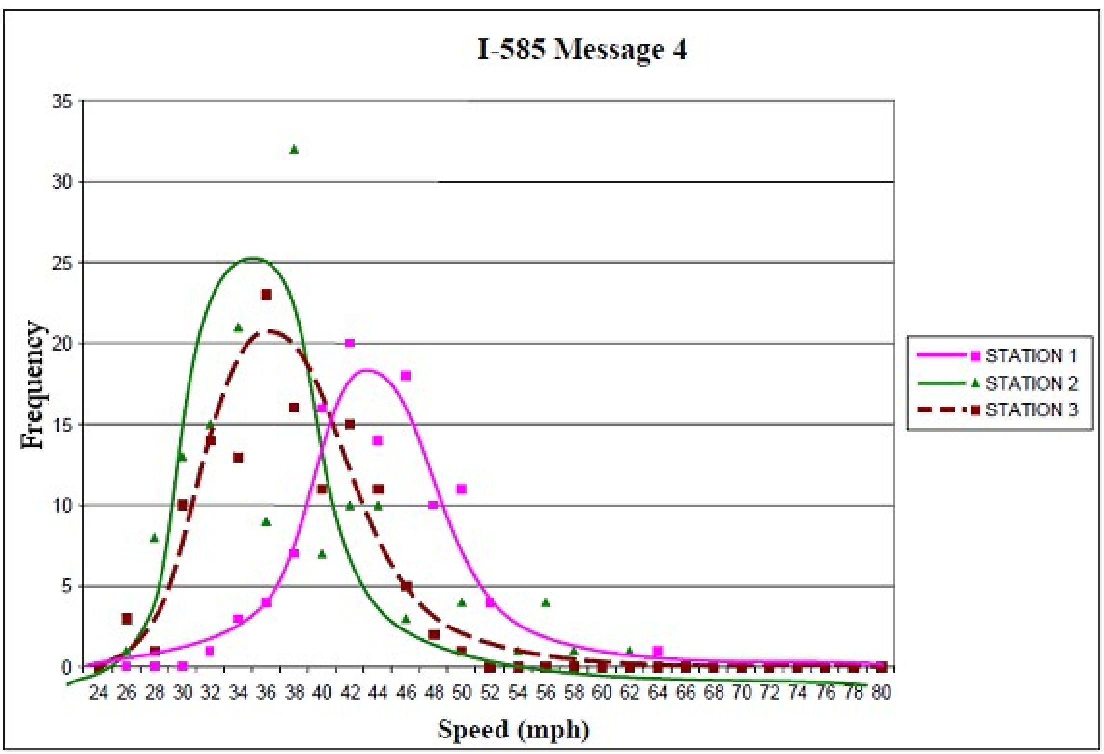


Figure 9. Phase 1: Speed vs. Frequency for I-585 Message 4. (Sarasua et al. 2006)

PHASE 2 RESULTS: TWO MESSAGE SEQUENCES COMPARED AT FOUR SITES

In the second phase of their study, Sarasua et al. (2006) chose Messages 3 and 4 for further analysis and eliminated Messages 1 and 2. Based on their literature review, neither Message 3 nor 4 had been studied previously, while Message 1, which had performed well, had been studied extensively by other researchers. The authors had included Message 1 in the study primarily to serve as a baseline for the other messages used. They concluded that Messages 2 and 3 performed similarly in the Phase 1 findings, so Message 2 was eliminated in favor of Message 3 primarily because it involved a more novel approach to driver feedback. Message 4 was of special interest because it involved feedback to drivers about a potential traffic fine for speeding. Additionally, the data collection sites were expanded to locations on South Carolina State Routes 101 (SC 101) and 290 (SC 290) (Table 1), and new data were taken at all four sites.

The mean speed reductions were determined for Messages 3 and 4 at the four sites, and the results are shown in Table 4. The greatest reductions in speeds occurred between the first two stations, and then nearly half of the reduced speed was regained by Station 3. Generally, speeds dropped from approximately 3 mph over the speed limit at Station 1 to between 5 mph and 8 mph below the speed limit at Station 2. At Station 3, most mean speeds were measured to be at or slightly below the posted speed limit. The researchers suggested that drivers possibly overreacted to the CMSR message initially and then, realizing this, accelerated back to the speed limit by Station 3.

Table 4. Phase 2: Reductions in Mean Speeds. (Sarasua et al. 2006)

Site	**Characteristics**	**Station 1 to 2**				**Station 1 to 3**			
	(45 mph = 72.4 km/h)	**Message 3**		**Message 4**		**Message 3**		**Message 4**	
	(55 mph = 88.5 km/h)	mph	km/h	mph	km/h	mph	km/h	mph	km/h
SC 101	45 mph, two lane	10	16.1	10	16.1	3	4.8	6	9.7
SC 290	45 mph, two lane	12	19.3	12	19.3	6	9.7	7	11.3
	Mean	11	17.7	11	17.7	4.5	7.2	6.5	10.5
I-585	45 mph, four lane	7	11.3	0	0	2	3.2	1	1.6
SC 72	55 mph, two lane	8	12.9	6	9.7	14	22.5	11	17.7

The researchers observed reductions in the 85th percentile speeds among the four sites as seen in Table 5. No apparent significant differences were observed between the two messages for the speed reductions observed at Station 3 at all four sites. Station 2 reductions, however, do show inconsistencies.

Table 5. Phase 2: Reductions in 85th Percentile Speeds. (Sarasua et al. 2006)

Site	Characteristics	Station 1 to 2				Station 1 to 3			
	(45 mph = 72.4 km/h)	Message 3		Message 4		Message 3		Message 4	
	(55 mph = 88.5 km/h)	mph	km/h	mph	km/h	mph	km/h	mph	km/h
SC 101	45 mph, two lane	10	16.1	8	12.9	3	4.8	3	4.8
SC 290	45 mph, two lane	10	16.1	13	20.9	4	6.4	7	11.3
	Mean	10	16.1	10.5	16.9	3.5	5.6	5	8.0
I-585	45 mph, four lane	5	8.0	*-6*	*-9.7*	2	3.2	2	3.2
SC 72	55 mph, two lane	8	12.9	4	6.4	10	16.1	10	16.1

The decrease in speeding drivers is highly important and can be seen in Figure 10 and Figure 11 for the SC 290 site. Drivers speeding 5 mph or more above 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 message sequences. In the second phase, only Message 4 produced this trend. Message 3 had a percentage at Station 3 that was more than twice that of Station 2, but still less than half that of Station 1 (Figure 10).

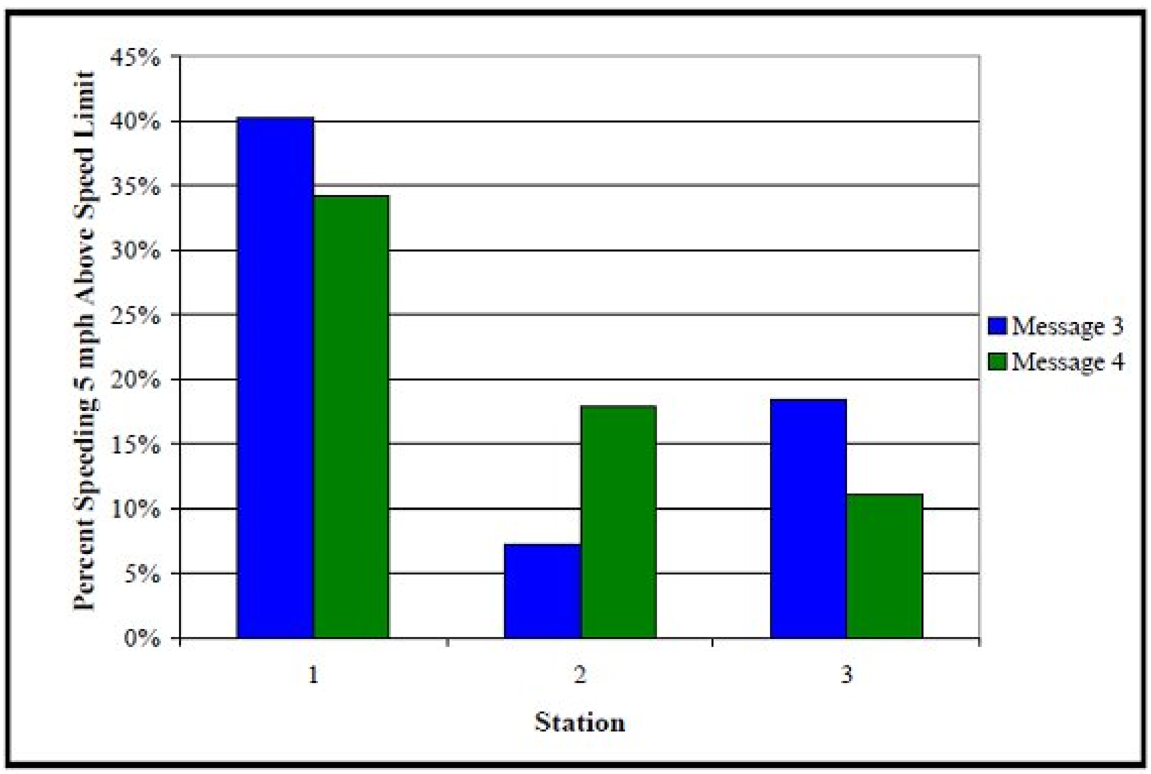


Figure 10. Phase 2: SC 290 Drivers Speeding 5 mph or More Above Speed Limit. (Sarasua et al. 2006)

The same relationship was observed for drivers speeding 10 mph or more above the speed limit, with the exception of the decrease in response to Message 4. At 5 mph or more above the speed limit, the majority of the decrease occurred between Stations 1 and 2, while for 10 mph or more, the largest drop occurred between Stations 2 and 3 (Figure 11).

In general, researchers observed that the frequency of measured speeds was similar to that observed in the Phase 1 data collection (Figure 12). Some differences, such as lower variability (or spread of the curve) at Station 1 and higher variability at Station 3, can be observed, but these do not appear to lead to any practical conclusions.

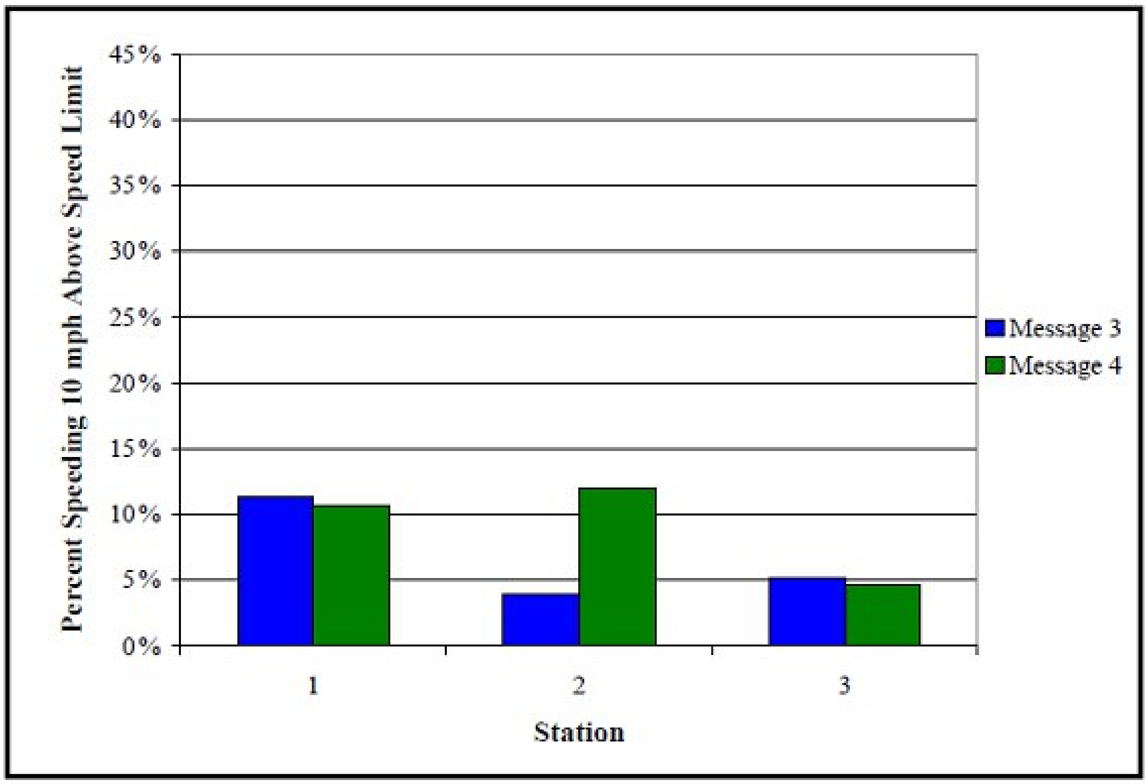


Figure 11. Phase 2: SC 290 Drivers Speeding 10 mph or More Above Speed Limit. (Sarasua et al. 2006)

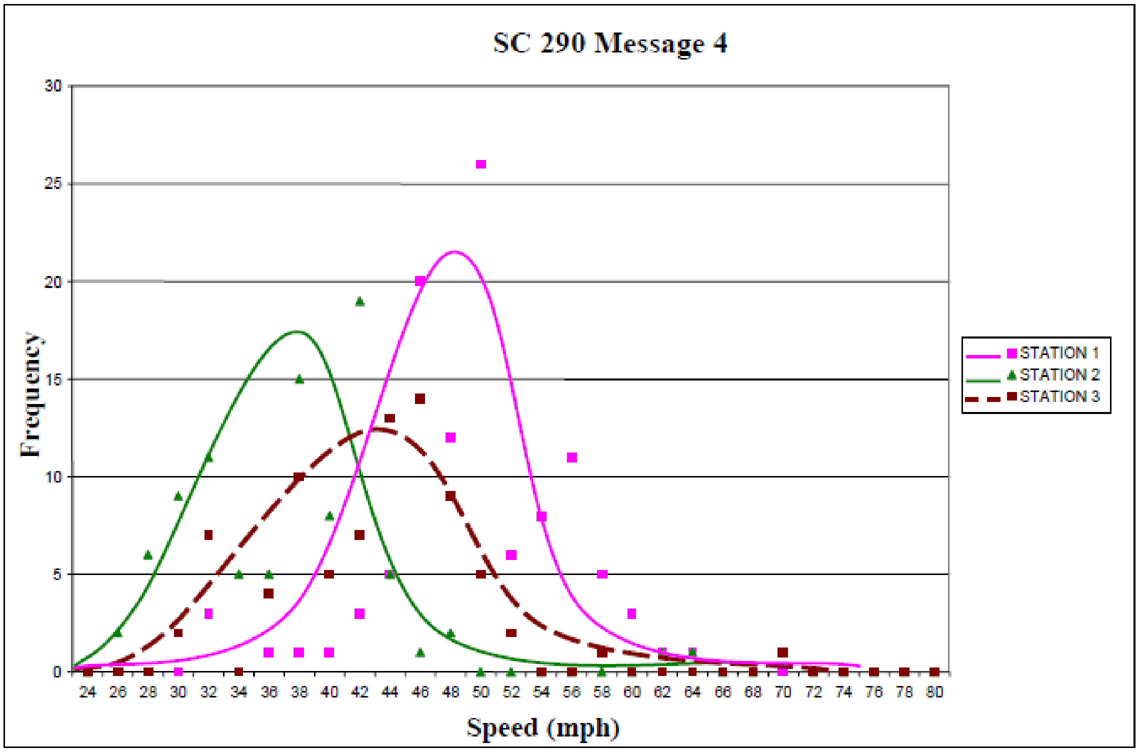


Figure 12. Phase 2: SC 290 Frequency Curve for Message 4.
(Sarasua et al. 2006)

CONCLUSIONS AND RECOMMENDATIONS

Sarasua et al. drew several conclusions from their study of using CMSR in roadway work zones:

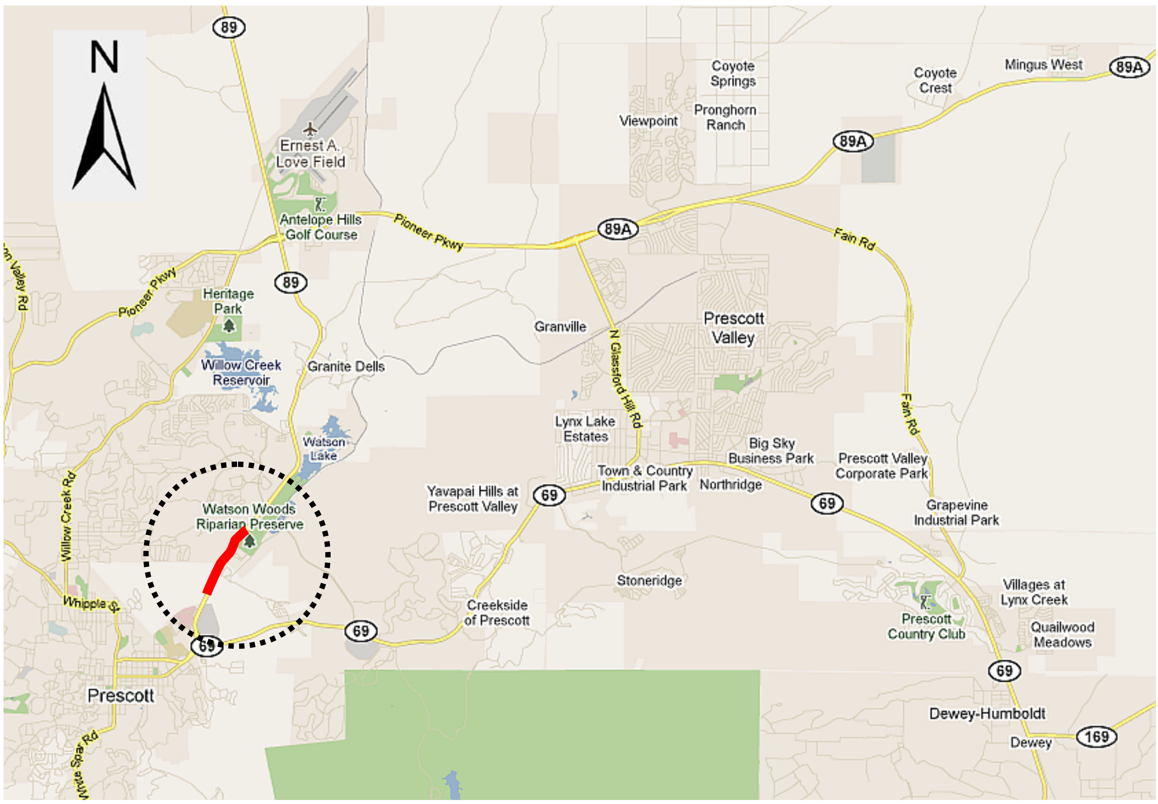
- Previous research had proved that using a CMSR is an effective means of reducing vehicle speeds in work zones.
- Message 1, "YOU ARE SPEEDING" followed by "SLOW DOWN," was the baseline they used for comparison with other message variations. Based on data collected in Phase 1 of their study and on extensive previous studies by others, this message effectively reduced speeds.
- Message 2, "YOUR SPEED IS __ MPH" followed by "SLOW DOWN," effectively reduced work-zone speeds during the study's Phase 1. It also served as a basis for comparison to Message 3's positive feedback to compliant drivers.
- Message 3, "YOUR SPEED IS __ MPH" followed by either "THANKS FOR NOT SPEEDING" or "SLOW DOWN," did not produce results significantly different from those of Message 2, even though some had assumed that a positive message for compliance might curb the tendency of drivers to increase speeds at Station 3, downstream from the CMSR.
- Message 4, "YOU ARE SPEEDING" followed by "MINIMUM FINE $200," which incorporated a different tactic by displaying potential consequences, produced speed reductions comparable to the other messages.

Standard CMS have been used in South Carolina work zones to convey road conditions, construction activities, and other general information. Sarasua et al. (2006), along with previous studies they reviewed, determined that equipping these signs with radar and using them to aid in speed control will decrease speeds. While some of the message sequences resulted in greater speed reductions than others, any of the four messages studied would improve driver compliance with posted speed limits near the CMSR. For their study, Sarasua et al. recommended Message 3 because it indicated actual speeds to the drivers rather than a general statement that they were speeding. (Note: In the South Carolina study, Message 4 did not display a vehicle's actual speed, only the potential fine.)

CHAPTER 4. ARIZONA SITE DESCRIPTION AND DATA COLLECTION METHODOLOGY

SITE LOCATION

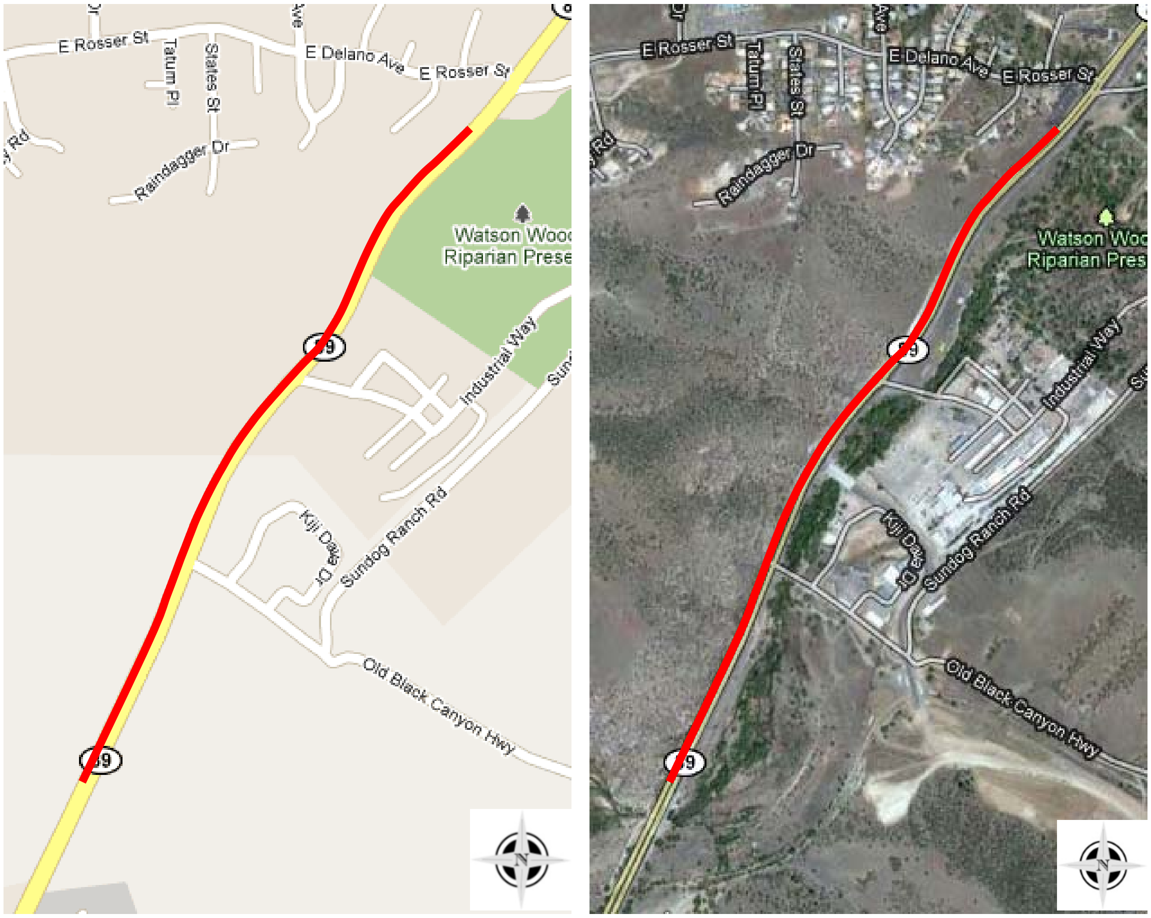
The Arizona work-zone site selected for data collection was State Route 89 (SR 89) through Prescott, Arizona, which is locally called the Granite Creek Bridge area. (See area map in Figure 13.) This bridge was undergoing reconstruction, which created a work zone in both directions.



Source: Google Maps; Map and Map Data © 2011 (Google Permissions 2011).

Figure 13. Map of Site Location in Prescott, Ariz. (Approximate scale: 1 inch = 2.7 miles)

SR 89 runs northeast/southwest through this area, but its overall direction is north/south; therefore the traffic is described as southbound (SB) and northbound (NB). A map and aerial photo of the data collection site are shown in Figure 14. The SR 89 roadway through the work zone is a four-lane divided roadway. On the north end of the work zone, the roadway uses a median demarked by striping, which when traveling SB changes into a raised divided median shortly before the approach to the Granite Creek Bridge and continues to the south end of the work zone.



Source: Google Maps; Map and Map Data © 2011 (Google Permissions 2011).

Figure 14. Map and Aerial View of SB SR 89 Data Collection Site in Prescott, Ariz.

SITE WORK-ZONE SIGNAGE

Researchers used the two SB lanes on the north end of the work zone as the data collection site. This portion of the roadway has a striped median changing to a turn lane where appropriate. It has full-width, paved shoulders. The signage from the beginning of the work zone through the data collection area follows. All signs have black lettering on an orange background unless otherwise noted.

- "ROAD WORK ON SR 89 AUG 2009 TO SEPT 2010 EXPECT DELAYS": This sign was mounted on a post to the right of the paved shoulder.
- "ROAD WORK AHEAD" (W20-1): One of these signs was mounted on each side of the roadway. The left-side sign was in the median on a portable, bend-over stand with a flasher and flags on the top. The right-side sign was to the right of the paved shoulder on two posts with flags on top.
- "SPEED LIMIT 50 MPH" (R2-1): This standard sign with black lettering on a white background was mounted on a post located to the right of the paved shoulder.

- “REDUCE SPEED AHEAD” (W3-5aAZ): One of these signs was mounted on each side of the travel lanes on a portable, bend-over stand with a flasher and flags on the top. The left-side sign was in the median, and the right-side sign was to the right of the paved shoulder.
- “SPEED LIMIT 45” (R2-1): One of these signs was mounted on each side of the travel lanes on a portable, bend-over stand. Each sign was oversized, with black lettering on a white background. The left-side sign was in the median, and the right-side sign was to the right of the paved shoulder.
- “SPEED LIMIT 35” (R2-1): This single, oversized sign with black lettering on a white background was mounted on a portable, bend-over stand to the far right of the paved shoulder.
- “LEFT LANE CLOSED 1/2 MILE” (W20-5L): One of these signs was mounted on each side of the travel lanes on a portable, bend-over stand. Each sign was oversized, with black lettering on a white background. The left-side sign was in the median, and the right-side sign was to the far right of the paved shoulder.
- “LEFT LANE CLOSED AHEAD” (W20-5L): One of these signs was mounted on each side of the travel lanes on a portable, bend-over stand. Each sign was oversized, with black lettering on a white background. The left-side sign was in the median, and the right-side sign was to the far right of the paved shoulder.
- “SPEED LIMIT 35” (R2-1): This single, oversized sign with black lettering on a white background was mounted on a portable, bend-over stand to the far right of the paved shoulder.
- Left Lane Drop Symbol Sign (W4-2L): One of these signs was mounted on each side of the travel lanes on a portable, bend-over stand. Each sign was oversized, with black lettering on a white background. The left-side sign was in the median, and the right-side sign was to the far right of the paved shoulder.

A detailed drawing showing the data collection site layout, including distances, is shown in Figure 15. This drawing is in three sections, with each section moving from right to left, beginning with Station 1 (Tube set 1A and Tube set 1B) in the upper right-hand corner.

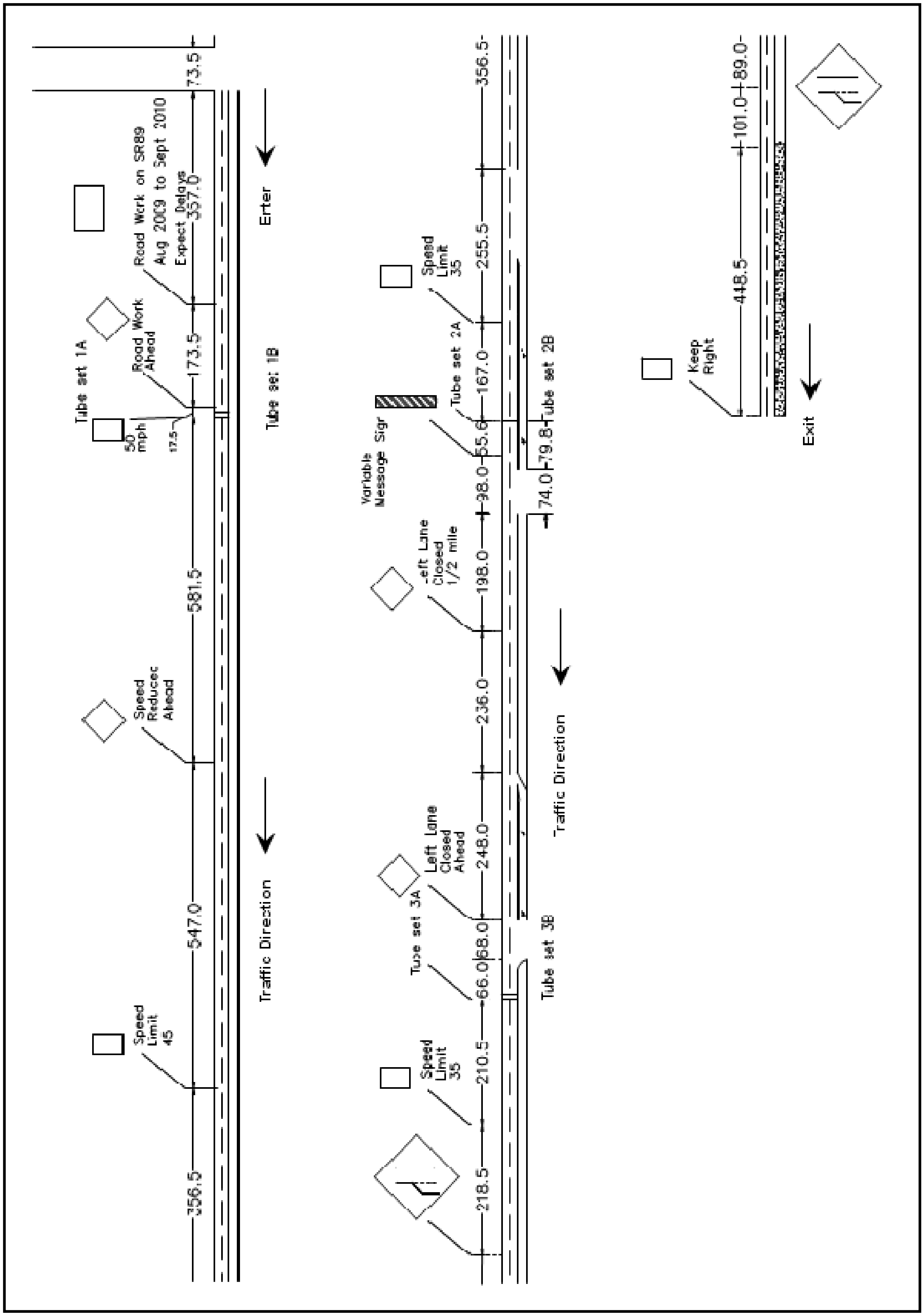


Figure 15. Detailed Layout of Work Site Signage and Distances (ft).

DATA COLLECTION METHODOLOGY

The best method to assess driver behavior is to track individual vehicles through a work zone. However, because this is difficult and expensive, a surrogate method of tracking all vehicles that pass a designated point in or near the work zone was used for this study. For statistical testing to be useful, a large sample size is desirable with samples taken over several days. While manual and automated types of technology can be used for data collection, the criteria of this study dictated using automated data collection equipment. Manual technology, such as hand-held speed radar guns, could not practicably acquire the desired sample sizes over long time spans.

Pneumatic Tubes

To collect speed and vehicle classification data, researchers used pneumatic tubes because their characteristics are well-known, pneumatic tubes and recorders needed were readily available, and they could be deployed for long time spans at a remote site with minimal supervision. Also, the recorders could capture and store individual tube actuations rather than aggregating data into bins before storing, which loses data resolution.

Pneumatic tubes are used in pairs across a single lane. The distance between the tubes is fixed at 2 ft. The two tubes are connected to a data recorder box, which records each individual tube's activation with a time stamp and stores that data. The tube is activated by the weight of a vehicle's tire crossing it. For example, a two-axle, four-wheel automobile activates each tube twice: once when the front set of tires crosses the tube (which happens essentially simultaneously so only one activation is recorded for both front tires) and a second time when the back set of tires crosses the tube. Therefore, for the pair of tubes, four time stamps are recorded when a two-axle vehicle crosses it: two on the first tube and two on the second tube.

When the data is postprocessed, the speed and type of vehicle can be inferred from the individual time stamps. The inductive reasoning used is based on the known distance between the pair of tubes (2 ft) and the known distance between the front set of tires and the back set of tires (axle-to-axle distance) for various classifications of vehicles. Using these measurements and the time stamps recorded, the type of vehicle and its speed can be inferred for each passing vehicle. (Similar logic is used for multi-axle vehicles.)

Since the data collection site had two lanes, individual pairs of tubes were placed across each lane and connected to separate data recorders. These data were later merged during postprocessing.

Location of the Pneumatic Tubes, Data Recorders, and CMSR

Data were collected at three stations, as shown in Figure 15; a schematic of the data collection station locations is shown in Figure 16. Station 1 was located at a pair of signs—"SPEED LIMIT 50" and "ROAD WORK AHEAD"—to record data before drivers began to react to the temporary traffic control signage in the work zone.

Station 2 was located 1,910 ft downstream from Station 1. At this station the vehicles had likely reacted to two speed limit changes: "SPEED LIMIT 45," located 790 ft upstream from Station 2, and "SPEED LIMIT 35," located 170 ft upstream from Station 2. The CMSR was located 55 ft downstream from Station 2 and could be seen well ahead of Station 2 (Figure 17). Station 2 was located so as to record data that captures drivers' reactions to the CMSR.

Station 3 was located 970 ft downstream from Station 2. At this station, vehicles had encountered two impending-lane-drop signs: "LEFT LANE CLOSED 1/2 MILE" and "LEFT LANE CLOSED AHEAD." However, the actual lane drop did not begin for another 1,050 ft downstream from Station 3. Station 3 is located to record data that captures any short-term retained reactions to the CMSR, which is located 910 ft upstream from it.

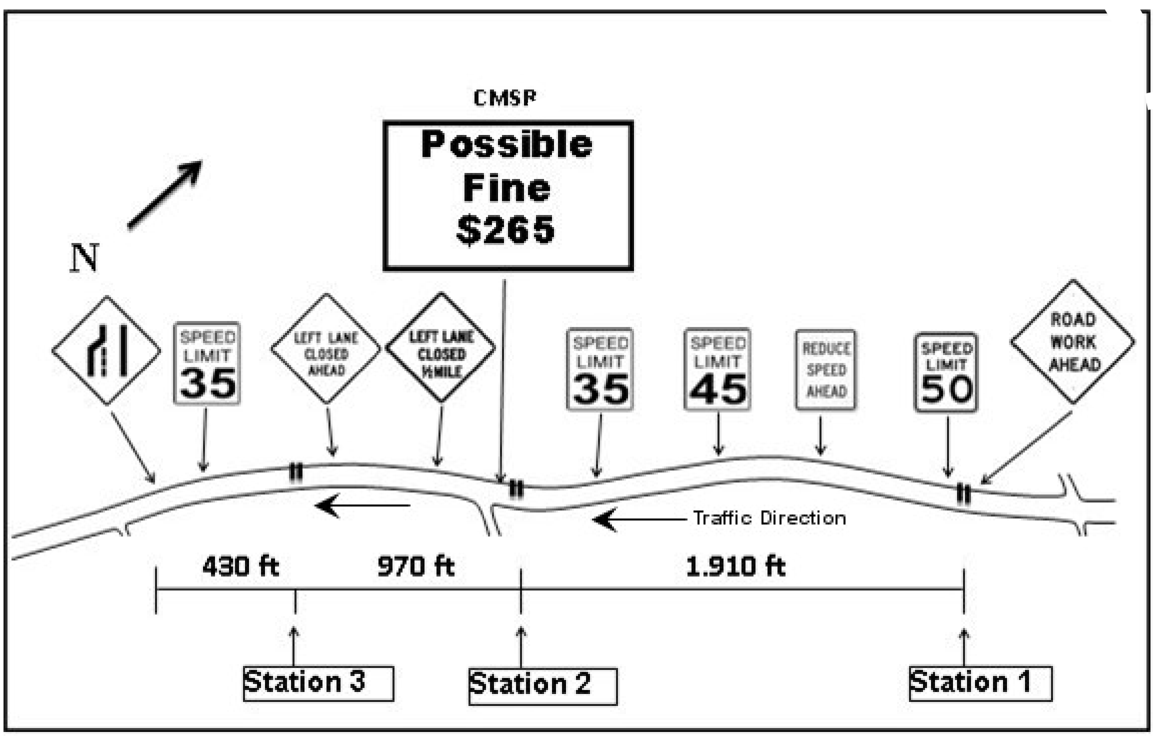


Figure 16. Locations of Data Collection Stations.

Figure 17. View of Relative Positions of Station 2 and CMSR.

CHAPTER 5. DATA COLLECTION AND ANALYSIS

CMSR SETUP AND PROGRAMMING

The CMSR used in this study was a Ver-Mac PCMS-1210 with radar, which generally conforms to *MUTCD* standards (FHWA 2009b). It has three lines of display with eight characters on each line. Each character is 12 inches wide by 18 inches high, resulting in a display panel size of 69 inches by 131 inches. The sign is mounted on a trailer that allows the sign to be raised (when stationary) from its lower position, which is used during transport. When raised, the display panel is approximately 7.5 ft above the ground at its bottom and 13 ft above at its top.

Before being deployed at the study site, the CMSR was pretested in a school zone in Flagstaff, Arizona, which the researchers constantly monitored due to its location. The pretest was prototypical of almost every aspect of the setup and data collection at the eventual study site as well as the subsequent data analysis. During the pretest, researchers confirmed the programming and calibration of the CMSR, observed the distances needed for drivers to see and react to the sign messages, and became familiar with aiming the CMSR's radar unit and with the unit's limitations. They also improved methods for attaching the tubes to the pavement, and gained extracting and manipulating large data sets from the recorders. Researchers also verified that the size of the data sets was sufficient to achieve the statistical significance desired.

At the study site, the CMSR was programmed to display only speeds below 75 mph (20 mph over the nonwork-zone speed); the sign went dark if speeds of 75 mph or greater were detected. The radar unit picked out the vehicle that was most directly in its line of sight and reported that vehicle's speed until it moved out of its line of sight, and then it picked up the next vehicle. If no vehicle was detected, the sign went dark. After experimentation, the radar unit on the sign was aimed between the inside and outside lanes, which resulted in the best compromise to detect a lead vehicle in either lane. Researchers calibrated the radar unit on the sign with a speed radar gun that had been regularly tested for accuracy (Figure 18).

At the beginning of the data collection period when baseline data were collected, the CMSR was not at the site to avoid affecting drivers simply by being present. After the testing, it was again removed entirely, and another set of data was taken.

Two modes of CMSR operation were tested. (Note: In the following descriptions, the "/" indicates the end of each line on the three-line sign display board, and the "XX" represents vehicle speed.):

- "YOUR / SPEED IS / XX MPH": This was the first mode tested, where only speed feedback was given to drivers. It varied as the radar detected speed changes (Figure 18).

Figure 18. Calibrating the CMSR with a Radar Gun.

- "YOUR / SPEED IS / XX MPH" alternating with "POSSIBLE / FINE/ $XXX": This was the second mode tested, where the two messages were alternated continuously. Each message was displayed for 0.7 seconds. Both messages varied as the radar detected speed changes greater than or equal to 10 mph over the speed limit (40 mph). When the vehicle was traveling at less than 10 mph over the speed limit, the only message displayed was "YOUR / SPEED IS / XX MPH."

Speeding fines at the work zone were researched and the appropriate values programmed for the feedback message to drivers. This was more difficult than anticipated because three jurisdictions overlapped at the study site: the State of Arizona, the Yavapai-Prescott Indian Tribe, and the City of Prescott. According to law enforcement and court staff of the three parties, the tribe had jurisdiction, so its fine structure was used.

The following fines were shown alternately with the vehicle speed detected (The work-zone speed limit at the sign was 35 mph.):

- 0 mph to 45 mph detected speeds: No fine displayed; only the speed was shown, with no alternation.
- 46 mph to 50 mph detected speeds: $155.
- 51 mph to 55 mph detected speeds: $265.
- 56 mph to 60 mph detected speeds: $365.
- 61 mph and greater detected speeds: $480.

In all cases, the sign was programmed to go dark if the speed reached 75 mph or greater.

DATA COLLECTION PERIODS

As stated previously, the benefit of automated data collection methods is the ability to obtain large sample sizes over extended periods. On the other hand, automated methods are only visited periodically, so any problems that arise are not handled immediately. The primary data collection problem in this study occurred when a pneumatic tube became detached, notwithstanding its securement to the asphaltic concrete pavement with brackets and nails and with tape applied at several places between the brackets (the tape can be seen in Figure 17). However, detachment could happen at any time and was typically due to repeated "hits" at a bracket until it loosened or the taped tubes between the brackets pulled up. As the data collection team obtained more experience, fewer tube detachments occurred.

Each station collected data using a data recorder and a pair of pneumatic tubes for each lane. In total, the three stations required six data recorders and 12 tubes. The data needed to be complete from all stations for comparison purposes, meaning that all 12 tubes had to be operating simultaneously for any of the data to be useful. Therefore, a single tube detachment at any station resulted in unusable data at all stations until the tube was successfully reattached. Periods where one or more tubes were not recording valid speeds were removed from the data.

The experiment was designed to evaluate the effectiveness of the CMSR in two modes: first was the display of speed feedback information to the approaching drivers, and second was to display speed feedback alternating with feedback about the amount of potential speeding fine. Data from these two modes were compared to each other and to data collected both before any CMSR was placed at the site and after it was removed from the site. This procedure resulted in four sets of usable data, each spanning from four to 13 days:

- <u>Before: No Sign (BNS)</u>: August 2, 2010, 5:00 a.m. to August 6, 2010, noon; and August 14, 2010, 8:00 a.m. to August 17, 2010, 1:00 a.m. (seven days).
- <u>Speed Only (SO) Displayed on CMSR</u>: August 21, 2010, 4:00 a.m. to August 27, 2010, 2:00 a.m. (six days).

- Speed and Fine (SF) Displayed on CMSR: August 31, 2010, 7:00 a.m. to September 13, 2010, 1:00 a.m. (13 days).
- After: No Sign (ANS): September 13, 2010, 1:00 p.m. to September 17, 2010, 10:30 p.m. (four days).

DATA CLEANING

Automated data are especially susceptible to anomalies that must be removed if the data are to accurately represent the condition intended. The removal of unrepresentative samples is called data cleaning. Using Microsoft Excel Version 14 to clean the data, researchers removed samples with the following characteristics (in the order listed):

- Speed = 0: These occurred for short periods of time when setting up the recording device and when downloading data from it. They are false readings.
- Gaps less than or equal to (LTE) 5 seconds: This removes vehicles that might be traveling in platoons and therefore do not have the ability to choose their own speed.
- Axles greater than or equal to (GTE) six axles: These are most probably false readings caused by such things as driving over the tubes on a diagonal or being stopped on a tube. Also, while vehicles with GTE six axles could technically be present in the work zone, it is doubtful.
- Length of vehicle GTE 1000 inches: These are most probably false readings caused by situations similar to those causing axles GTE six axles.

Data cleaning resulted in the removal of a significant number of samples as shown in Table 6, Table 7, and Table 8.

Table 6. Station 1 Data Cleaning.

Station 1	BNS	SO	SF	ANS
Original total samples (after removal of zero speed samples)	39,472	37,134	77,737	25,648
Gaps LTE 5 seconds	16,963	17,116	34,625	12,241
Axles GTE 6 axles	13	17	36	9
Length GTE 1000 inches	6	0	18	9
Total samples used in analysis (after removals)	**22,490**	**20,001**	**43,058**	**13,389**

Table 7. Station 2 Data Cleaning.

Station 2	BNS	SO	SF	ANS
Original total samples (after removal of zero speed samples)	38,341	35,812	74,376	24,589
Gaps LTE 5 seconds	17,069	16,956	34,161	12,325
Axles GTE 6 axles	12	20	53	9
Length GTE 1000 inches	26	27	49	9
Total samples used in analysis (after removals)	**21,234**	**18,809**	**40,113**	**12,246**

Table 8. Station 3 Data Cleaning.

Station 3	BNS	SO	SF	ANS
Original total samples (after removal of zero speed samples)	38,683	31,774	69,740	22,878
Gaps LTE 5 seconds	17,818	14,394	31,943	11,321
Axles GTE 6 axles	14	5	53	13
Length GTE 1000 inches	6	5	20	16
Total samples used in analysis (after removals)	**20,845**	**17,370**	**37,724**	**11,528**

The primary reason samples were removed was because of short gaps between vehicles, probably caused by vehicles in a queue or platoon that cannot adjust their speed in response to the work-zone signage or CMSR.

About 15 percent to 20 percent of the samples with gaps LTE 5 seconds have gaps of 4 or 5 seconds. It could be argued that 5 seconds is too generous and that some of these vehicle drivers do have sufficient maneuvering time and distance to choose their own speeds. To check this, researchers also prepared data with gaps LTE to 3 seconds removed and compared them to the data with gaps LTE 5 seconds removed. While statistically significant differences resulted, they were due to the very large number of samples, which allows statistical tests to determine very small differences in sample statistic values (for example, means). However, these differences were so small as to be of no practical significance. Therefore, the data with gaps LTE 5 seconds removed were used for all the analyses presented in this report.

STATISTICAL TESTING

Using TIBCO Spotfire S+ 8.2 for Windows, researchers conducted statistical tests to analyze the data collected and verify that the differences noted in the sample data were not due to chance alone. A 95 percent confidence level (unless specifically noted otherwise) was the threshold used to exclude chance and have confidence that the sample differences represented true differences. Then the data was organized into four data sets (BNS, SO, SF, and ANS), with each set consisting of three stations (Stations 1, 2, and 3). Specifically, within each data set and across data sets, researchers compared:

- Mean and median speeds.
- 85th percentile speeds.
- Percentages exceeding the speed limit by 5 mph, 10 mph, 15 mph, 20 mph, and 25 mph.

Comparison of Means

Speed means were compared using the *t* test for two independent samples. For this test, researchers need to verify the following assumptions (Sheskin 1997, 153):

- The compared samples are independent from one another.
- Each sample has been randomly selected from the population it represents.
- The distribution of the data in the underlying population from which each of the samples is derived is normal.
- The variances have homogeneity, that is, the variance of the underlying population represented by the first sample is equal to the variance of the underlying population represented by the second sample.

The independence assumption can easily be defended when data are compared between two data sets because they were taken at different times and from different populations. When comparing data within a data set, the vehicles captured at Station 3 had all passed through Stations 2 and 1, and those captured at Station 2 had all passed through Station 1, albeit at different times. So they could be dependent. An example of the logic for dependent data would be if a sample of a specific vehicle at Station 2 was altered (dependent) on what that vehicle did at Station 1. Continuing, if the speed of a vehicle at Station 1 was very high, does this mean the speed of the vehicle was very high (or in some other way predictable) at Station 2? Probably not, so the case can be made that the samples from each station within a data set were independent from each other.

The assumption of random selection was met. Specifically, no systemic bias occurred in the collection of the sample that represented the total population passing each station. The elimination of the samples with gaps LTE to 5 seconds did systemically alter the population but it simply redefined the underlying population to be all those vehicles that had a gap between them of 6 seconds or more, which was the target population of interest.

The assumption that the underlying distributions are normal was somewhat more difficult to defend. The distributions were approximately normal but have some deviations, probably classified as minor. However, with large samples sizes as in this study, most normal-theory-based tests like the *t* test are robust to nonnormality and probably won't have a serious effect on the results of a normal-theory-based test (BBN Corporation 1997, TIBCO Software, Inc. 2010a).

The homogeneity of variances assumption was not universally met among the data sets. However, the *t* test used employed the Welch modified two-sample *t* test, which is not derived under the assumption of equal variances. Therefore, it allows users to compare the means of two populations without first having to test for equal variances (Welch 1947). Therefore, homogeneity of variances did not need to be satisfied.

Comparison of Medians

Speed medians were compared using the Wilcoxon rank sum test for two-sample data, which is equivalent to the Mann-Whitney test (Conover 1980, 215). For this test, researchers needed to verify the following assumptions:

- Each sample is a random sample from its respective population.
- The two samples are mutually independent.
- The measurement scale is not ordinal.

The first two assumptions were met and have been addressed previously. The last assumption was also met because the data were interval-scale data and not ordinal. For large data sets as in this study, a normal approximation is used for the distribution of the test statistic (Sheskin 1997, 83-94).

Comparison of 85th Percentiles

Researchers compared 85th percentiles by first estimating quantiles ($p = 0.85$) empirically from the data groups. They created the empirical cumulative distribution function (cdf) with the smallest and largest observations used as the 0th and 100th percentile, respectively. Linear interpolation was used to estimate the *p*th quantile. More observations are needed to use the nonparametric method, but a sample GTE to 100 was sufficient for a 99 percent confidence interval (CI). Next, they estimated CIs nonparametrically for each quantile with a confidence level of 99 percent (Conover 1980, 111-116). Two (or more) 85th percentile values can be compared to each other only if their CIs do not overlap. Overlapping CIs indicates that the two (or more) values cannot be statistically distinguished from each other at the confidence level used to estimate the CIs (99 percent in this case).

Comparison of Percentages Exceeding the Speed Limit

To compare percentages of the population exceeding the speed limit by a given amount, researchers used the proportions test, which uses the chi-square statistic and tests if all the probabilities of success are the same in the groups that are compared. The proportions test uses counts of successes (number of samples exceeding the speed limit by *x* mph) and trials (total sample size) to create a contingency table for the data sets being compared. For this test, researchers needed to verify the following assumptions:

- The samples are independent of each other.
- Each sample consists of a predetermined number of independent trials, for which the true probability of success is constant.

The first assumption was met as discussed previously. While the trials were independent, the predetermined portion of the second assumption was rarely met because the sample size was not predetermined, but the test was still employed as it is the typical practice (Sheskin 1997, 221).

When only two proportions are compared in the contingency table, the chi-square statistic coincides with the square of the *Z* statistic used to compare two proportions. A CI can be constructed for this case for the differences in probabilities of success between the first and second groups. For this, the normal approximation to the binomial distribution with continuity correction was used (TIBCO Software, Inc. 2010b, 185).

DATA ANALYSIS

The data collected were evaluated to ensure that the differences represented by the sample statistics were statistically significant, which was almost universally the case because of the large sample sizes, which enabled the statistical tests to be highly significant despite the samples' very small differences in values. While the test of statistical significance must be done as a first step (to exclude random chance as the reason for the observed differences), the evaluation of usefulness of an outcome depends on the difference being of practical significance, that is, large enough to be meaningful as a practical matter. The statistics calculated for the collected data are tabulated in Table 9. Unless noted, whenever a sample's statistic is directly compared to another sample's statistic, the difference has been verified as being statistically significant.

Table 9. Table of Data Statistics.

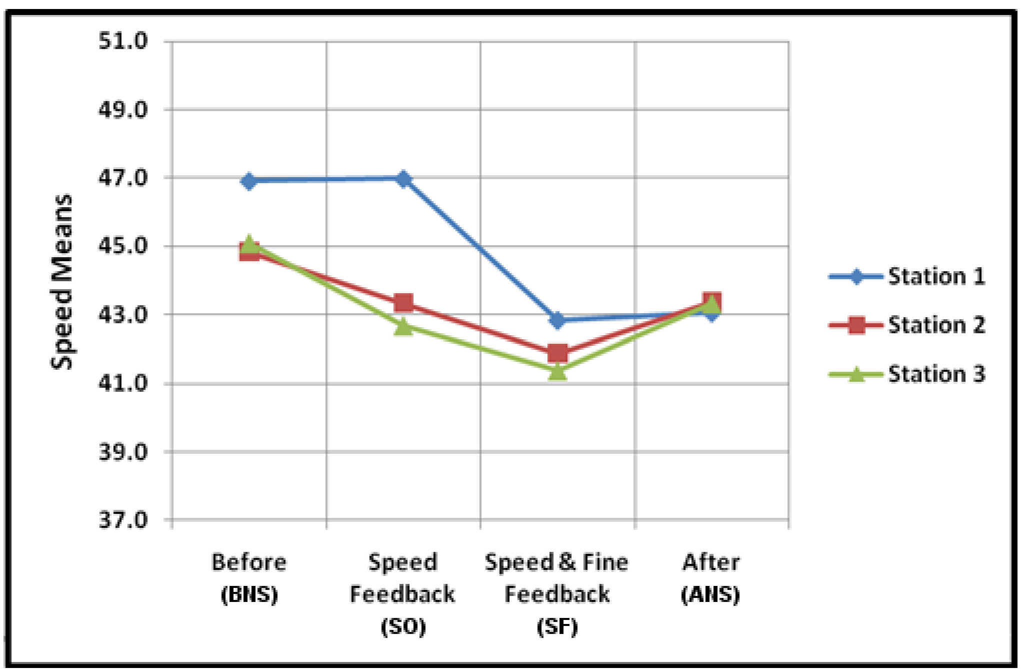
Data Set	Station	Median	Mean	Standard Deviation	85th Percentile	Percent Drivers Speeding Above 35 mph Speed Limit				
						+5 mph (40 mph)	+10 mph (45 mph)	+15 mph (50 mph)	+20 mph (55 mph)	+25 mph (60 mph)
BNS	1	47[(a)]	46.9[(d)]	6.2	53[(g)]	88%[(j)]	67%[(m)]	35%[(o)]	10%[(q)]	1.6%[(t)]
	2	45	44.8	5.7	51[(h)]	83%	51%	20%	5%	0.6%[(u,v)]
	3	45	45.1	6.8	52	82%	52%	35%	8%	1.6%
SO	1	47[(a)]	47.0[(d)]	6.2	53[(g)]	88%[(j)]	66%[(m)]	36%[(o)]	11%[(q)]	1.5%[(t)]
	2	43[(b)]	43.3[(e)]	5.8	49[(i)]	73%[(k)]	40%[(n)]	15%[(p)]	3%[(r)]	0.5%[(u,w)]
	3	42	42.7	6.1	49[(i)]	70%	34%	13%	3%	0.7%
SF	1	42	42.8	6.8	51	66%[(l)]	36%	18%	6%[(s)]	0.9%[(x)]
	2	41	41.9	5.8	48	63%	31%	10%	2%	0.3%
	3	41	41.4	6.0	47	60%	25%	9%	2%	0.5%
ANS	1	42	43.1	6.9	51[(h)]	66%[(l)]	37%	19%	6%[(s)]	1.0%[(x)]
	2	43[(b,c)]	43.4[(e,f)]	5.6	49[(i)]	74%[(k)]	40%[(n)]	14%[(p)]	3%[(r)]	0.5%[(v,w)]
	3	43[(c)]	43.3[(f)]	6.5	50[(i)]	73%	39%	17%	5%	0.9%

Note: Pairs of values whose differences were not statistically significant are shown with identical superscripts. For example, the two means with the superscript (d) have the different values of 46.9 and 47.0, but cannot be distinguished from each other statistically and therefore cannot be said to be different.

Comparison of Speed Means

The data means can be compared directly in Table 9, but the graph in Figure 19 helps to interpret the comparison. The lines in the graph connect the values for the same station across the four data sets. Each column shows the three station values for that data set. The speed means for Station 1 is expected to be approximately the same across all data sets since Station 1 was located before the work zone, but that was not the observed outcome. Station 1 mean speeds were essentially the same for the BNS and SO cases but dropped by a consistent 4 mph in the SF and ANS cases.

The data were taken in the sequence shown on the graph from left to right. One possible theory for the change in speeds at Station 1 is that a large portion of the drivers went through the site repeatedly (commuters) and after first encountering the SF CMSR message, reacted by anticipating the device and approaching the work zone thereafter at reduced speeds. However, no evidence could be found to support this theory. Mean speeds on the beginning days of the SF message were essentially the same as on all subsequent days. Further, those means were all lower than the means of the SF message days, which also had daily means essentially the same, albeit lower, throughout the SF data collection period.



Note: The speed limit at Stations 2 and 3 was 35 mph, but the speed limit was 50 mph at Station 1 (before the work zone).

Figure 19. Comparison of Speed Means.

The South Carolina DOT study (Sarasua et al. 2006) also tested two CMSR that contained a speed feedback message and a fine feedback message. The two messages that are closest to those of this study are contrasted below:

- Speed feedback (SO):
  - Arizona: "YOUR SPEED IS XX MPH."
  - South Carolina: "YOUR SPEED XX MPH" alternating with "SLOW DOWN" (if speeding) or "THANKS FOR NOT SPEEDING" (if not speeding).
- Speed and fine feedback (SF):
  - Arizona: "YOUR SPEED IS XX MPH" alternating with "POSSIBLE FINE $XXX" (if speeding more than 10 mph over speed limit).
  - South Carolina: "YOU ARE SPEEDING" alternating with "MINIMUM FINE $200" (if speeding) or "STAY ALERT" alternating with "WORK ZONE" (if not speeding).

The SO messages are quite similar and results would be expected to be similar. The SF messages are different in that speeding drivers in the Arizona study saw a potentially higher fine amount, which changed dynamically if they reduced (or increased) their speed by 5 mph.

The graph of the speed means in Figure 19 directly compares the absolute mean values. In the South Carolina study, researchers compared the reductions in mean values rather than the actual mean values. Table 10 lists the reductions in mean speeds for this study (Table 9) and the South Carolina study (Table 4).

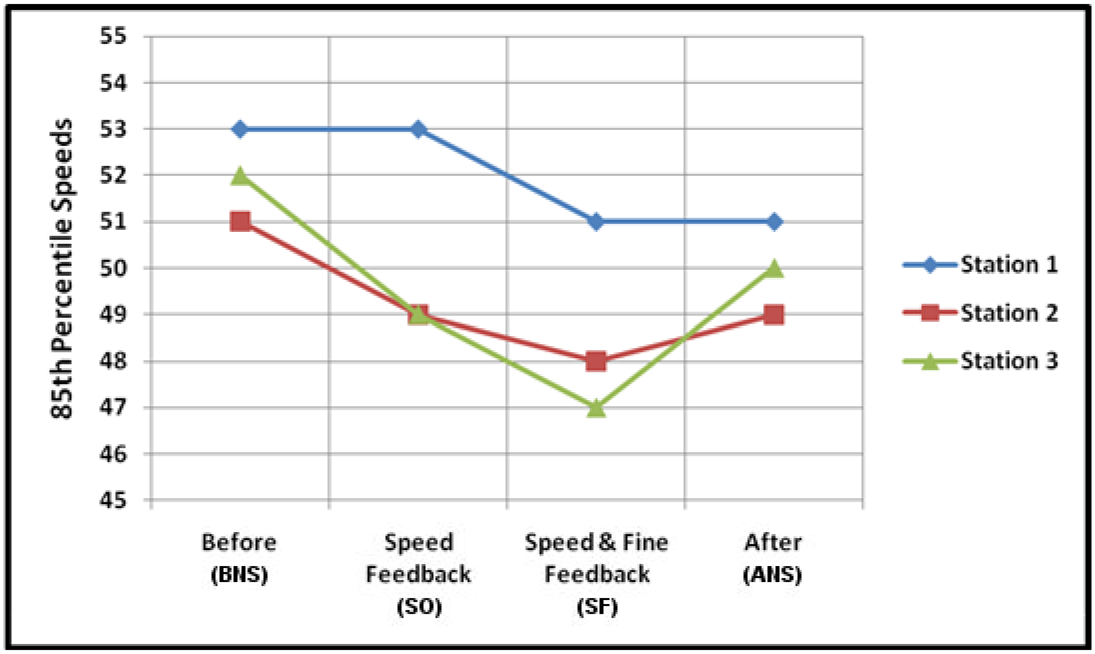
Table 10. Reductions in Mean Speeds.

	Station 1 to 2		**Station 1 to 3**	
	SO (mph)	**SF (mph)**	**SO (mph)**	**SF (mph)**
Arizona	4	1	4	1
South Carolina	7 to 12	6 to 12	2 to 14	1 to 11

The South Carolina speed reductions are considerably higher than those of this study. Furthermore, the data for this study indicate a drop of 4 mph for the SO case and a drop of only 1 mph for the SF case. Based on this study's mean speed data, the absolute speed observed in the SF case is lower than in the SO case (41.9 mph versus 43.3 mph, respectively), but its reduction in speed is less (1 mph versus 4 mph, respectively).

Comparison of 85th Percentile Speeds

The 85th percentile speeds can be compared directly in Table 9, but the graph shown in Figure 20 aids in interpreting the comparison. As with the speed means data in Figure 19, the 85th percentile speed for Station 1 is expected to be approximately the same across all data sets because Station 1 was located before the work zone. Instead, the 85th percentile speeds at Station 1 are essentially the same for the BNS and SO cases but drop by a consistent 2 mph in the SF and ANS cases.



Note: The speed limit at Stations 2 and 3 was 35 mph, but the speed limit was 50 mph at Station 1 (before the work zone).

Figure 20. Comparison of 85th Percentile Speeds.

Figure 20 directly compares the absolute values while the South Carolina researchers compared the reductions in values rather than the actual values. Table 11 lists the 85th percentile speed reductions for this study (Table 9) and the South Carolina study (Table 5). Again, the speed reductions from the South Carolina study are considerably higher.

Table 11. Reduction in 85th Percentile Speeds.

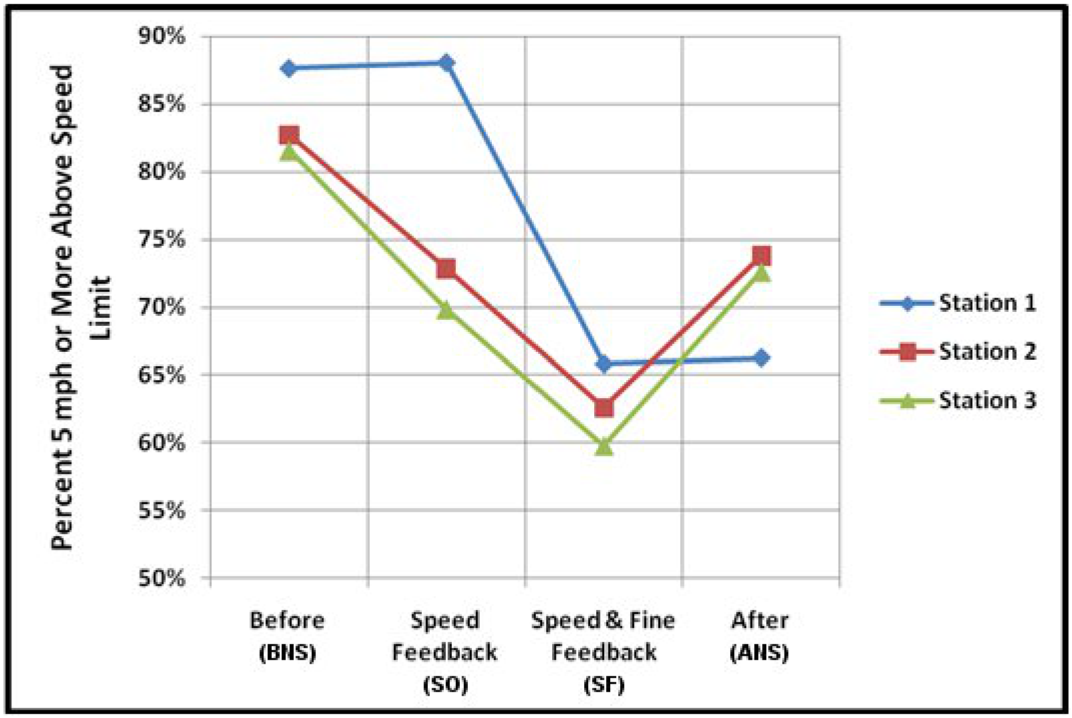
	Station 1 to 2		Station 1 to 3	
	SO (mph)	SF (mph)	SO (mph)	SF (mph)
Arizona	4	3	4	4
South Carolina	5 to 10	-6 to 13	2 to 10	2 to 10

An important observation is that the SF case reductions in 85th percentile speeds are essentially the same as in the SO case, whereas its mean speed reductions were noticeably less. This suggests that the SF case may be affecting the higher-end speeders more than the “average” driver, whereas the SO case appears to be affecting both the average and higher-end driver the same (at least the 85th percentile higher-end driver). This leads to the next investigation of the upper end of the speed distributions and what impact the CMSR messages are having on it, if any.

Comparison of Speeds at the Upper End of the Speed Distributions

One way to explore the impact of the CMSR messages on those drivers traveling at higher speeds is to compare the percent exceeding the speed limit by various amounts of speed. Researchers calculated statistics for the percentages of drivers exceeding the speed limit by increasing amounts, specifically, 5 mph, 10 mph, 15 mph, 20 mph, and 25 mph over the speed limit. These are tabulated in Table 9 and are illustrated in the series of graphs from Figure 21 to Figure 30. The graphs are in pairs, each including a line graph organized by data set, followed by a bar chart of the same data organized by station. The y-axis values change for the line graphs but remain constant for the bar charts.

To interpret the graphs, the BNS case needs to be examined. At all levels of speeding, the percentages at Station 2 for the BNS case are always higher than for either of the CMSR messages, which implies that without the CMSR, more drivers tend to travel through the work zone at higher speeds. This is true for both CMSR messages, but their impacts do differ markedly, with the SF case always exhibiting lower levels of speeders than the SO case.



Note: The speed limit at Stations 2 and 3 was 35 mph, but the speed limit was 50 at Station 1 (before the work zone).

Figure 21. Percent Speeding 5 mph or More Above Speed Limit.

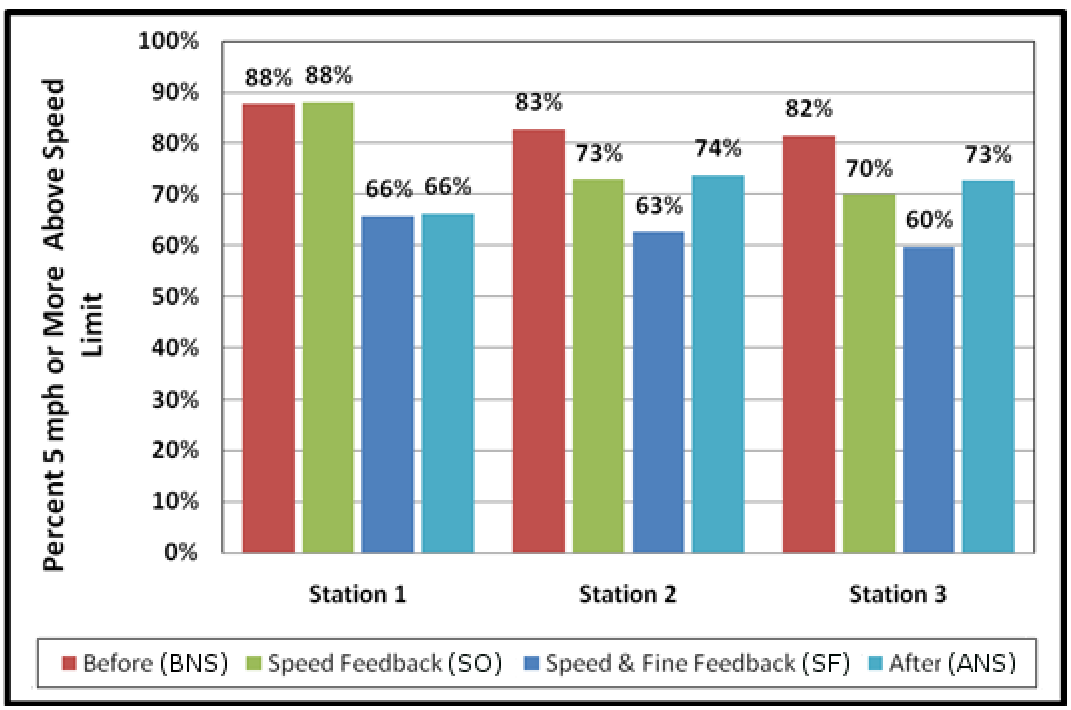
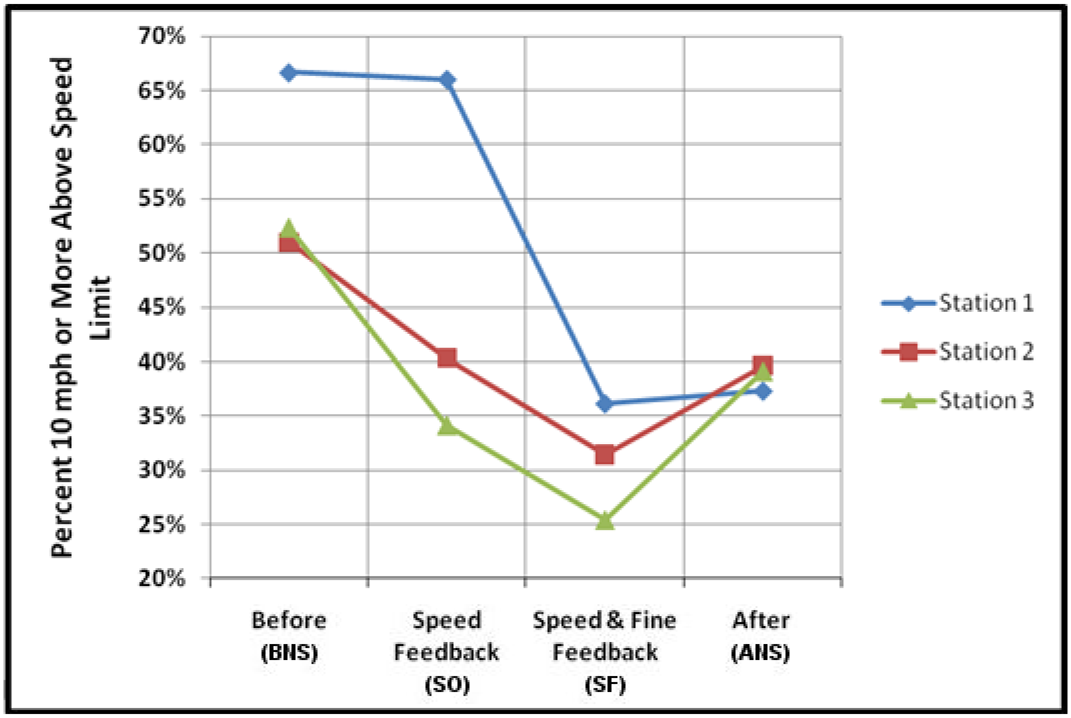


Figure 22. Percent Speeding 5 mph or More Above Speed Limit.



Note: The speed limit at Stations 2 and 3 was 35 mph, but the speed limit was 50 at Station 1 (before the work zone).

Figure 23. Percent Speeding 10 mph or More Above Speed Limit.

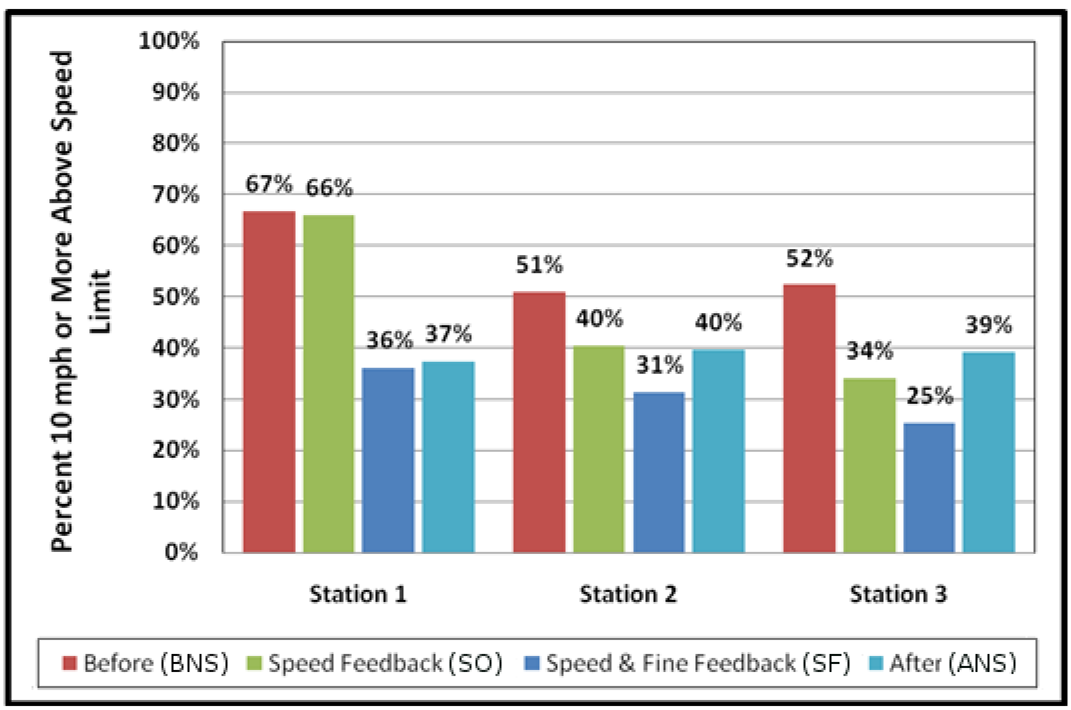
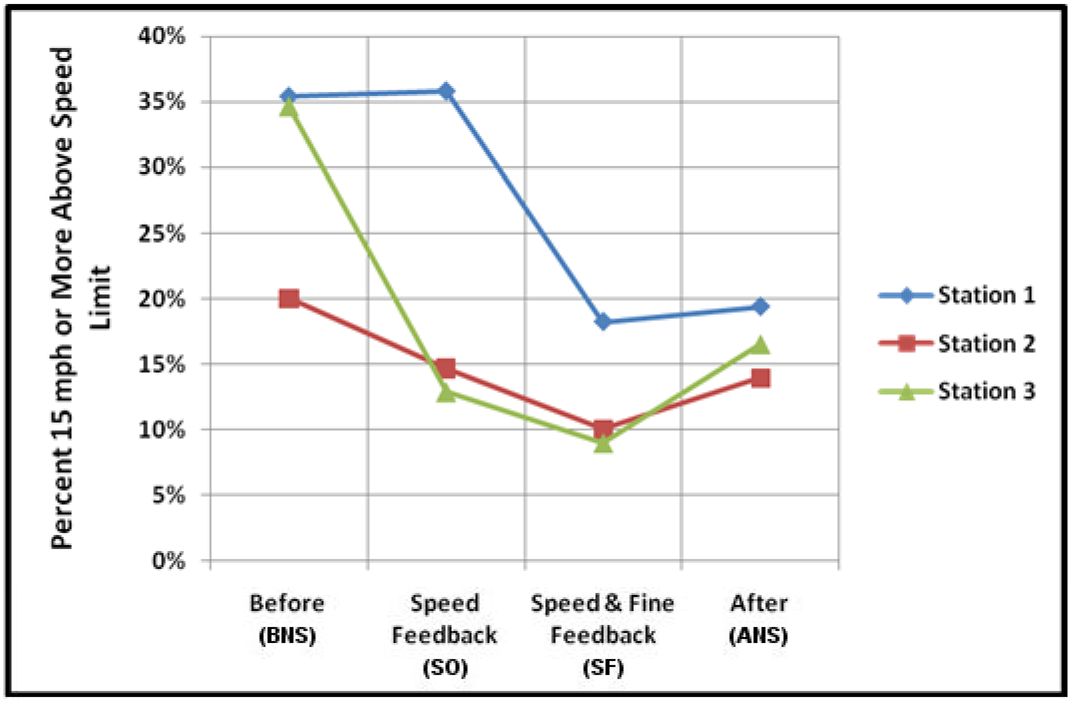


Figure 24. Percent Speeding 10 mph or More Above Speed Limit.



Note: The speed limit at Stations 2 and 3 was 35 mph, but the speed limit was 50 at Station 1 (before the work zone).

Figure 25. Percent Speeding 15 mph or More Above Speed Limit.

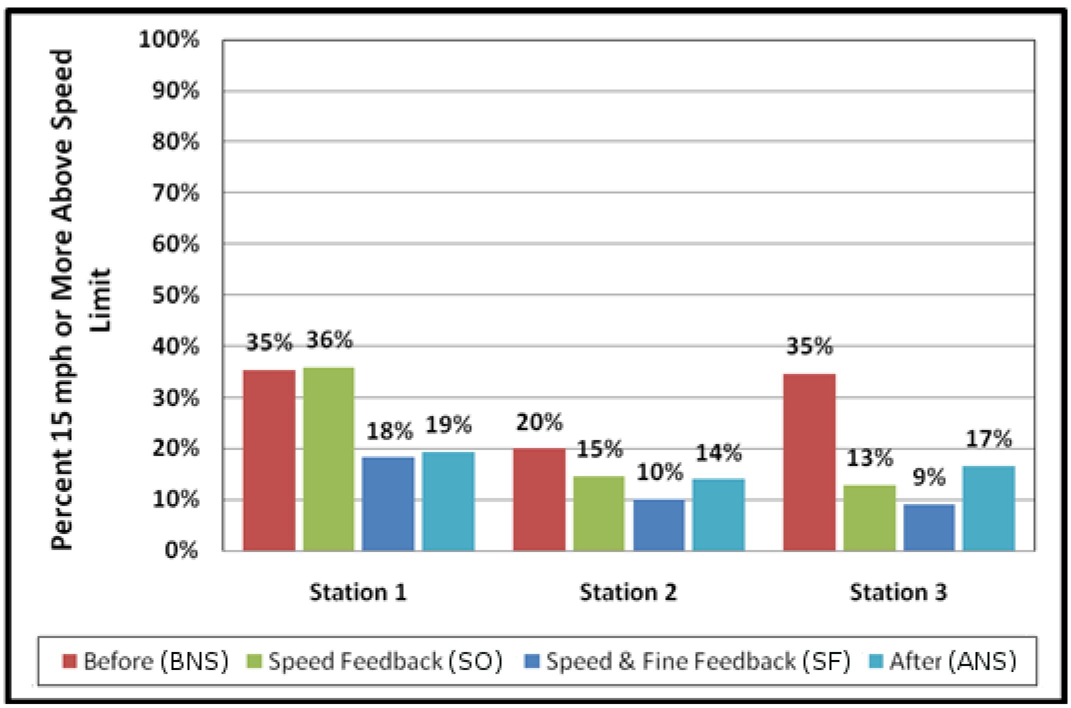
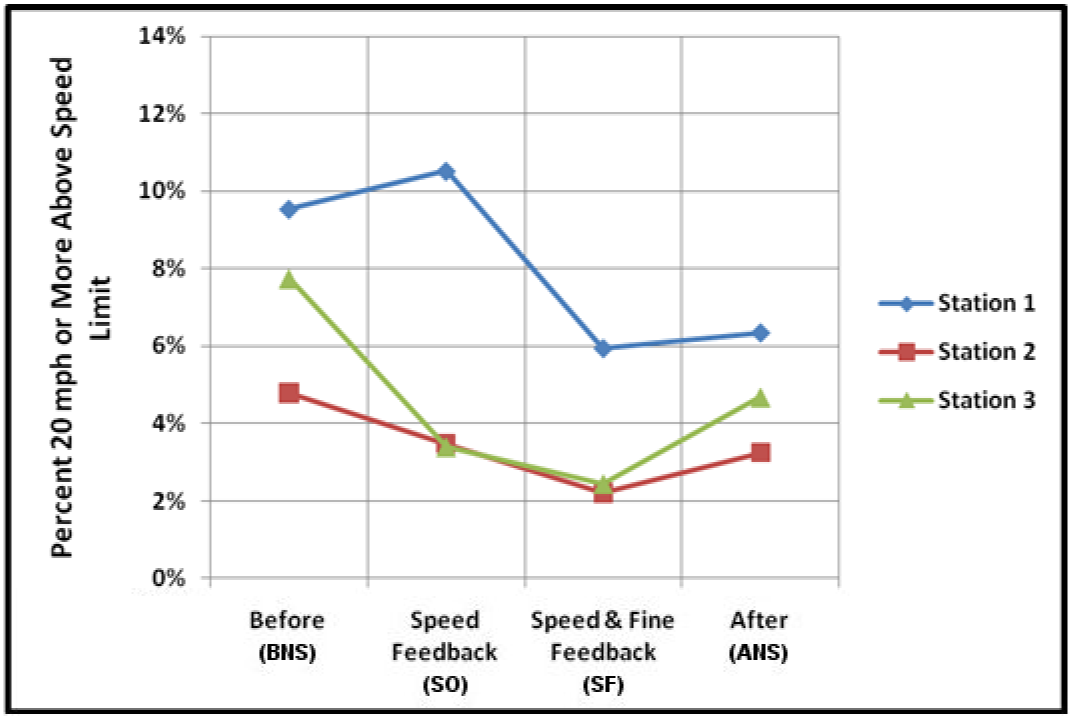


Figure 26. Percent Speeding 15 mph or More Above Speed Limit.



Note: The speed limit at Stations 2 and 3 was 35 mph, but the speed limit was 50 at Station 1 (before the work zone).

Figure 27. Percent Speeding 20 mph or More Above Speed Limit.

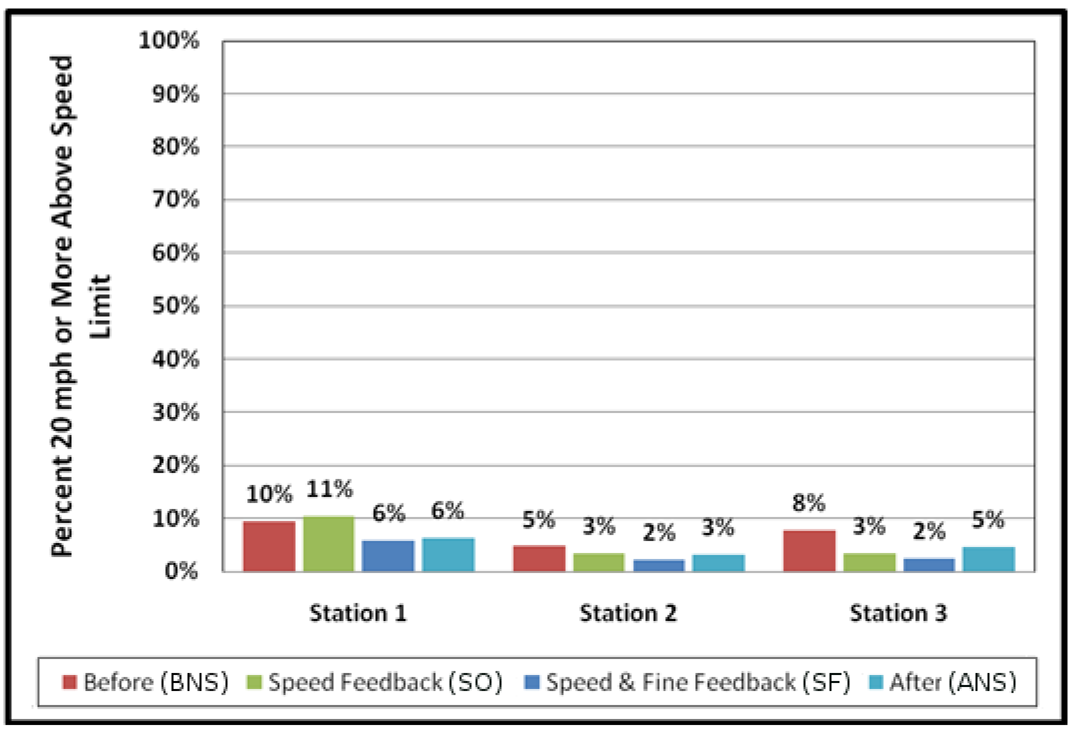
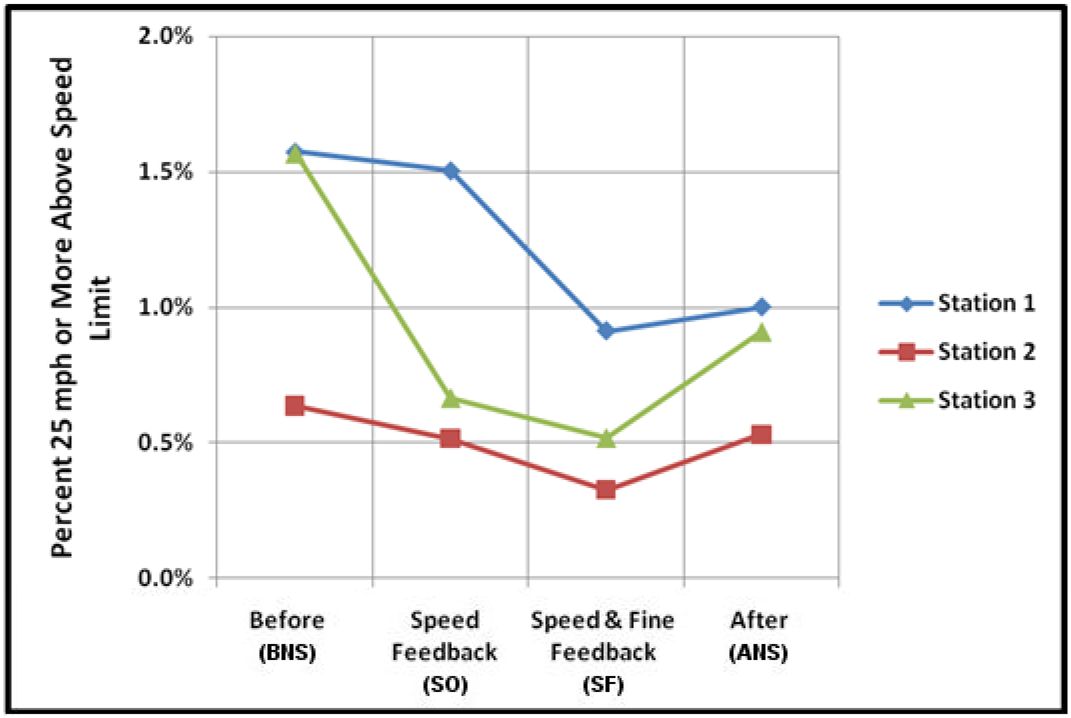


Figure 28. Percent Speeding 20 mph or More Above Speed Limit.



Note: The speed limit at Stations 2 and 3 was 35 mph, but the speed limit was 50 at Station 1 (before the work zone).

Figure 29. Percent Speeding 25 mph or More Above Speed Limit.

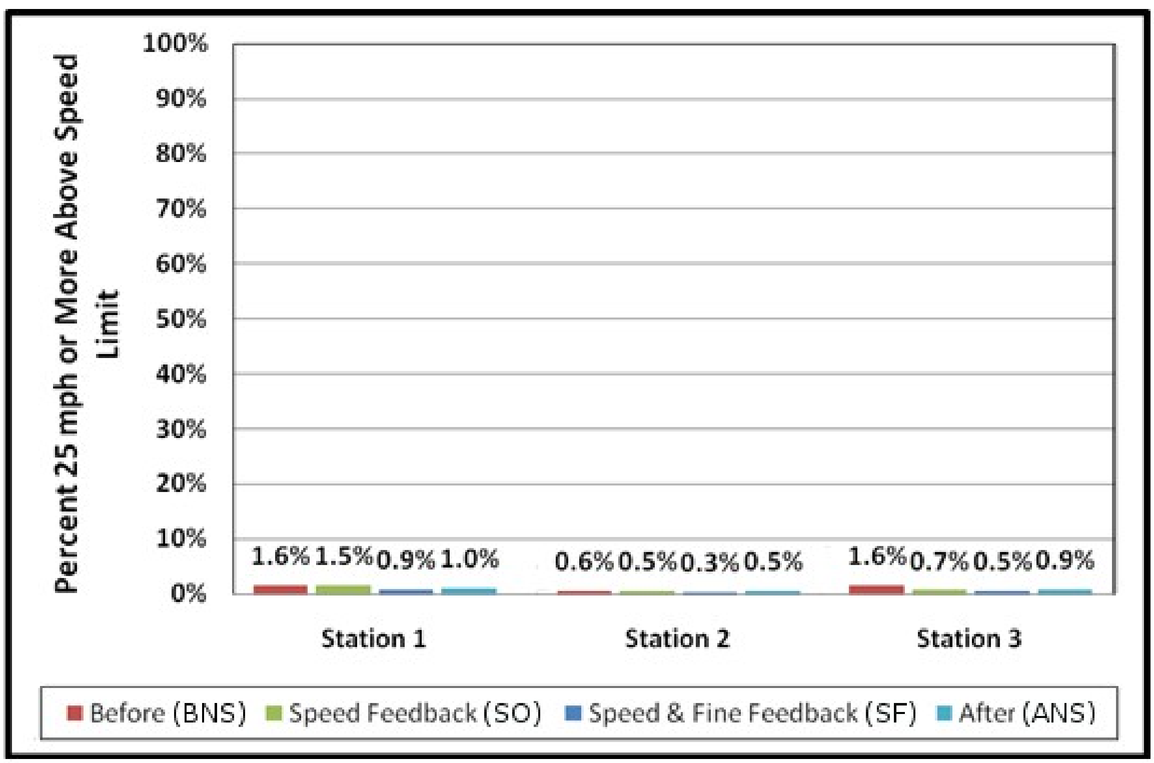


Figure 30. Percent Speeding 25 mph or More Above Speed Limit.

Approximately 5,300 vehicles per day traveled through the data collection area. The data analyzed excluded those vehicles having gaps of 5 seconds or less after the vehicle ahead of them, lowering the count to 2,900 vehicles per day. Using a daily traffic volume helps to understand the practical impact of the CMSR supplementing the regular *MUTCD* (FHWA 2009b) work-zone signage. Therefore, researchers estimated the number of speeding vehicles traveling through the work site based on 2,900 vehicles per day.

Before the CMSR was installed at the site (BNS), about 580 vehicles per day passed Station 2 traveling 15 mph over the speed limit (that is, traveling 50 mph in the 35 mph work zone). With the CMSR displaying the SO message, this amount was reduced to about 425 vehicles, and when displaying the SF message, it was reduced to about 291 vehicles. Both of these are substantial reductions in high-speed travelers through the work site. The residual effect at Station 3, which was 960 ft downstream of Station 2, was also significant. At Station 3, the approximate number of speeders exceeding the speed limit by 15 mph or more was 1005, 374, and 262 for the BNS, SO, and SF cases, respectively.

These trends hold for both 20 mph and 25 mph over the speed limit. At 20 mph over the speed limit, the BNS, SO, and SF case estimates were 139, 100, and 64 speeding vehicles per day, respectively, at Station 2 and 225, 98, and 71, respectively, at Station 3. At 25 mph over the speed limit, the estimates for the same cases were 18, 15, and 9 speeding vehicles per day, respectively, at Station 2, and 46, 19, and 15, respectively, at Station 3. These are important reductions because high-speed vehicles are of particular concern to workers in a work zone. The extremely high speeders traveling 25 mph over the speed limit were reduced by one-half near the CMSR with the SF message, with downstream residual reductions nearer the actual lane drop of two-thirds. The SO reductions were also impressive, but to a lesser degree than with the SF feedback.

Another way to visualize the reductions in high speeders is to view a comparison of their speed-density plots taken at Station 2, which is shown in Figure 31. Using the BNS case as the baseline, the SO plot is shifted to the left, and the SF plot is shifted even farther to the left. The peak of each plot is the approximate location of its mean, and the ends of the plots are their tails. The right tail of the SF case has been shaded. The area of the shaded portion of the tail is the probability that drivers will be driving at a speed greater than or equal to 50 mph when they pass Station 2 (15 mph over the 35 mph work-zone speed limit). A similar area for greater than or equal to 50 for the SF tail would be larger, which means that there is a higher probability for drivers to be speeding at greater than or equal to 50 mph (proportional to the two areas). Likewise, the BNS case will yield the largest probability of speeders. Therefore, the shifting to the left of the distribution density plots indicates a reduction in both the mean speed and the number of vehicles going over a given speed (here, 50 mph). Similar shaded areas could be constructed for any speed, such as greater than or equal to 60 mph.

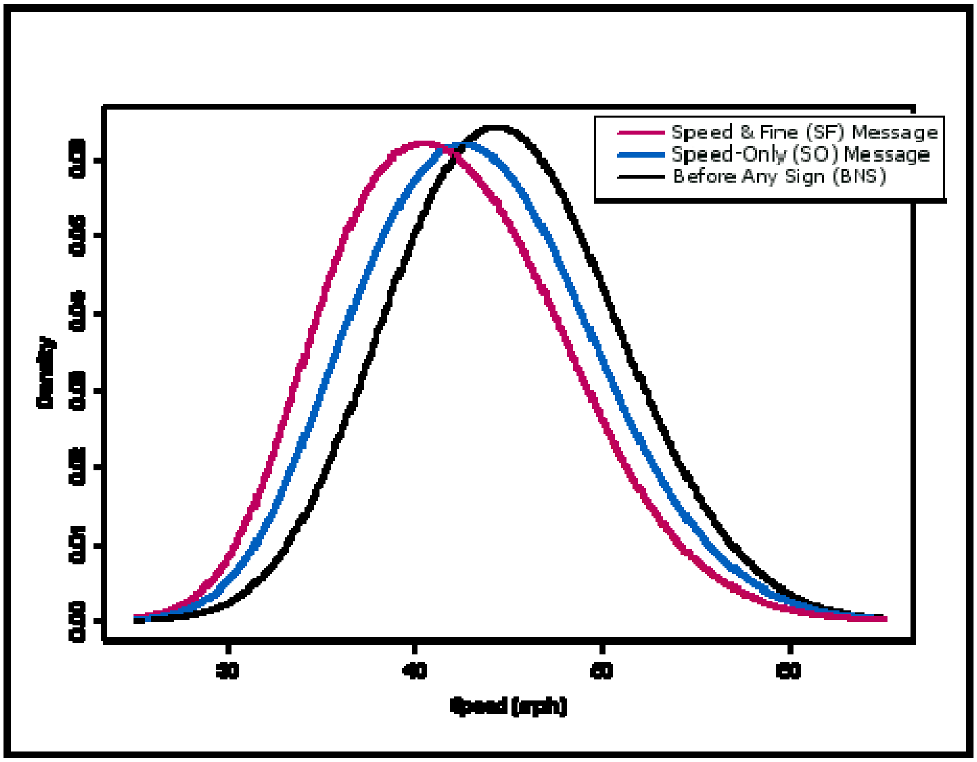


Figure 31. Comparison of Speed Distribution Densities at Station 2.

CHAPTER 6. CONCLUSIONS AND RECOMMENDATIONS

This research was motivated by the continuing national and state focus on work-zone safety and the correlation of excessive speeds with work-zone crashes (Wasson et al. 2011; Pigman and Agent 1990), with some researchers finding that up to 25 percent of fatal crashes in work zones involved high speeds and large variances in speeds (Hou et al. 2011). The Arizona research compared using a CMSR in a work zone as a supplement to the standard *MUTCD* signage at the same site. Two CMSR messages were tested: one providing only speed feedback to an approaching vehicle and the other alternating the same speed feedback with the possible traffic fine message.

Both CMSR messages resulted in observed reductions in absolute work-zone speeds and in the numbers of drivers traveling at speeds 10 mph or more higher than the posted limits. Of the two messages, the speed feedback alternating with the possible traffic fine achieved better results, with observed mean speeds at the sign 3 mph lower than before the CMSR was present at the site. Observed 85th percentile speeds were also 3 mph lower than before the sign. Observed reductions in the percentages of speeders were particularly important. Without the sign, percentages for vehicles traveling greater than the work zone speed limit were 83 percent at 5 mph over, 51 percent at 10 mph over, 20 percent at 15 mph over, 5 percent at 20 mph over, and 0.6 percent at 25 mph over the speed limit. With the CMSR speed and fine feedback message deployed, these percentages dropped to 63 percent, 31 percent, 10 percent, 2 percent, and 0.3 percent, respectively. These are marked reductions in observed numbers of vehicles speeding near the CMSR and a reduction by half of the number of very high speeders. Equally important, there was also an observed continued reduction in drivers speeding 15 mph or more above the speed limit about 1000 ft downstream of the CMSR.

The message with only speed feedback also performed well compared to no CMSR present. Both observed mean speeds and 85th percentile speeds at the sign were 2 mph lower than before the sign. Without the sign, percentages for vehicles traveling greater than 5 mph, 10 mph, 15 mph, 20 mph, and 25 mph over the speed limit were 83 percent, 51 percent, 20 percent, 5 percent, and 0.6 percent, respectively. With the CMSR speed feedback message deployed, these percentages were 73 percent, 40 percent, 15 percent, 3 percent, and 0.5 percent, respectively. Again, these are important reductions in observed numbers of high-speed vehicles passing near the CMSR and 1000 ft downstream. These speeds were about 25 percent less than without the sign present.

While only small reductions in mean speeds were observed in the presence of the CMSR messages, the numbers of high-speed vehicles showed reductions from 25 percent for the speed feedback message to 50 percent for the combined speed and fine feedback messages. Reducing this high end of the speed distribution at a work site is an important finding. This evidence supports the conclusion that providing drivers in a work zone with traffic fine feedback information in real time does change their driving behavior by reducing their speed.

The use of a supplemental, portable CMSR in this study provided data indicating a small reduction in mean speeds and greater reductions in drivers traveling 15 mph or more than the posted limit. (A similar study performed by the South Carolina DOT (Sarasua et al. 2006) reported much larger decreases in mean speeds. That study did not include speed feedback in its speeding fine message, which those researchers believed to be very important. Consequently, they recommended using the speed feedback only sign as a better choice than the fine feedback only sign.)

The Arizona research was limited to a single site. Generally additional research at more sites would be recommended before considering deployment. However, the South Carolina DOT study was a credible and extensive study at multiple sites. Its reported results, combined with the Arizona data, support deploying CMSR without conducting additional research.

Based on these findings and the South Carolina research, these researchers recommend that ADOT deploy mobile CMSR with speed feedback alternating with fine feedback messages in work zones wherever practicable.

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