FINAL REPORT

EFFECTIVENESS OF CHANGEABLE MESSAGE SIGNS IN CONTROLLING VEHICLE SPEEDS IN WORK ZONES PHASE II

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(The opinions, findings, and conclusions expressed in this report are those of the authors and not necessarily those of the sponsoring agencies)

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ABSTRACT

Highway work zones have been plagued with increasing numbers of accidents in recent years. Drivers' lack of compliance with speed restrictions within work zones has been cited as one of the major contributing factors to this trend. The conventional practice for regulating work zone speeds has been static signing procedures (using regulatory or advisory speed signs). It has been found that drivers do not slow down in response to these static control measures. Changeable message signs (CMS) equipped with a radar unit 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. This offers a more dynamic speed control environment and therefore may prove to be more effective in influencing drivers to reduce their speeds

This report is the second phase of a longitudinal research study. The first phase of the project, conducted by Garber and Patel, examined the short term effectiveness of CMS in reducing vehicle speeds in work zones. That research established that the CMS (with the radar unit) is more effective in reducing speeds in work zones than the standard Manual on Uniform Traffic Control Devices (MUTCD) signs. This study, while attempting to replicate the results obtained in phase I of the project, concentrated on evaluating the effect of duration of exposure of the CMS with radar on its effectiveness in reducing speeds and influencing speed profiles in work zones. The impact of length of the work zone and vehicle type on speed reductions was also studied. Three work zone sites in southwest Virginia, two on Interstate 81 and one on a primary highway on Route 19, were selected for the study. Speed and volume data for the population were collected using automatic traffic counters at the beginning, middle and end of each work zone. In addition, the speeds of individual drivers who triggered the CMS by exceeding the threshold speed were also recorded (using a video camera) at two other locations within the work zone to study the behavior of high speed drivers in particular and to compute their average speed reduction in response to the warning message.

The results of the study indicate that the duration of exposure of the CMS does not have a significant impact on speed characteristics and driver behavior. Therefore, the CMS continues to be effective in controlling speeds in work zones for projects of long duration. It was also determined that the drivers exceeding the speed limit, in both interstate work zones have on average reduced their speeds by around 12.86 km/h (8 mph) at the middle of the work zone. At the third site (Route 19) the speed reductions at the middle of the work zone were about 16.08 km/h (10 mph). It was also found that there were no distinctive differences among the different types of vehicles with regard to speed reduction. The study also established that in longer work zones, drivers who reduced their speeds in response to the speed control effort frequently have a tendency to speed back up as they approach the end of the work zone. This indicates that very long work zones might warrant the installation of a second CMS to maintain speed reductions through the work zone.

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INTRODUCTION

A major concern of highway and traffic engineers is the safety of workers and vehicle occupants in work zones because accident rates tend to be relatively higher in these areas. The current trend of rehabilitating existing facilities rather than constructing new highways will likely continue in the foreseeable future, resulting in a proliferation of work zones on the nation's highways, particularly when work on the new National Highway System (NHS) begins. Unless effective measures are taken to increase safety in these work zones, a significant increase in accident rates could result.

Data for Virginia highways indicate that work zones continue to increase in number and represent a major safety concern. For example, between January and September 1994 there were 16 fatalities as a result of work zone related crashes, the highest number since 1986 when 24 fatalities occurred.[1] Also the number of work zone related accidents has been on a steady rise from 382 in 1993 to 461 in 1994 to 548 in 1995. A primary cause of a significant number of work zone related accidents is speeding, a problem which may be exacerbated by the absence of useful guidelines for determining posted speeds for work zones.[2] Motorists driving at or above the maximum speed limit (88.44 or 104.52 km/h [55 or 65 mph]) on primary or interstate highways are apparently reluctant to reduce their speeds in work zones unless they are influenced to do so. It is, therefore, necessary to identify and implement strategies that will influence the driver to reduce his or her speed to that appropriate for the site.

Several studies[3,4,5] have been conducted to determine the effectiveness of different devices in reducing speeds in work zones. One such study[4] concluded that passive, nonspecific control measures such as generalized signing are not very effective in slowing drivers even under normal conditions. On the other hand, active measures such as flagging, stationary speed enforcement (patrol car), changeable message signs (CMS) and effective lane width reduction tend to be somewhat more effective. The level of effectiveness, however, depends on the active measure used and the prevailing conditions.

A study by Richards and Dudek[3] indicated that equipment that utilizes changeable message signs and automated speed recording seems to be effective in influencing drivers to reduce speeds in work zones. One such piece of equipment is the automated speed and message display (ASMD). This equipment is an automated driver information system capable of monitoring the speed of a vehicle using loop sensors or radar and displaying this speed to the driver on a changeable message sign. In addition to displaying the speed of the vehicle, other messages such as "HIGH SPEED, SLOW DOWN" can be added to a changeable message sign to create the impression of a personal communication to the driver of a specific vehicle. Although several studies have been done on this technique, emphasis has so far been principally placed on its impact on average speed. Unfortunately, average speed is not always the factor that most affects accident rates. Other speed characteristics such as variance and 85th and 95th percentile speeds are more likely related to accident occurrence at work zones, although the severity of the accident depends on vehicular speed. It is necessary to identify the impact of ASMD not only on average speed but also on other speed characteristics in work zones.

A study by Garber and Patel[6] evaluated the effectiveness of the CMS with radar in influencing drivers to reduce their speeds in work zones, especially in the case of high speed drivers. The project studied four different messages at work zones on interstate highways to determine the effect on speed profiles, described by characteristics such as average speeds, 85th percentile speeds, speed variance and the odds for speeding. Based on the results obtained, the authors concluded that the changeable message sign with radar is a dynamic speed control measure which is more effective than static MUTCD signs in altering drivers' behavior in work zones. They also concluded that using personalized messages for high speed drivers will result in these drivers being more inclined to reduce their speed in work zones. Unfortunately, in that study all the data were collected within seven days of placing the CMS with radar at the work zone. Therefore no determination was made on whether the equipment had the same effect on high speed drivers over a longer period of time. It is possible that the system may prove effective only when the drivers are exposed to it for short durations (i.e. seven days or less) but becomes less effective for longer durations. In that case the system can be used only for work zones with durations less than seven days. In addition, the impact of the length of the work zone on the effectiveness of the system was not investigated. As a result, the authors recommended that additional research be carried out to investigate the impact of these two factors on speed reductions caused by the CMS with radar.

PURPOSE AND SCOPE

The purpose of this project was to evaluate the impact of duration of exposure to the CMS with radar, as well as work zone length, on the effectiveness of this equipment to reduce speeds and other speed characteristics (such as variance, 85th percentile speeds) of speeding drivers in work zones. The study is limited to work zones on interstate and primary highways in Virginia and does not include work zones on secondary roads. Work zones in which speed reduction was not required were excluded from the study.

The specific objectives of this study were:

(1) To determine speed characteristics and speed profiles in work zones on interstate and primary highways using just standard MUTCD signing.
(2) To determine speed characteristics and speed profiles in work zones on interstate and primary highways using both standard MUTCD signing and the CMS radar and evaluate the effect of CMS on speed characteristics by comparing these results with those of objective 1.
(3) To determine whether this technique is effective in influencing high speed drivers to reduce speed in work zones after the CMS with radar has been exposed to the drivers for time periods greater than seven days.
(4) To determine whether the effectiveness of the CMS varies with the type of vehicle (cars, pickups, buses, tractor trailers) being driven.
(5) To determine the effect of the length of the work zone on speed reductions in response to the CMS with radar.

METHODOLOGY

Literature Review

This part of the project involved conducting a literature search to identify and study previous publications involving work zone speed control and the use of changeable message signs. The major sources of information included the Transportation Research Information Service (TRIS), the University of Virginia libraries and the VTRC library. The materials reviewed can be summarized under the following sub-headings.

(1) Determining the need for speed control within work zones.
(2) Predominant speed control techniques and their effectiveness.
(3) Human factors evaluation for work zone speed control.
(4) General guidelines for use of changeable message signs.
(5) Effectiveness and implementation of changeable message signs and radar units.

A large part of the discussions under 2, 3, and 5 were based on the conclusions of previous experiments and studies performed at various locations. Since the results of these studies were influenced by the conditions under which they were carried out it was necessary to look at them within the context of their experimental settings and the scope of the study.

Determining The Need For Speed Control Within Work Zones

Highway work zones have become danger zones for both motorists and workers. The National Transportation Safety Board[2] says that fatal auto accidents in work zones increased significantly as spending on highway construction started growing. The available data indicated that unless additional efforts were made to reduce work zone accidents, the number of fatalities would continue to increase.[1]

Research[7] has shown that excessive vehicle speeds in work zones are a major contributing factor in crashes. The National Transportation Safety Board (NTSB) has issued recommendations concerning the need to conduct research to determine what kind of traffic advisories and signage best convey critical information. They have also urged the FHWA to determine whether lowering speed limits at work zones would further reduce the number and severity of accidents at construction sites.

Potential Hazards and the Need for Speed Reduction

The need for speed reduction must be properly substantiated by a thorough engineering study of the site under consideration. This study should base its conclusions on the following two basic premises of speed reduction.[3]

(1) Decreasing the number and/or severity of work zone accidents.
(2) Decreasing the potential for accidents at sites where speed related potential hazards exist. Speed related potential hazards are conditions that worsen traffic flow because traffic is traveling too fast. Some typical examples could be:
- Unprotected work space where an errant vehicle could cause catastrophic damage
- Hidden work zone features

Types of Speed Control

(1) Passive: Passive speed control refers to posting a reduced speed limit on a conventional regulatory or advisory static sign. This alone is sometimes sufficient at sites where drivers have plenty of time and information available to make reasonably safe speed decisions without any special additional prompting.

(2) Active: Active speed control techniques display real time dynamic information or enforce compliance to a passive control. Typical examples of active control include flagging, law enforcement, changeable message signs, effective lane width reduction, and rumble strips. These kinds of speed control measures would be needed in cases where drivers are unable or unwilling to select the appropriate safe speed without active encouragement.

Choice of a Reasonable Speed

After it has been determined that reduced speeds are desirable and practical, a safe and reasonable speed should be selected. One important observation based on previous studies has been that drivers slow down only to a certain level regardless of the presence of speed control treatment. A study[3] conducted by Richards and Dudek revealed that reductions in design speeds for work zone speeds ranged from 8.04 to 32.2 km/h (5 to 20 mph) depending on the type of facility.

Before attempting to slow traffic at a work zone, it should be recognized that speed reductions can have adverse effects. In particular, speed reductions can reduce roadway capacity and cause localized traffic congestion if traffic volumes are moderate to heavy. The congestion in turn can increase the potential for rear end accidents. The basis for selecting a suitable speed should also be based on the various work zone features like horizontal curvature, sight distance, superelevation, etc. If the work zone design speed is too low, even active speed control may not be enough. Selecting an appropriate speed for a particular set of conditions requires experience, objectivity and good judgement. It is extremely important that the chosen speed is reasonable for the given conditions. If unreasonably low speeds are chosen, drivers will lose respect for the speed control effort. The loss of credibility and respect will result in reduced effectiveness of the speed control technique at the site and possibly other sites too.

Selecting an Appropriate Speed Control Treatment

Once a reasonable speed reduction that is both safe and effective has been chosen, it is necessary to select a speed control treatment to implement the chosen speed reduction. Static speed control measures are found to be more effective at the majority of long duration work zones where drivers become conditioned to the work zone environment and select their own safe and reasonable speed. In this case static speed control measures can reinforce the existing speed control devices and provide basis for speed enforcement. These kinds of static signs can also be used to warn unfamiliar drivers against common potential hazards experienced regularly in work zones.

The selection of an appropriate speed control method depends on the following factors:[3]

(1) Duration of potential hazard requiring speed control
(2) Type of facility
(3) Desired speed reduction
(4) Overall cost of treatment
(5) Availability of speed control measures mentioned above.

Location of Speed Control Devices

The location of speed control devices within a work zone should take into consideration the following factors :

(1) Maximizing motorist safety
(2) Maximizing worker safety
(3) Maintaining smooth flow of traffic
(4) Maintaining existing or reduced operating speeds
(5) Maintaining existing traffic flow rate.

The FHWA[8] has recommended the development of a Traffic Control Plan (TCP) for this purpose. The main objective of the TCP is to show the type and placement of traffic control devices to be used in each phase or stage of the project. The number of devices, their size and their placement depends on five basic conditions, namely highway type, prevailing traffic speed, proximity of work area to travel lanes, nature of activity, and duration of activity. A survey that evaluated TCPs at reconstruction sites[9] showed that 62% of TCP preparers are never present at the site when the traffic control devices are first installed. Also 40% stated that they never visited the work zones to see if the TCP was performing as intended. Thus it was recommended that TCP preparers make visits to work zones to gain insight on how well the TCP is performing. The relative location of the speed control treatments to other work zone signing is also important. A study[3] showed that ideally, speed control should be initiated after the first advanced sign and in a section that is relatively free of other work zone signs. This practice will lessen the probability of overloading the drivers with too much information and maximizes the amount of driver attention focused on the speed control effort.

Another study conducted in Alabama[10] revealed that advanced warning signs did not consistently reduce motorist speeds and that excessive use of traffic control devices on construction projects can reduce the effectiveness of individual devices. In addition, advanced speed signs were not effective in controlling speeds unless drivers perceived that such speeds are reasonable. So, for a speed control to be effective, the posted speed should be close to the maximum safe speed for that area.

Predominant Speed Control Techniques and Their Effectiveness

This section reviews some of the primary speed control techniques used in work zones and evaluates the effectiveness of these techniques based on experimental results.

Flagging

Two primary types of flagging procedures are implemented:

(1) *MUTCD Flagging*: This follows the flagging procedure described in the Manual on Uniform Traffic Control Devices (MUTCD). The flagger equipped with a red flag and range vest performs the 'alert and slow' actions detailed in part VI of the MUTCD.

(2) *Innovative Flagging*: This technique combines the MUTCD procedure with having the flagger use the other hand to motion the traffic to slow and then point to a nearby speed limit sign.

Flagging enables high speed reductions in general, but involves high labor costs for long duration applications. It causes little or no disruption to traffic flow but safety considerations may warrant considering some work zone sites as unsuitable for implementing a flagging procedure.

Based on a study conducted by Richards and Dudek[3] certain implementation considerations were developed for most effective use of flagging.

- Flaggers should be attired in a fluorescent orange vest with reflective material.
- Flaggers should be well trained in the proper flagging procedures and techniques
- Flagging was found to be well suited for short duration applications but diminished in effectiveness over longer durations
- For most effective implementation flaggers must be relieved every 1.5 to 2 hrs
- Flagging was found to be quite effective on two lane, two way rural highways and urban arterials where the flagger could get most drivers' attention easily.

Law Enforcement

This technique requires a marked patrol car with lights and radar in operation to be stationed at the site or a uniformed officer standing on the side of the road near a speed limit sign manually motioning the traffic to slow down.

A study by Richards et al[4] has also revealed that manual police traffic control with a marked patrol car was the most effective law enforcement strategy. On the other hand a uniformed police officer was no more effective in slowing drivers than a properly attired flagger using proper flagging procedures. This is probably because a stationary patrol poses more of a threat to the driver (like getting a speeding ticket), whereas a uniformed police officer standing at the side of the road would not have that much of an effect on the drivers. The marked patrol car is quick and easy to deploy or remove and can be especially effective at night with the flashing lights.

A study conducted by Noel et al[5] indicated that the use of a police patrol car and radar system reduced, on an average, the speeds of cars by 10.13 km/h (6.3 mph) and those of trucks by 8.84 km/h (5.5 mph), which for the data collected was shown to be statistically significant. Though this particular technique has been shown to influence large speed reductions, it is constrained by availability of police officers and patrol cars. It is also costly in the case of long duration applications. The disadvantages associated with using this procedure are that the contractor does not have direct control on its performance, long work zones may require additional police car units and success depends on co-operation from enforcement agencies.

Another study conducted by Benekohal[11] which studied the effect of police presence on speed reductions in a highway work zone suggested that this procedure was quite effective in slowing down drivers, but it is very expensive to have a law enforcement officer in every work zone. The location of the police officer at one point induced larger speed reductions close to that point in general. On the other hand a circulating police car covered a larger area but could effect only moderate speed reductions. A circulating police car caused a speed reduction of 6.91 - 7.07 km/h (4.3 - 4.4 mph) for cars and 6.91 - 8.04 km/h (4.3 - 5.0 mph) for trucks.

Effective Lane Width Reduction

This technique is good for long duration applications as it is relatively inexpensive to maintain (only the implementation or start up costs are high) but it is not suitable for short duration applications. This procedure also disrupts traffic flow by reducing capacity and in some cases could also increase certain types of accidents. Effective lane width reduction appears to be more practical for long duration applications of several days or more; however, a research study[3] has suggested that lane reduction, if effective, also increases speed variances and thereby erratic maneuvers. Also it was found that effective lane width reduction techniques may not suppress speeds long after the narrow sections. Thus narrow lanes must be continued throughout the area where reduced speeds are desired.

Changeable Message Signs

The CMS is a control device that provides the drivers with reliable and up-to-date information on the existing conditions. It can be used to display information or warnings and generally be changed in response to changing conditions in the area. It operates on a real time basis. These type of signs are also very flexible in the sense that they can be used for a variety of signages or can be blanked during inactivity. Because of this, they are very cost effective and relatively inexpensive for both short and long duration applications.

A study conducted by Richards et al[4] compared the effectiveness of the different speed control techniques, finding that in addition to the advantages associated with flagging and law enforcement (suitable for all types of highway facilities, relatively quick and easy to implement and remove, causes little or no disruption in traffic, and suitable for short term projects), the CMS can also perform well on the long term and in inclement weather. CMS, when used alone, produced only moderate results,[4] but in combination with other techniques like static signs or flagging CMS can be very effective.

Human Factors Evaluation for Work Zone Speed Control

Motorists' understanding of the Traffic Control Plan (TCP) and their perception of problems in work zones may be different from that of an engineer who prepares the plans. Understanding problems from a driver's perspective would be helpful in preparing more effective TCPs.

A survey conducted to evaluate drivers' opinions in a rest area 3.2 km (2 miles) south of a construction zone on I-57 indicated the following key observations:[11]

(1) 77.3% paid more attention to work zone signs after entering the work zone
(2) 82.7% saw the flagger (there was one flagger with a stop/slow paddle to slow traffic) and 14.3% said they did not see the flagger at all
(3) 87.9% correctly interpreted flaggers message, 3.3% interpreted the message as just a caution message and saw no need to slow down and 2.5% did not remember the message.

Among the 87.9% who correctly interpreted the flagger's message, 92.1% reduced speed if the flagger asked them to but 6.2% did not.

One more important piece of information drawn from the survey was that 94.2% of speeding drivers felt that their speed was safe and 4.4% knew it was unsafe but still continued to drive at that speed. Another interesting result was that only 54% felt that going through the work zone was hazardous. Some of the general recommendations made by drivers were wider driving lanes, shorter construction zones, brighter clothing for workers and fewer workers in the traveled lane. They also suggested using two flaggers, one much before the work zone and the other just before the work zone. It is felt that the survey described above suffered from the limitation that the speed of the vehicle was not matched with the driver's response. Other demographic data like vehicle type, age of driver, and sex were also not included.

In another study conducted by Jonathan et al[12] three types of variable message signs, namely shuttered fiber optic (fiber optic), light emitting diode (LED), and electromagnetic flip disk (flip disk), were evaluated for effectiveness with respect to target value, legibility and viewing comfort. An observer group of 62 people was used for evaluation.

Target value describes how noticeable a sign is or how well it attracts the motorist's attention. Legibility distance is the maximum distance from which a driver is able to read a sign. Viewing discomfort describes any discomfort caused by glare or harshness of light. The study revealed that the night target values for both fiber optic and LED signs were much higher than for flip disks and also that bright sunlight and glare had a larger negative effect on older drivers than on younger drivers. With respect to legibility distances it was found that the fiber optic signs were in general better than the other two. The flip disks were found to have the highest discomfort rating.

On the whole it appears that the fiber optic technology performs better than the LED and flip disk signs. The LED also had acceptable performance in all of the categories.

General Guidelines for Use of CMS

Changeable message signs and real time motorist information displays are becoming more and more important in highway and safety operations. The FHWA came out with a series of reports covering general guidelines for the use and operation of CMSs. This section will highlight some of the key findings of this project.[13]

CMSs can be conveniently placed into three categories:

(1) *Light Reflecting Signs*: reflect light from some external light source such as sun or headlights (e.g. reflective disk)

(2) *Light Embodying Signs*: generate their own light on or behind the viewing surface (e.g. fiber optic)

(3) *Hybrid*: In this case the two CMS technologies (reflective disk and fiber optic) are combined to produce hybrid displays that exhibit the qualities of both.

The photometric and physical design requirements for CMSs are based on the following four functional requirements that the signs have to satisfy:

(1) *Conspicuousness (or target value)* is the quality of an object or a light source to appear prominent in the surroundings.

(2) *Legibility* is a measure of how readily an observer may recognize words and symbols. Quantitatively this is given by the threshold distance at which the sign becomes legible to the driver.

(3) *Comprehensibility* is a measure of how well the observer can understand the message intended to be conveyed by the sign.
(4) *Credibility* is the extent to which drivers believe that a traffic sign is reliable and accurate.

It was found that it would be better to display less information or no information at all if the sign operator was unsure of the traffic conditions. It was observed that telling drivers trivial information (something they already know) only led to the loss of credibility of the sign.

The study indicated that run-on messages are not suitable for displaying messages to drivers traveling at high freeway speeds and are therefore not recommended for incident management and route diversion. Also, the message must be legible at a distance that allows sufficient exposure time for drivers to read and comprehend the message. The minimum exposure time of one second per short word (four to eight characters) or two seconds per unit of information, whichever is larger, should be used for unfamiliar drivers. Some of the other recommendations were:

(1) For most freeway applications CMS should have characters at least 18 inches in height
(2) Limited research[11] has shown that 40% of drivers have difficulty in reading light-embodying CMSs at night.

The selection of the appropriate CMS is a complex task, so specific guidelines have been developed for this purpose:[13]

(1) Establish the objectives of the use of the CMS
(2) Prepare the messages necessary to accomplish the objectives
(3) Determine the legibility distance required to allow motorists to read and comprehend the messages
(4) Determine the CMS locations which allow motorists ample distance to read, comprehend, and react to the messages
(5) Identify type and extent of localized constraints that might affect the legibility of the CMS
(6) Identify the environmental conditions under which the CMS will operate
(7) Determine target value and legibility of candidate CMSs
(8) Determine costs of candidate CMSs
(9) Select the CMS that will allow the selected messages to be read under all environmental conditions within the cost constraints of the agency.

Effectiveness and Implementation of CMSs and Radar Units

Effectiveness of the CMSs and Radar Units

A study conducted by Benekohal and Shu[14] observed that the placement of a single CMS in advance of a work zone reduced speeds of cars by 4.5 km/h (2.8 mph) and speeds of trucks by 2.25 km/h (1.4 mph) (with the speed data being collected 1094.4 m (3600 ft) before the CMS and 334.4 m (1100 ft) after the CMS). Though the speed reductions were statistically significant in general they were not practically significant for trucks. They did reduce the number of cars exceeding the speed limit by 20%. The project was also carried out in two more stages (with one and two CMSs within the work zone).

A general conclusion drawn was that the CMS was effective in reducing speeds near itself but the effect attenuated as the vehicles moved further away from the CMS. It was found that in the case of experiment 3 of Benekohal's study (where 2 CMSs were used within the work zone) the effect of speed reduction was sustained through out the length of the work zone. The study also concluded that the messages affected the cars at a location close to the CMS and was consistent, whereas the impact on trucks was not consistent and therefore no conclusions could be drawn.

The Minnesota Department of Transportation (MnDOT) conducted a similar study using a radar controlled speed sign.[15] The study revealed that the 85th percentile speeds were reduced from 109.3 to 93.26 km/h (68 mph to 58 mph) with the installation of just the static signs. The installation of the radar controlled speed sign reduced the 85th percentile further, down to 85.22 km/h (53 mph). This study has used 85th percentile speed reductions as its measure of effectiveness because it is the 85th percentile speeds rather than the average speeds that control safety conditions over the region.

Tying a radar unit in with a CMS has been shown to be very useful when it becomes necessary to identify and single out high speeding vehicles to alert the drivers of the hazardous area ahead (like a work zone area). One general concern with this system has been that drivers suddenly apply the brakes and decelerate when they perceive a radar signal. Although this helps slow down the vehicles, the sudden deceleration may cause increased vehicle conflicts, accidents, and other safety problems.

A study conducted by Ullman[16] evaluated the effect of using radar transmissions to reduce speeds without visible enforcement present. The study showed that the radar signal on an average reduced speeds by 4.82 km/h (3 mph) and that the radar was also found to have a greater effect on trucks compared to automobiles.

Benekohal[11] studied the speed reduction effects of drone radar in rural interstate work zones. The project was carried out in three stages. The first looked at the effect of the radar when applied at the beginning of the work zone. The second and third experiments used one and two additional radars. The results of the experiments indicated that the drone radar can be most effective in short periods of time when drivers have not identified the radar. But over longer durations the effectiveness goes down, because the drivers find out it is not a police radar. Also it was suggested that the drone radar be used in conjunction with police enforcement, so that drivers are kept off balance as to when the radar is real and when it is a drone. In other words, the drivers should not be able to conclude that the signals are coming from a drone radar.

Summarizing, it is observed that the effectiveness of the CMS in reducing speeds is influenced by several factors:

(1) The placement of the CMS
(2) The type of message used
(3) The type of vehicle
(4) The length of the zone over which speed reduction is desired
(5) The duration of time over which speed reduction is desired.

Though studies have researched the impact of factors 1 and 2 above, additional research is necessary to study the impact of factors 3, 4, and 5 so the CMS can be implemented most efficiently and provide maximum benefit for influencing drivers to reduce their speeds.

Implementation of CMS with Radar

The CMS in combination with radar has the capability of influencing large speed reductions when installed and implemented properly. Since the CMS with radar gives a sense of personalized communication to speeding drivers, they feel urged to slow down.

It has been suggested that the CMS be placed on only one side of the road as it may cause distraction when placed on both sides. Also, the placement of the CMS within the work zone is critical. An attempt should be made to place the CMS near a point where a serious problem or hazardous condition is perceived. In this case the drivers will tend to react more promptly to the CMS. Though there have been a few prior studies involving the CMS with a radar at work zones, most of them have looked only at the short term effects. Since it is perceived that the effect on speed reduction could be altered with sustained implementation of the combined CMS and radar unit, this particular study will look at the long term effects of these units.

Data Collection

Identifying Suitable Work Zone Study Sites

The selection of appropriate study sites for this project was an important task since it is unlikely that all work zones will be suitable for the study. For example very short work zones on urban highways with high AADTs will not be suitable since congested flow usually predominates under these conditions.

The principal criterion for site selection is that free flow conditions must exist during a significant proportion of the data collection period so that the opportunity will exist for drivers to select their desired speed and drive at that speed along the work zone. Information was obtained from resident engineers on their anticipated maintenance and reconstruction activities during the study period and the locations of these activities. Specific information was obtained on the type of highway on which work was being carried out or was to be undertaken in the future, the length of the work zone, the number of lanes, the number of lanes to be closed, the configuration of the site and the AADT on that section of the highway. The information received was reviewed to determine a preliminary list of sites that would have free flow conditions during a significant proportion of the time work was being carried out. The sites that were selected for data collection had to meet the following requirements.

(1) The estimated free flow traffic must be at least 30 percent of the total traffic to facilitate the monitoring of the individual speed of an adequate number of vehicles being driven at the drivers' desired speeds.

(2) The length of the work zone should be 456 m (1,500 ft) or more (allowing drivers who wish to vary their speeds to do so).

(3) The minimum safety conditions must be met (For example, space must be available for setting up the CMS with radar without any interference from construction vehicles and workers, and research personnel must be able to safely collect data)

(4) The population of drivers evaluated consisted of a high percentage of repeated drivers (as this study involved duration of exposure). In order to ensure this, a survey of drivers was carried out at adjacent rest areas, ramps, and employment centers. A total of 326 completed survey forms were returned. The format of the questionnaire used in this survey is shown in Appendix A.

Three test sites that met the above mentioned criteria were selected for data collection activities. Two of the work zone sites were on Interstate 81 and the third site was on Route 19, which is a primary route. The first site was on I-81 South at Bristol, the second was on I-81 North also at Bristol and the third site was on Route 19 North in Lebanon. The results of the survey determining the percentage of repeated users showed that on both the sites on I-81 about

65% of those surveyed said they used the section of road through the work zone at least once a day. On Route 19 at Lebanon this percentage was close to 80%. A profile of the three work zone sites studied is shown in Table 1. Line diagrams of all three work zones along with dimensions are also shown in Figures 1 to 3.

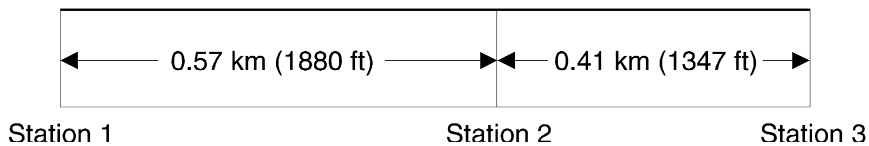

Figure 1. Line diagram for I-81 South Bristol work zone site (not to scale).

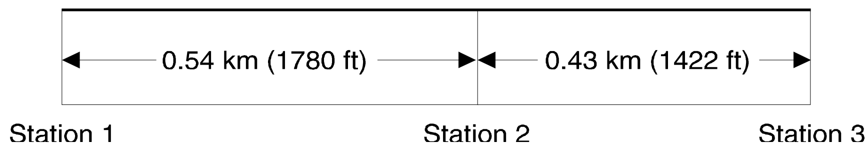

Figure2. Line diagram for I-81 North Bristol work zone site (not to scale).

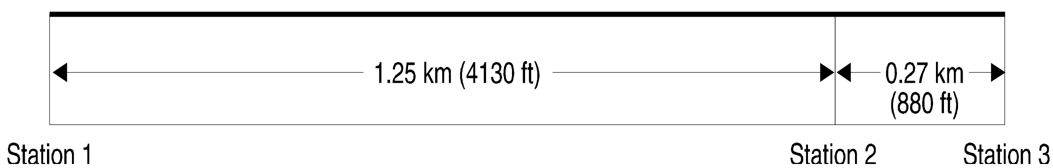

Figure 3. Line diagram for Rte 19 North Lebanon work zone site (not to scale).

Data Collection Activities

Data collection at the I-81S site was carried out in June, July and August 1995 for four alternating weeks, i.e. first, third, fifth and seventh weeks after the installation of the equipment. At the I-81N site data were collected for three consecutive weeks, i.e. first, second and third weeks. Data collection at the US 19 site was carried out in May, June, and July 1996 for four alternating weeks, i.e. first, third, fifth and seventh weeks after the installation of the equipment. Data collection was carried out over several weeks to study the effect of duration of CMS exposure on speed reductions due to CMS. It was not possible to collect data for longer than three weeks at the second site because of schedule of work zone activities in that site. But since data from this site showed trends similar to the other two sites (which were over a seven week period) with respect to duration of exposure, it was felt that this data could still be used for analysis concerning duration of exposure without biasing the results.

Table 1. Profile of Work Zone Study Sites

Route Number	Nearest City or Town	County	Number of Lanes	Normal Speed Limit	Posted Speed Limit	Type of Work Zone	Date of Study
81 South	Bristol	Washington	2	104.52km/h (65mph)	88.44km/h (55mph)	Bridge Reconstruction & Construction of Additional Lane	06/14-07/26/95
81 North	Bristol	Washington	2	104.52km/h (65mph)	88.44km/h (55mph)	Bridge Reconstruction and Construction of Additional Lane	08/09-08/24/95
19 North	Lebanon	Russell	1	88.44km/h (55mph)	72.36km/h (45mph)	Construction of Additional Lane	05/21-07/12/96

Automated Traffic Counts With the Standard MUTCD Signs in Place

The first step to be carried out was laying down pneumatic road tubes and automated traffic counters to collect speed and volume data for all vehicles traveling through the work zone. This data was collected continuously throughout the course of the data collection period for the given site. This provided a good estimate of the behavior of the whole population during that period. The tubes that were used to record vehicle speeds were installed at the following three locations:

(1) At approximately the beginning of the work zone (station 1)
(2) Within the work zone (station 2)
(3) Just before the end of the work zone (station 3).

These three locations were chosen because they represent the entrance point where the vehicle speeds are usually those preferred by the drivers, within the work zone where vehicle speeds may be influenced by the speed control effort, and the end of the work zone where drivers may start speeding up again assuming they have passed the monitored area. Two sets of tubes were laid at each of these locations to record speed data.

Each of these sets of tubes was connected to a traffic counter. The StreeterAmet T240 programmer was used to program these counters. The tubes that were used to record vehicle classification and volume data were laid at the beginning of the work zone (Station 1). At the end of each day the data were downloaded onto the T240 programmer and then onto a disk using a laptop.

The high traffic volume at the work zone caused several problems for the pneumatic tubes during the data collection procedure. The most common of these problems was tearing of nails that held the tube down from the asphalt, formation of holes on the tube, and splitting of the tubes. Other contributing factors could have been high vehicle speeds, high percentage of heavy vehicles, and high temperatures. To prevent excessive loss of these automated counts due to tube failure, each site was checked regularly and the tubes replaced whenever necessary.

Installing the Changeable Message Sign

The CMS equipped with a radar unit was placed a short distance behind the first set of tubes in order to detect vehicle speeds as they entered the work zone. The CMS used a standard display board (CMS-T300, American Signal Company). The radar (TRACKER TDW-10 Wide Beam Vehicle Detector) was connected to a central processing unit (CPU) that controlled the functions and display of the message board of the CMS. The radar activated the CPU when it detected a speed higher than the preset threshold. The message display was programmed to flash the message "YOU ARE SPEEDING SLOW DOWN" when a speeding vehicle was detected. This message was used because it was found to be the most effective among the four messages that were tested in the first phase of this study.[6] The display was formatted in such a way that the text had the maximum allowable font size that could still fit in the display. The actual format of the display is shown in Figure 4.

Figure 4. The CMS with message display.

Both the test sites on I-81 had a speed limit of 88.44 km/h (55 mph) in the work zone and the test site on Route 19 had a speed limit of 72.36 km/h (45 mph). The threshold speed for the automated speed display was set at 93.26 km/h (58 mph) (4.82 km/h (3 mph) more than the work zone speed limit) on the interstates and 77.18 km/h (48 mph) on Route 19. The radar was attached to the side of the message display. The message display had to be adjusted so that the radar was picking up speeds of all entering vehicles at a distance of about 120 m - 180 m (400 ft - 600 ft) away from the radar.

Data Collection After CMS Has Been Installed

Additional tubes were set down at a distance of 45.6 m (150 ft) apart at stations 2 and 3. The layout of the tubes is shown in Figure 5 for the site on Route 19. Each of the tubes was then connected to a lighting device which consisted of an air pressure activated device and a light emitting diode (LED) (see Figure 6). The light on the LED was activated every time a vehicle passed over the tube. When a speeding vehicle was first detected by the radar unit on the CMS, the message display was activated and the driver of the vehicle was able to see the warning message and react to it. At the same time the observer at station 1 made note of the characteristics of the vehicle such as type, make, size, and color, and relayed this over a walkie talkie to the observers at stations 2 and 3. The progress of the speeding vehicle was monitored by two cameras positioned at a distance of about 91.2 m - 152 m (300 ft - 500 ft) beyond the tubes so that movement of the vehicle over these tubes and also the corresponding display on the LED can be recorded on film. The cameras provided the means to determine vehicle travel times over a fixed distance (45.6 m or 150 ft) and thus determine the speeds of these individual vehicles at stations 2 and 3.

Figure 5. Layout of tubes across the road.

Figure 6. The LED (Light Emitting Diode).

In addition to videotaping, the camera operator at station 3 was also required to record manually on a pre-designed data collection sheet (see Appendix B) the vehicle description information relayed by the observer at station 1. This information would be used later on for identifying individual vehicles during data extraction from the video tapes. Data were collected for around 600 speeding vehicles for each week of data collection. The layout of a typical work zone area prepared for data collection is shown in Appendix C.

The traffic data were collected along with the data obtained during videotaping. Traffic counters recorded the speeds and vehicle types of the entire population passing through the work zone during the data collection period. Also, the counters were set up to collect data at 15 minute intervals when the camera data were being collected, to obtain greater accuracy during this period. Reducing the counter intervals from 60 minutes to 15 minutes greatly reduced the length of time the counters could continue to collect data due to memory constraints. After the videotaping was finished the counters were reset to collect data at 1 hour intervals.

Data Reduction

Data Extraction from Video Tapes

The first step in data extraction was to convert the normal 1/2" videotapes on which the speeders were recorded to professional 3/4" tapes. The reason for doing this was that the 3/4" editing system had the capability of slowing frames down to 1/30th of a second. The editing system was equipped with a jog control that allowed easy movement of the tape both forward and back. The editing system was also connected to a control tracker which recorded the timing on the video equipment.

Once the tapes had been converted, the jog control was used to adjust the position of the vehicle such that the front tires were just resting on the first tube and the LED light was activated. This time was programmed into the tracker as the input time. The jog control was then used to adjust the position of the vehicle on the monitor so that the front tires rested on the second tube. This time was programmed into the tracker as the output time. The tracker then automatically calculated the vehicle travel time and displayed this in a numeric format where the integer value denoted whole seconds and the decimal part denoted thirtieths of a second. This procedure was repeated for each of the vehicles that had been recorded by the camera. These data were later entered into a spreadsheet and the speeds of the individual vehicles at stations 2 and 3 were calculated.

Compilation of Data from Traffic Counters

The StreeterAmet T240 programmer was used to download the speed and volume data from the counters both in the morning and evening during each data collection session. These were then downloaded onto a disk using a laptop and the T240 software. The data were studied manually after each download to look for any noticeable abnormalities like sudden reduction or increase in traffic counts. This was done to ensure that the counters being used were not defective and also that the tubes were in good condition. There were a few instances where the data obtained from the counters had to be rejected for one of following reasons: (1) accident within the work zone, (2) defective counter recording or faulty counts, or (3) tube failure causing faulty readings. The counter speed and volume data were then classified into the following categories :

(1) Prior to the installation of the CMS
(2) During the period the CMS was in place with the data collection team present
(3) During the period the CMS was in place but without the data collection team.

These data would then be used later in the analysis to determine how the speed profiles varied under each of these three conditions.

Analysis

Computing Vehicle Speeds from Camera Data

Once the vehicle travel times had been determined as explained in the previous section, each vehicle's speed at station 1 as recorded by the radar was entered in the first column in a spreadsheet. The corresponding travel times of the vehicle (in whole seconds and thirtieths of a second) at stations 2 and 3 were entered in subsequent columns and the spreadsheet was programmed in such a way that the actual vehicle speeds were computed by the computer and displayed in a separate column. The formula used to compute the actual vehicle speeds from

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the travel times is given below:
where T = travel time in seconds
S = speed in mph. The speeds were subsequently converted to the units of km/h.
A typical computation of vehicle speeds is shown in Table 2.

Preliminary Data Analysis

Once the travel times of the speeding vehicles at stations 2 and 3 had been extracted from the video tapes and the speeds computed as outlined in the previous section, the data for all the vehicles exceeding the speed limit were available in spreadsheets for further computation. The whole population data collected using the traffic counters were also downloaded onto a disk from the programmer. These data were then subjected to certain preliminary analyses as described in greater detail in the following sections.

Table 2. Sample Speed Computation - Camera data (I-81 South Bristol)

Station 1	**Station 2**			**Station 3**		
Speed km/h *(mph)*	Whole Seconds	Thirtieths of a second	Speed km/h *(mph)*	Whole Seconds	Thirtieths of a second	Speed km/h *(mph)*
99.7 *(62)*	2	1	80.88 *(50.3)*	1	28	85.06 *(52.9)*
99.7 *(62)*	1	26	88.1 *(54.79)*	1	26	88.1 *(54.79)*
96.5 *(60)*	2	6	74.75 *(46.49)*	2	5	75.89 *(47.2)*
98.1 *(61)*	1	27	86.55 *(53.83)*	1	29	83.62 *(52)*
104.5 *(65)*	1	18	102.78 *(63.92)*	1	17	104.97 *(65.28)*
99.7 *(62)*	1	19	100.69 *(62.62)*	1	23	93.08 *(57.89)*

The traffic counters were also used to collect speed data for the entire population of vehicles entering the work zone during the study period. The traffic counters categorized speeds into 12 speed ranges (Figure 7). The speed ranges (also called bins) were programmed in increments of 3.22 km/h (2 mph), ranging from 80.4 to 115.78 km/h (50 mph to 72 mph) for the data collected at the sites on I-81 and ranging from 48.24 to 93.26 km/h (30 mph - 58 mph) for data collected at the site on Route 19. The speed ranges were selected to accommodate the majority of traffic traveling through the study area. The counter recorded the number of vehicles in each bin. For example the first bin (80.4 km/h or 50 mph) recorded the number of vehicles traveling at 80.4 km/h (50 mph) or below. The next bin (83.62 km/h or 52 mph) recorded the number of vehicles with speeds higher than 80.4 km/h (50 mph) and up to 83.62 km/h (52 mph) and so on. The last bin (115.78 km/h or 72 mph) recorded the number of vehicles traveling at speeds more than 112.56 km/h (70 mph).

The counter data for each week of data collection activity were then divided into three distinct categories based on field conditions. These categories were:

(1) Only the standard MUTCD signs present
(2) With the CMS in place but without the data collection team present
(3) With the CMS in place and with the data collection team present.

This was done to help study the effect the CMS had on the population and also to analyze the impact of the presence of the data collection team on speed profiles in the region. The data which represent the whole population can also serve as a yardstick to compare with the data on the sample of speeders. The analyses for this set of data included the computation of the average speeds, 85th percentile speeds and speed variances, and percentages of vehicles speeding. The average and 85th percentile speeds were automatically computed and generated by the T240 program which was used to download the counter data. The speed variance had to be computed separately. One point to be made here is that since the counter recorded speeds only in speed ranges, a certain degree of approximation had to be made while computing the variance. This process was repeated for the data collected during all the weeks for all three sites. The data from different weeks was then compared to study the effect of duration of exposure on the speed reductions.

The camera data consisted of the sample of speeders at station 1 and their corresponding speeds after they saw the warning on the CMS, at stations 2 and 3. This set of data was reordered using a sort program at each station to determine the 85th percentile speeds. The average speeds and speed variances were also determined at all three stations for the data set for each week at all three sites.

Statistical Tests

T-tests to Determine the Effect of Presence of Data Collection Team

Before the results of the T-tests and ANOVA were interpreted, it was necessary to research the impact the presence of the data collection team and the video cameras had on the vehicle speeds and speed profiles in the work zones. This was carried out through T-tests conducted on the average speeds (whole population data) of vehicles entering the work zone with and without the data collection team present. The following hypotheses were developed for this purpose:

Hypothesis: {1} The average speeds at station 2 with the data collection team present are the same as the average speeds at station 2 without the data collection team present.

Hypothesis: {2} The average speeds at station 3 with the data collection team present are the same as the average speeds at station 3 without the data collection team present.

T-tests to Determine the Effect of CMS on Speeders

Before the long-term impact of the CMS with radar was studied, it was necessary to ensure that the CMS was still effective in reducing speeds of speeders between stations 1 and 2 and stations 1 and 3. A previous study[6] has shown that the vehicles exceeding the posted speed limit did reduce their speeds significantly at stations 2 and 3 in response to the message "YOU ARE SPEEDING SLOW DOWN." T-tests were carried out on the speeds of speeders for each week to reinforce the results of that study. The tests had to be carried out on each week of data individually, because clubbing data for each site would neglect the interaction effects of the different weeks, or in other words would not take into consideration the long-term impact of the CMS. The long-term impact will be studied separately, as explained in the next section. The hypotheses developed for the T-tests were:

Hypothesis: {3} The mean of the speed reductions of the vehicles exceeding the speed limit from station 1 to station 2 is zero.

Hypothesis: {4} The mean of the speed reductions of the vehicles exceeding the speed limit from station 1 to station 3 is zero.

ANOVA to Determine the Effect of Duration of Exposure of CMS

The ANOVA was carried out on the speed data obtained from videotapes to determine whether duration of exposure of the CMS caused any significant changes in speed reductions (or increases) of individual speeders in the following categories:

Category 1: Speed reductions from station 1 to station 2
Category 2: Speed reductions from station 1 to station 3

Tests of statistical significance were then performed on four weeks of data (collected over a seven week period) on the first site, three weeks of data (collected over a three week period) on the second site and four weeks of data (collected over a seven week period) on the third site. The following null hypotheses were formulated for this test:

Hypothesis: {5} The mean speed reductions between stations 1 and 2 is the same for all weeks of CMS exposure.

Hypothesis: {6} The mean speed reductions between stations 1 and 3 are the same for all weeks of CMS exposure.

ANOVA for Vehicle Classification Data

The data on speeders obtained from the cameras were classified according to four vehicle categories:

Class 1: Passenger Cars
Class 2: Pickups, Minivans and Vans
Class 3: Single unit trucks and buses
Class 4: Tractor Trailers.

Two types of analysis were performed with the classification data. At first each week's data was taken and classified for each of the four vehicle types. ANOVA was then performed to test for any significant differences in speed reductions between any of the four vehicle types. This test would, for example, indicate if tractor trailers had a greater tendency to slow down in response to the CMS with radar. The other test carried out was an ANOVA which studied the differences in speed reductions for each vehicle class over the different weeks. This would test separately if each class of vehicles was being influenced by the duration of exposure to the CMS with radar. The following null hypotheses were formulated:

Hypothesis: {7} The mean speed reductions from station 1 to station 2 are the same for all four vehicle classes.

Hypothesis: {8} The mean speed reductions from station 1 to station 3 are the same for all four vehicle classes.

Hypothesis: {9} The mean of the speed reductions from station 1 to station 2 for vehicles in Class 1 is the same for all weeks of CMS exposure.

Hypothesis: {10} The mean of the speed reductions from station 1 to station 3 for vehicles in Class 1 is the same for all weeks of CMS exposure.

Tests {9} and {10} were repeated for all four vehicle classes (Hypotheses {11}-{16}).

T-tests on Whole Population Data

Once the long term impact of the CMS on speeding drivers had been studied, data for each site were taken to study the effectiveness of the CMS in reducing various speed characteristics of the whole driver population. The speed data from the counters were grouped together for each site into two categories, with the CMS and without the CMS (only MUTCD signs) and T-tests were performed for average speeds, 85th percentile speeds, speed variance, percentage of vehicles speeding by any amount, percentage of vehicles speeding by 8.04 km/h (5 mph) or more and percentage of vehicles speeding by 16.08 km/h (10 mph) or more. The following hypotheses were formulated:

Hypothesis: {17} The average speed at station 2 with the sign is the same as the average speed at station 2 without the sign.

Hypothesis: {18} The average speed at station 3 with the sign is the same as the average speed at station 3 without the sign.

The T-tests were also repeated for 85th percentile, variance and percentages of vehicle speeding (Hypotheses {19}-{28}).

Statistical Estimates

Estimating the Probability of Speeding

The "Probability of speeding P_s" is an estimate developed to determine the impact the CMS had in reducing the likelihood for speeding. The conditions before and after the application of the treatment will be the primary inputs in determining the probability. This was calculated for each site separately in the following manner:

Probability of Speeding P_s : This is the probability that a vehicle picked at random was

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exceeding the speed limit and was computed as follows:

The effectiveness of the CMS was evaluated by comparing the reduction in the P_s values

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from stations 1 to 2 and from stations 1 to 3 before and after the installation of the CMS:

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where %reduction of P_s between stations 1 and 2 is computed as:
P_{s1} - Probability of speeding computed at station 1 (i.e.) P_s at station 1.
P_{s2} - Probability of speeding computed at station 2 (i.e.) P_s at station 2.
P_{s3} - Probability of speeding computed at station 3 (i.e.) P_s at station 3.

The equation for % reduction of P_s between stations 1 and 3 is similar to equation [4] above. The term "Effectiveness of CMS" computed in equation [3] gives an estimate of the percentage of population that is being influenced by the CMS. This was computed for each week of data separately to see whether the proportion of drivers being influenced by the sign increases or decreases as time goes by.

ANOVA was also carried out on $\boldsymbol{P_s}$ values for the different weeks to study if there were any significant reductions in probabilities over the long term. The following null hypotheses were formulated:

Hypothesis: {29} The probability of speeding at station 2 with the CMS is the same for all weeks of CMS exposure.

Hypothesis: {30} The probability of speeding at station 3 with the CMS is the same for all weeks of CMS exposure.

Estimating Speed Reductions (Confidence Intervals)

The mean speed reductions in response to the CMS of the sample of speeders for which data were collected were computed directly from the spreadsheets. This, however, was not a true estimate of the actual speed reduction of the population as a whole. As a result confidence bands have also been developed for these speed reductions. For example, there is an interval within which the true mean lies with a probability of 95% confidence at a 5% significance level. The narrower the confidence band for a fixed confidence level, the more accurately the unknown parameter can be assumed to be estimated.

Confidence interval estimates were developed for the camera data to estimate the range of the speed reductions for each of the two speed categories outlined in this report. Each week's data were analyzed separately using a statistical package at a confidence level of 95%.

Effect of Length of Work Zone on Speed Reductions

For this analysis, data from seven of the sites from the first phase of this project[6] were combined with the data for the first week from the three sites in this study. The lengths of the work zone (from station 1 to station 3) were compared with the corresponding speed reductions from station 1 to station 3 for each site. These data were then used to perform a correlation analysis and also plot graphs to see if there was any relationship between the length and speed reductions.

RESULTS

The data from both the camera and the counters were organized in a spreadsheet (QuattroPro) in a form convenient to carry out statistical analysis. In some cases the spreadsheet was incapable of performing certain complex analyses. The data were imported into a statistical analysis package (SPSS) to carry out these tasks. Because of the extensive amount of data collected, the individual data files containing data obtained from the camera and the counters are not included in this report. The summaries of statistical quantities that were computed from these data are, however, included in Appendices D and E. The summary of results of the various statistical tests and estimates are detailed below with references provided to appropriate tables and graphs where these results are better illustrated. A summary of the statistical tests performed (along with the purpose of the test, type of statistical analysis used, type of data used and table of results) is provided in Table 3 for quick reference.

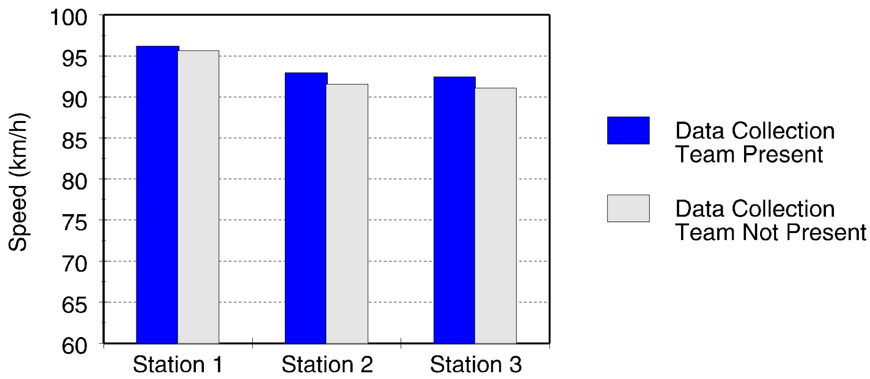
Results of Statistical Tests

Effect of Presence of Data Collection Team

The average and 85th percentile speeds of the vehicles in all three conditions under which data collection was performed (i.e. without the CMS and with the CMS, both with and without the data collection team present) are depicted in Appendix D. A cursory glance at the tables will indicate the general trend. Speeds were marginally lower when drivers saw the data collection team than when the team was not present. The effect of the data collection team's presence in reducing speeds was slightly more at the third site, which was a primary route, than the two interstate sites (Figures 8-10). This was anticipated since speeds were generally lower (speed limit of 72.36 km/h [45 mph]) on the primary road and therefore the drivers had more time to look at the cameras and react and slow down. This result needs to be kept in mind when interpreting the results from the analysis done on the camera data, since all of the speeds obtained from the cameras were collected when the data collection team was present.

Though the presence of the data collection team caused speeds that were lower (statistically significant in some cases, indicating that hypotheses 1 and 2 cannot be rejected) than when the team was not present, the mean speed reductions due to the presence of the data collection team were only about 0.804 km/h to 2.41 km/h (0.5 mph to 1.5 mph) on the interstates and around 3.22 km/h (2 mph) on the primary. This, when compared with the reductions in speeds from stations 1 to 2 and 1 to 3 of the speeders, which were between 12.86 km/h and 14.47 km/h (8 mph and 9 mph), is not of practical significance. The results of the T-tests carried out are shown in Tables 4-6.

The ANOVA that was carried out to determine if the effect of presence of the data collection team showed significant differences with respect to length of exposure indicated that the impact of this factor (effect of data collection team's presence) was not significantly different between the different weeks of data collection. The ANOVA carried out to demonstrate this result is also shown in Appendix F (Table F-1).



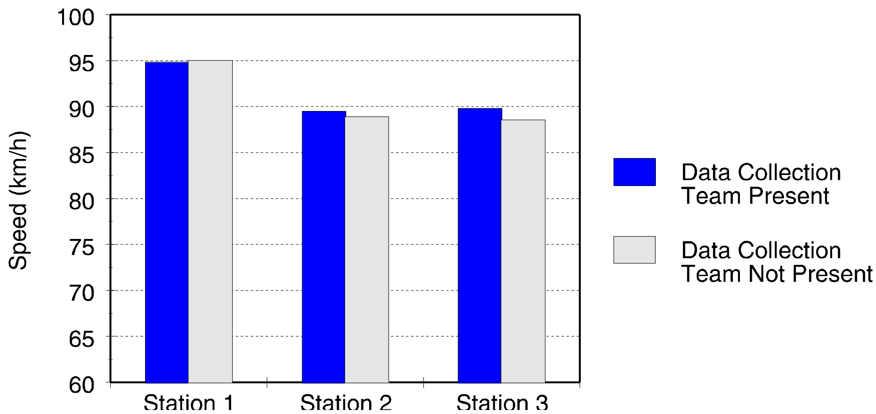


Figure 8. Average speeds with and without data collection team present (I-81 South Bristol).

Figure 9. Average speeds with and without data collection team present (I-81 North Bristol).

Figure 10. Average speeds with and without data collection team present (Rte 19 North Lebanon).

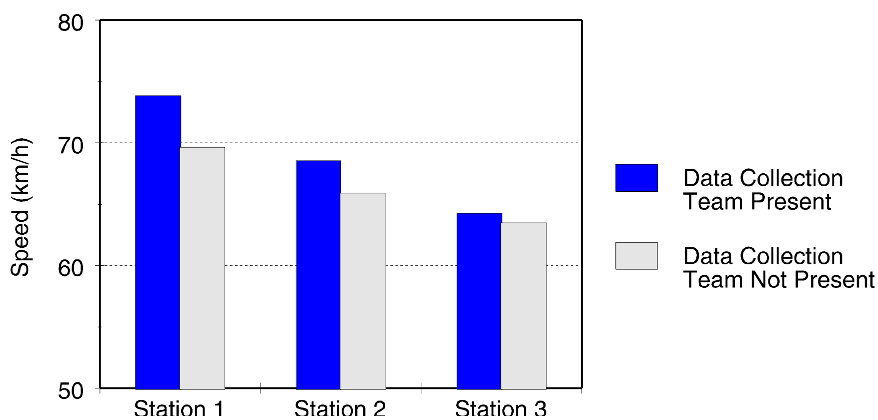


Table 4. Results of T-test: Average Speeds Using Whole Population Data With Data Collection Team vs Without Data Collection Team (I-81 South Bristol)

Weeks During Which Data Were Collected	**Station 2 (Hypothesis 1)**				**Station 3 (Hypothesis 2)**			
	T	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***	**T**	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***
Week 1	2.002	2.015	NO	2.46 *(1.53)*	---	---	---	---
Week 3	3.202	1.69	YES	1.59 *(0.99)*	4.03	1.69	YES	2.35 *(1.46)*
Week 5	---	---	---	---	2.61	1.69	YES	1.24 *(0.77)*
Week 7	4.46	1.68	YES	1.48 *(0.92)*	4.62	1.68	YES	1.11 *(0.69)*

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 5. Results of T-test: Average Speeds Using Whole Population Data With Data Collection Team vs Without Data Collection Team (I-81 North Bristol)

Week During Which Data Were Collected	**Station 2 (Hypothesis 1)**				**Station 3 (Hypothesis 2)**			
	T	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***	**T**	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***
Week 1	1.82	1.68	YES	0.74 *(0.46)*	1.38	1.69	NO	1.17 *(0.73)*
Week 2	2.79	1.69	YES	0.75 *(0.47)*	5.11	1.69	YES	1.28 *(0.8)*
Week 3	1.54	1.71	NO	0.43 *(0.27)*	10.75	1.69	YES	3.34 *(2.08)*

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 6. Results of T-test: Average Speeds Using Whole Population Data With Data Collection Team vs Without Data Collection Team (Rte 19 North Lebanon)

Week During Which Data Were Collected	**Station 2 (Hypothesis 1)**				**Station 3 (Hypothesis 2)**			
	T	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***	**T**	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***
Week 1	---	---	---	---	---	---	---	---
Week 3	9.05	1.657	YES	7.12 *(4.43)*	10.94	1.657	YES	7.94 *(4.94)*
Week 5	7.44	1.701	YES	8.57 *(5.33)*	7.94	1.701	YES	8.2 *(5.10)*
Week 7	8.96	1.689	YES	9.36 *(5.82)*	8.23	1.689	YES	9.12 *(5.67)*

* Yes - reject null hypothesis
No - do not reject null hypothesis

T-tests on Camera Data

The data from the camera, which recorded the speeds at stations 2 and 3 of individual speeders, were compiled and the average and 85th percentile speeds are shown in Appendix E. T-tests were carried out on each week's data to find out if there were significant speed reductions between stations 1 and 2 and stations 1 and 3. Paired T-tests were performed for both these cases and the results indicate significant reductions and reconfirmed the results borne by phase I[6] of this study. Therefore null hypotheses 3 and 4 are rejected for all three sites. The results of the paired T-tests are shown in Tables 7-9.

As can be seen from tables E1 and E2 the mean speed reductions between stations 1 and 2 and stations 1 and 3 on both the sites on I-81 were between 8.04 km/h and 16.08 km/h (5 mph and 10 mph). The data also indicated larger reductions (12.86 km/h to 19.30 km/h [8 mph to 12 mph]) on Route 19 (see Figures 11- 13). All of the three sites showed no specific trend or significant speed reductions between stations 2 and 3 which indicate that drivers who did reduce their speeds are not speeding back up when they approached the end of the work zone. The 85th percentile also indicated significant reductions between stations 1 and 2 and stations 1 and 3 in all three sites.

Table 7. Results of Paired T-test for Camera Data (I-81 South Bristol)

Week During Which Data Were Collected	**Reductions from Station 1 to 2 (Hypothesis 3)**				**Reductions from Station 1 to 3 (Hypothesis 4)**			
	T	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***	**T**	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***
Week 1	23.37	1.647	YES	9.21 *(5.73)*	21.35	1.647	YES	8.51 *(5.29)*
Week 3	33.47	1.647	YES	10.9 *(6.83)*	32.59	1.647	YES	10.6 *(6.62)*
Week 5	34.27	1.647	YES	11.4 *(7.11)*	32.56	1.647	YES	11.1 *(6.88)*
Week 7	31.91	1.647	YES	11.4 *(7.09)*	25.96	1.647	YES	9.66 *(6.01)*

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 8. Results of Paired T-test for Camera Data (I-81 North Bristol)

Week During Which Data Were Collected	**Reductions from Station 1 to 2 (Hypothesis 3)**				**Reductions from Station 1 to 3 (Hypothesis 4)**			
	T	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***	**T**	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***
Week 1	52.06	1.647	YES	14.1 *(8.75)*	52.06	1.647	YES	17.4 *(10.8)*
Week 2	46.94	1.647	YES	14.4 *(8.93)*	46.94	1.647	YES	17.9 *(11.1)*
Week 3	39.76	1.647	YES	15.9 *(9.89)*	39.76	1.647	YES	15.9 *(9.89)*

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 9. Results of Paired T-test for Camera Data (Rte 19 North Lebanon)

Week During Which Data Were Collected	**Reductions from Station 1 to 2 (Hypotheses 3)**				**Reductions from Station 1 to 3 (Hypotheses 4)**			
	T	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***	**T**	**Tcrit**	**Significant? (yes/no)***	**Mean Difference km/h *(mph)***
Week 1	31.96	1.649	YES	14.4 *(8.93)*	32.19	1.649	YES	13.8 *(8.58)*
Week 3	33.08	1.648	YES	16.4 *(10.2)*	31.93	1.648	YES	15.9 *(9.91)*
Week 5	39.72	1.647	YES	16.8 *(10.4)*	44.49	1.647	YES	19.2 *(11.9)*
Week 7	30.9	1.648	YES	15.1 *(9.38)*	29.42	1.648	YES	14.7 *(9.19)*

* Yes - reject null hypothesis
No - do not reject null hypothesis

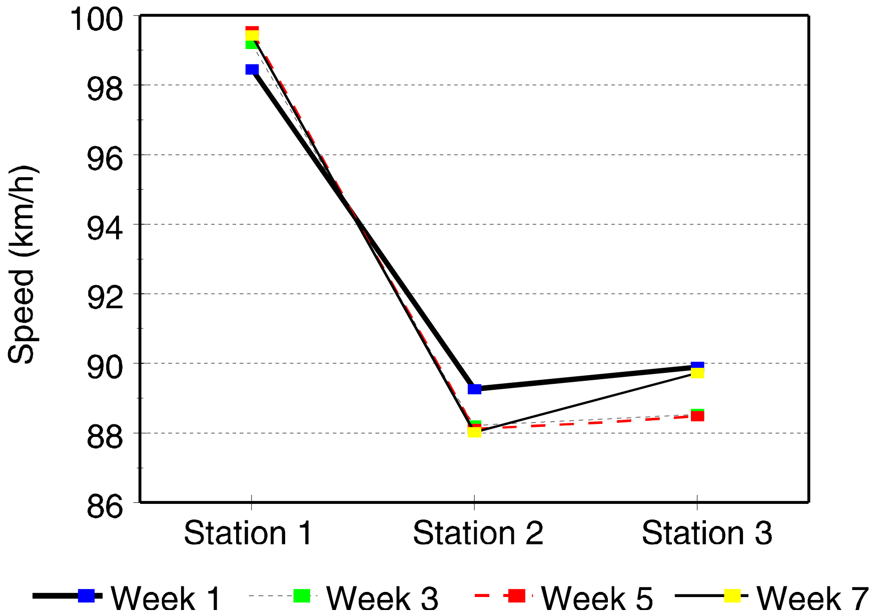


Figure 11. Average speeds using camera data (I-81 South Bristol).

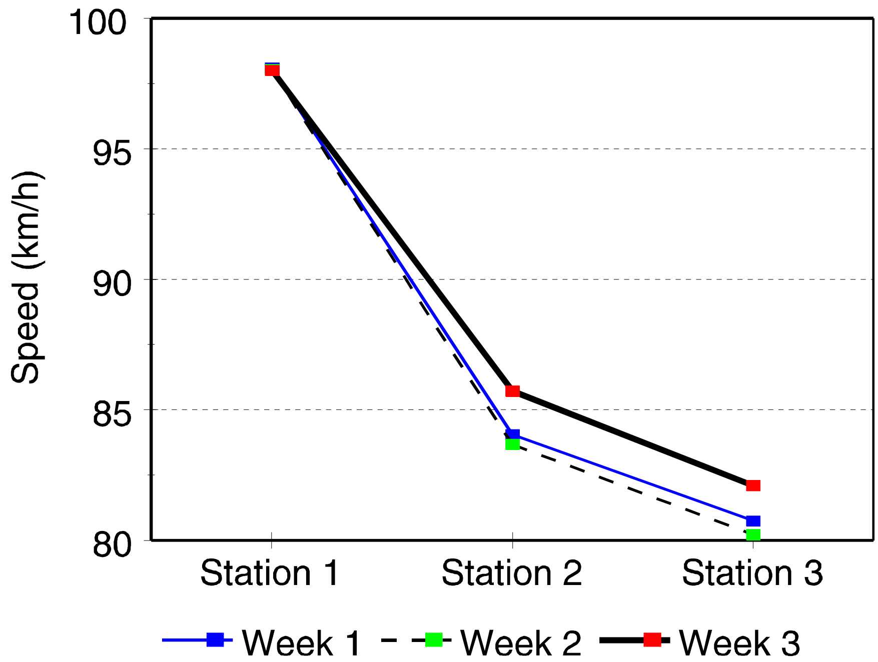
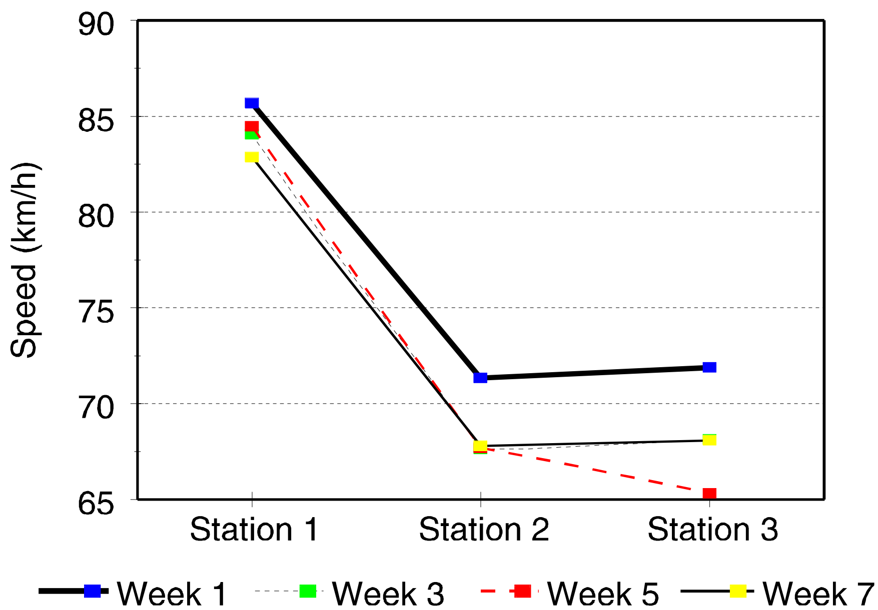


Figure 12. Average speeds using camera data (I-81 North Bristol).

Figure 13. Average speeds using camera data (Rte 19 North Lebanon)



Since all of the camera data were collected with the data collection team present, it was necessary to repeat these tests after correcting the speeds at stations 2 and 3 for the effect of presence of the data collection team. As mentioned earlier, though the speed reductions (0.804 - 3.22 km/h [0.5 - 2 mph]) due to the presence of the team were only marginal, T-tests were carried out with the adjusted speeds to ensure that the presence of the data collection team did not affect the results presented in this section. The results of these tests (carried out after the adjustments for the presence of the data collection team were made) also showed significant reductions indicating that the sign would be effective even without the data collection team present in slowing speeding drivers. These results confirm that hypotheses 3 and 4 should be rejected. The results of the T-tests are documented in Appendix F (Tables F-2 to F-4).

ANOVA for Effect of Duration of Exposure of CMS

The results of the ANOVA to test whether there were significant differences in speed reductions between the different weeks at each site are shown in Table 10. All of the sites turned out to have significant differences in mean reductions during the different weeks. Therefore hypotheses 5 and 6 can be rejected. As a consequence of this result, a more in depth analysis had to be performed to see how the different sets of data varied. The results of the Tukey-HSD multiple comparison test for each of the three sites are shown in Tables 11-13.

Table 10. Results of ANOVA for Speed Reductions Between Stations 1&2 and Stations 1&3
(test to determine if there is significant difference in reductions among weeks)

Site	**Speed Reductions from Station1 to Station2 (Hypothesis 5)**			**Speed Reductions from Station1 to Station3 (Hypothesis 6)**		
	F	**Significance of F**	**Significant (yes/no)***	**F**	**Significance of F**	**Significant (yes/no)***
81 South Bristol	7.97	.0022	YES	9.53	.0014	YES
81 North Bristol	9.84	.0001	YES	6.95	.0010	YES
19 North Lebanon	5.68	.0007	YES	26.22	0	YES

* Yes - reject null hypothesis
No - do not reject null hypothesis

Table 11. Tukey-HSD Test for Multiple Comparisons for Speed Reductions for Different Weeks - I-81 South Bristol (Positive mean differences indicate increase in speed reductions. Negative mean differences indicate decrease in speed reductions.)

Week	Compared with	Speed Reductions from Station1 to Station2		Speed Reductions from Station1 to Station3	
		Significant Difference? (yes/no)*	Mean Difference km/h *(mph)*	Significant Difference? (yes/no)*	Mean Difference km/h *(mph)*
Week1	**Week3**	YES	1.76 *(1.1)*	YES	2.14 *(1.33)*
	Week5	YES	2.23 *(1.39)*	YES	2.56 *(1.59)*
	Week7	YES	2.2 *(1.37)*	NO	1.16 *(0.72)*
Week3	**Week5**	NO	0.46 *(0.29)*	NO	0.42 *(0.26)*
	Week7	NO	0.43 *(0.27)*	NO	-.98 *(-0.61)*
Week5	**Week7**	NO	-0.037 *(-0.02)*	YES	-1.4 *(-0.87)*

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 12. Tukey-HSD Test for Multiple Comparisons for Speed Reductions for Different Weeks - I-81 North Bristol (Positive mean differences indicate increase in speed reductions. Negative mean differences indicate decrease in speed reductions.)

Week	Compared with	Speed Reductions from Station1 to Station2		Speed Reductions from Station1 to Station3	
		Significant Difference? (yes/no)*	Mean Difference km/h *(mph)*	Significant Difference? (yes/no)*	Mean Difference km/h *(mph)*
Week1	**Week2**	NO	0.29 *(0.18)*	NO	0.48 *(0.3)*
	Week3	YES	-1.77 *(-1.1)*	YES	-1.44 *(-0.9)*
Week2	**Week3**	YES	-2.06 *(-1.28)*	YES	-1.95 *(-1.2)*

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 13. Tukey-HSD Test for Multiple Comparisons for Speed Reductions for Different Weeks - Rte 19 North Lebanon (Positive mean differences indicate increase in speed reductions. Negative mean differences indicate decrease in speed reductions.)

Week	**Compared with**	**Speed Reductions from Station1 to Station2**		**Speed Reductions from Station1 to Station3**	
		Significant Difference? (yes/no)*	**Mean Difference km/h *(mph)***	**Significant Difference? (yes/no)***	**Mean Difference km/h *(mph)***
Week1	**Week3**	YES	2.06 *(1.28)*	YES	2.14 *(1.33)*
	Week5	YES	2.44 *(1.52)*	YES	5.39 *(3.35)*
	Week7	NO	0.72 *(0.45)*	NO	1 *(0.62)*
Week3	**Week5**	NO	0.37 *(0.23)*	YES	3.25 *(2.02)*
	Week7	NO	-1.33 *(-0.83)*	NO	-1.2 *(-0.72)*
Week5	**Week7**	YES	-1.72 *(-1.07)*	YES	-4.4 *(-2.74)*

* Yes means reject null hypothesis
No means do not reject null hypothesis

As can be seen from the tables most comparisons which were significant indicate positive mean differences implying that the amount of speed reductions was increasing over the long term. Though there were a few weeks (week 7 in site 1, week 3 in site 2, and week 7 in site 3) which indicated a slight decrease in speed reduction when compared with one or more of the previous weeks, the reductions were still extremely significant by themselves and so by no means indicate ineffectiveness of the sign (see Figures 14-16). Summarizing, we can say that the sign is still effective in reducing speeds on a long-term work zone, but the data did not indicate any discernable relationship between the duration of exposure and the amount of speed reduction.

ANOVA to Compare Speed Reductions by Vehicle Type

Two types of tests were carried out with the vehicle classification data. A representative set of results is shown in Tables G1- G4. First, each week's data were tested to see if there were any differences in speed reductions among the four vehicle types. The results of this test for each of the three sites are shown in Tables 14-16. The ANOVA results showed that there were no significant differences between the four vehicle types in all of the weeks except weeks 5 & 7 in site 1 (I-81 South, Bristol) mainly because tractor trailers had higher reductions (from station 1 to station 3) than the other three classes. Since the tractor trailers showed higher reductions only from station 1 to station 3 and not from station 1 to station 2, it is felt that the geometry (the sharp curvature in particular) of the road at this site between stations 2 and 3 could have affected the larger vehicles (tractor trailers) to slow down more in comparison with other vehicle types. Null hypotheses 7 and 8 cannot therefore be rejected except for the I-81 South Bristol site.

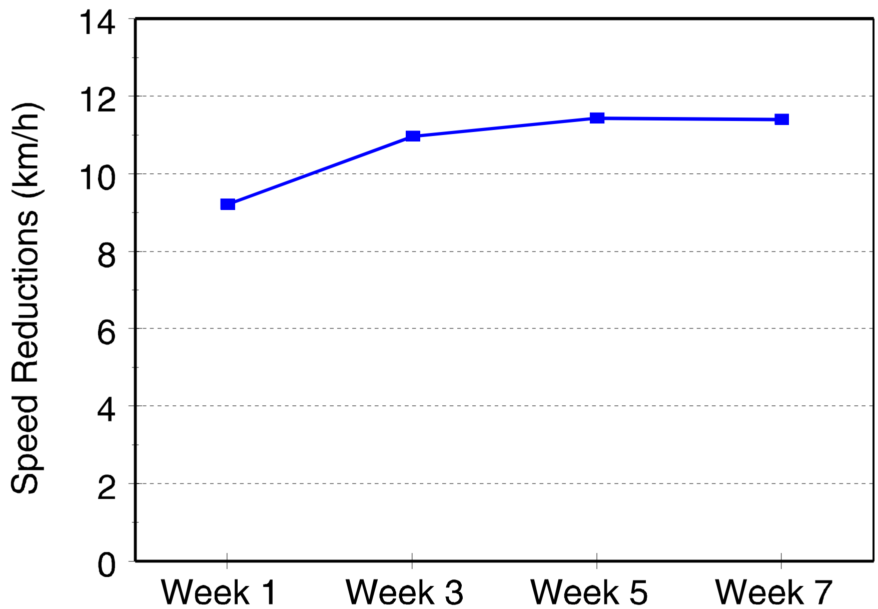
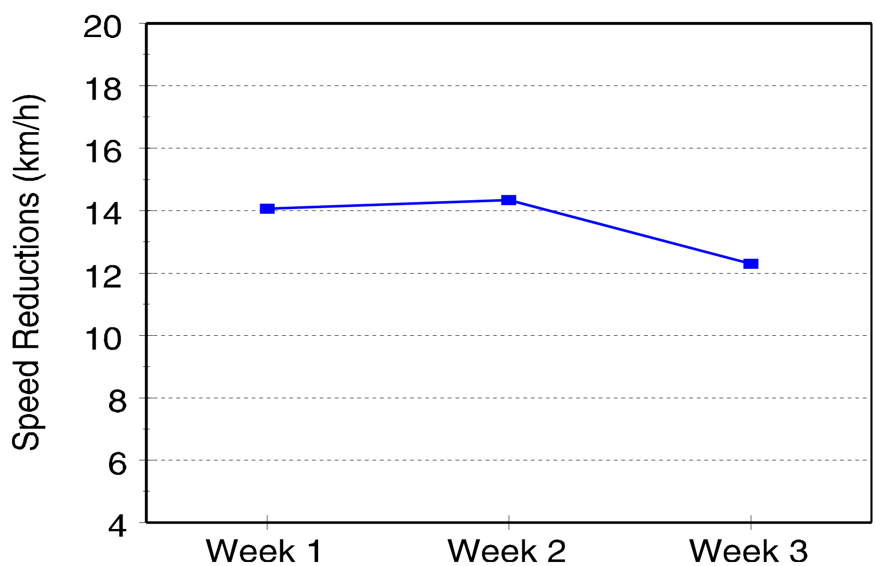


Figure 14. Mean speed reductions from Station 1 to Station 2 (I-81 South Bristol).

Figure 15. Mean speed reductions from Station 1 to Station 2 (I-81 North Bristol).



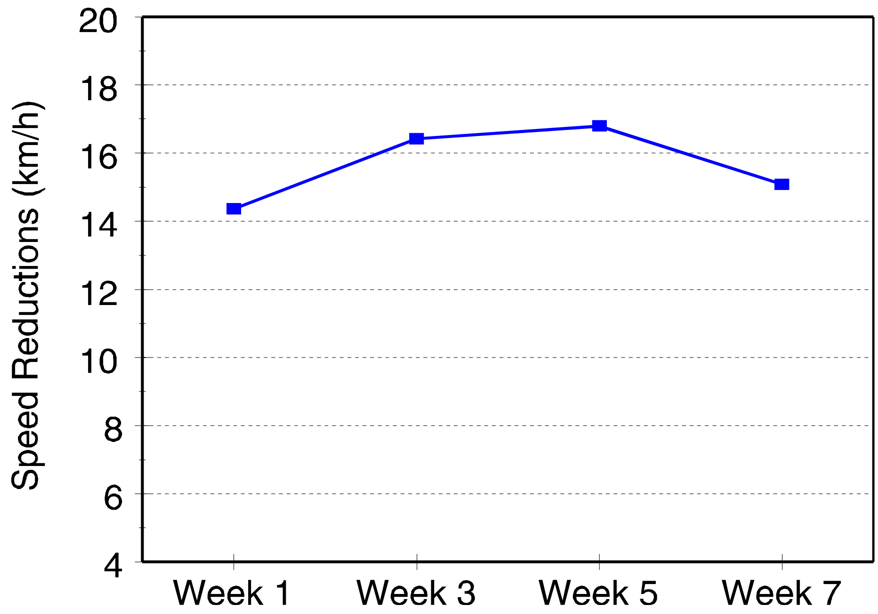


Figure 16. Mean speed reductions from Station 1 to Station 2 (Rte 19 North Lebanon).

Table 14. Results of ANOVA for Testing Differences in Speed Reductions for the Four Vehicle Classes (I-81 South Bristol)

Week During Which Data Were Collected	Speed Reductions from Station 1 to Station 2 (Hypothesis 7)			Speed Reductions from Station 1 to Station 3 (Hypothesis 8)		
	F	Significance of F	Significant Difference? (yes/no)*	F	Significance of F	Significant Difference? (yes/no)*
Week 1	2.34	.072	NO	2.14	.094	NO
Week 3	.947	.417	NO	.171	.916	NO
Week 5	2.54	.056	NO	3.46	.016	YES
Week 7	2.5	.058	NO	3.22	.022	YES

* Yes - reject null hypothesis
No - do not reject null hypothesis

Table 15. Results of ANOVA for Testing Differences in Speed Reductions for the Four Vehicle Classes (I-81 North Bristol)

Week During Which Data Were Collected	Speed Reductions from Station 1 to Station 2 (Hypothesis 7)			Speed Reductions from Station 1 to Station 3 (Hypothesis 8)		
	F	Significance of F	Significant Difference? (yes/no)*	F	Significance of F	Significant Difference? (yes/no)*
Week 1	2.16	.062	NO	1.37	.056	NO
Week 2	.954	.312	NO	1.65	.215	NO
Week 3	3.12	.092	NO	2.63	.074	NO

* Yes - reject null hypothesis
No - do not reject null hypothesis

Table 16. Results of ANOVA for Testing Differences in Speed Reductions for the Four Vehicle Classes (Rte 19 North Lebanon)

Week During Which Data Were Collected	Speed Reductions from Station 1 to Station 2 (Hypothesis 7)			Speed Reductions from Station 1 to Station 3 (Hypothesis 8)		
	F	Significance of F	Significant Difference? (yes/no)*	F	Significance of F	Significant Difference? (yes/no)*
Week 1	2.26	.082	NO	2.13	.096	NO
Week 3	1.28	.281	NO	1.1	.351	NO
Week 5	.235	.872	NO	.384	.764	NO
Week 7	1.02	.385	NO	1.88	.132	NO

* Yes - reject null hypothesis
No - do not reject null hypothesis

ANOVA was also carried out to test if each vehicle class behaved differently over the different weeks. The results of this analysis are shown in Tables 17-20. As can be seen from the tables, though there was no specific trend, most of the cases which showed significant differences indicated only an increase in speed reductions. Class 3 vehicles (single unit trucks and buses) showed no significant effect over the long term. Since the results were not consistent, no conclusions could be made on hypotheses 9 through 16.

Table 17. Results of ANOVA for Testing Significance of Differences in Speed Reductions for Different Weeks for Each Vehicle Class--Class 1 (cars)

Site	Speed Reductions from Station1 to Station2 (Hypothesis 9)			Speed Reductions from Station1 to Station3 (Hypothesis 10)		
	F	Significance of F	Significant (yes/no)*	F	Significance of F	Significant (yes/no)*
81 South Bristol	5.16	.0015	YES	5.69	.0007	YES
81 North Bristol	5.53	.0043	YES	2.22	.1102	NO
19 North Lebanon	2.14	.0939	YES	12.15	0	YES

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 18. Results of ANOVA for Testing Significance of Differences in Speed Reductions for Different Weeks for Each Vehicle Class--Class 2 (pickups, minivans and vans)

Site	Speed Reductions from Station1 to Station2 (Hypothesis 11)			Speed Reductions from Station1 to Station3 (Hypothesis 12)		
	F	Significance of F	Significant (yes/no)*	F	Significance of F	Significant (yes/no)
81 South Bristol	1.78	.1495	NO	2.62	.0497	NO
81 North Bristol	3.05	.0479	YES	2.73	.0660	NO
19 North Lebanon	3.68	.0118	YES	12.17	0	YES

* Yes means reject null hypothesis

No means do not reject null hypothesis

Table 19. Results of ANOVA for Testing Significance of Differences in Speed Reductions for Different Weeks for Each Vehicle Class--Class 3 (single unit trucks, buses)

Site	Speed Reductions from Station1 to Station2 (Hypothesis 13)			Speed Reductions from Station1 to Station3 (Hypothesis 14)		
	F	Significance of F	Significant (yes/no)*	F	Significance of F	Significant (yes/no)*
81 South Bristol	.446	.7205	NO	.471	.7028	NO
81 North Bristol	.979	.3801	NO	.686	.5064	NO
19 North Lebanon	.924	.4363	NO	1.08	.3635	NO

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 20. Results of ANOVA for Testing Significance of Differences in Speed Reductions for Different Weeks for Each Vehicle Class--Class 4 (tractor trailers)

Site	Speed Reductions from Station1 to Station2 (Hypothesis 15)			Speed Reductions from Station1 to Station3 (Hypothesis 16)		
	F	Significance of F	Significant (yes/no)*	F	Significance of F	Significant (yes/no)*
81 South Bristol	5.29	.0013	YES	4.96	.002	YES
81 North Bristol	3.82	.0223	YES	3.96	.0194	YES
19 North Lebanon	2.15	.1025	NO	4.48	.0063	YES

* Yes means reject null hypothesis
No means do not reject null hypothesis

T-tests on Whole Population Data

The results of the T-tests carried out on the various speed characteristics of the population data are shown in Tables 21-26. The results showed significant reduction in all cases for average speeds and percentage of vehicles speeding by any amount. Hypotheses 17, 18, 23, and 24 were therefore rejected. Although at some sites speed variances were reduced with the introduction of the CMS, this result was not consistent at stations 2 and 3 for all sites and weeks. The 85th % showed only significant reductions in station 2 in all three sites. Hypothesis 19 was rejected and hypothesis 20 was not rejected. Though percentages of vehicles speeding by >8.04 km/h (>5 mph) and >16.08 km/h (>10 mph) did not show consistent reductions in all cases, these categories also showed several reductions. Since the results for speed variance were not consistent for all three sites, no conclusions could be made for hypotheses 21 and 22.

One important thing to be noted from these results is that none of the negative reductions (or increases) are statistically significant indicating that the sign does not have any negative influence on any of the speed characteristics.

Table 21. Results of T-tests - Whole Population Data (Average Speeds)

	Station 2 (Hypothesis 17)			**Station 3 (Hypothesis 18)**		
	T	**Tcrit**	**Significant? (yes/no)***	**T**	**Tcrit**	**Significant? (yes/no)***
81 South Bristol	4.93	2.35	YES	31.68	2.91	YES
81 North Bristol	4.57	2.91	YES	3.75	2.91	YES
19 North Lebanon	51.82	2.91	YES	5.32	2.91	YES

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 22. Results of T-tests - Whole Population Data (85th Percentile Speeds)

	Station 2 (Hypothesis 19)			**Station 3 (Hypothesis 20)**		
	T	**Tcrit**	**Significant? (yes/no)***	**T**	**Tcrit**	**Significant? (yes/no)***
81 South Bristol	7.85	2.35	YES	2.41	2.91	NO

81 North Bristol	3.92	2.91	YES	0.67	2.91	NO
19 North Lebanon	5.35	2.91	YES	0.16	2.91	NO

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 23. Results of T-tests - Whole Population Data (Speed Variance)

	Station 2 (Hypothesis 21)			**Station 3 (Hypothesis 22)**		
	T	**Tcrit**	**Significant? (yes/no)***	**T**	**Tcrit**	**Significant? (yes/no)***
81 South Bristol	9.04	2.35	YES	12.03	2.91	YES
81 North Bristol	1.51	2.91	NO	1.97	2.91	NO
19 North Lebanon	3.35	2.91	YES	2.88	2.91	NO

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 24. Results of T-tests - Whole Population Data (% Speeding by Any Amount)

	Station 2 (Hypothesis 23)			**Station 3 (Hypothesis 24)**		
	T	**Tcrit**	**Significant? (yes/no)***	**T**	**Tcrit**	**Significant? (yes/no)***
81 South Bristol	7.39	2.35	YES	6.28	2.91	YES
81 North Bristol	21.38	2.91	YES	3.6	2.91	YES
19 North Lebanon	3.49	2.91	YES	18.73	2.91	YES

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 25. Results of T-tests - Whole Population Data (% Speeding by >5mph)

	Station 2 (Hypothesis 25)			Station 3 (Hypothesis 26)		
	T	**Tcrit**	**Significant? (yes/no)***	**T**	**Tcrit**	**Significant? (yes/no)***
81 South Bristol	1.07	2.35	NO	2.94	2.91	YES
81 North Bristol	3.57	2.91	YES	3.77	2.91	YES
19 North Lebanon	2.91	2.91	NO	12.97	2.91	YES

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 26. Results of T-tests - Whole Population Data (% Speeding by >10mph)

	Station 2 (Hypothesis 27)			**Station 3 (Hypothesis 28)**		
	T	**Tcrit**	**Significant? (yes/no)***	**T**	**Tcrit**	**Significant? (yes/no)***
81 South Bristol	2.17	2.35	YES	2.9	2.91	NO
81 North Bristol	3.65	2.91	YES	4.58	2.91	YES
19 North Lebanon	2.62	2.91	NO	7.09	2.91	YES

* Yes means reject null hypothesis
No means do not reject null hypothesis

Results of Statistical Estimates

Results of ANOVA on Probability of Speeding

Probabilities of speeding (Ps) for speeding by any amount, speeding by 8.04 km/h (5 mph) or more, and speeding by 16.08 km/h (10 mph) or more were computed for the free flow data (without the sign) and also for the data with the sign for the different weeks. These results are summarized in Tables 27-29.

All of the data show significantly lower probabilities at stations 2 and 3 with the CMS than without the CMS (at station 1 the drivers hadn't had time to react to the sign; therefore, the results did not indicate lower probabilities with the sign).

ANOVA was then carried out on Ps (with sign) values to see if the probabilities decreased over the long term. The results of the ANOVA for the three sites are shown in Table 30. Data from both the sites on I-81 indicated significant differences in probabilities among the weeks. Data from Route 19 indicated no significant changes in Ps values over the four weeks. The Tukey-HSD multiple comparison tests were performed on Ps for sites 1 and 2 and the results of this test are shown in Tables 31-32. As can be seen from the tables, most of the significant differences decreased in probabilities implying increased effectiveness of the sign in the long term work zone.

The percentage of population influenced by the sign was also studied. The percentage reduction in Ps values with and without the sign are shown in Tables 33-35. As expected the results show an increase in percentages of population influenced to reduce speeds with the introduction of the CMS with radar. The only exception was week 3.

Table 27. Probability of Speeding Table - I-81 South Bristol

		Probability of Speeding Station 1			Probability of Speeding Station 2			Probability of Speeding Station 3		
		Any amount	>5mph	>10mph	Any amount	>5mph	>10mph	Any amount	>5mph	>10mph
Week1	No CMS	.742	.417	.159	.624	.229	.092	.754	.322	.121
	With CMS	.664	.234	.068	.437	.208	.083	.431	.107	.034
Week3	No CMS	.742	.417	.159	.624	.229	.092	.754	.322	.121
	With CMS	.779	.385	.186	.578	.205	.088	.680	.244	.088
Week5	No CMS	.742	.417	.159	.624	.229	.092	.754	.322	.121
	With CMS	.684	.362	.161	.467	.153	.057	.543	.174	.064
Week7	No CMS	.742	.417	.159	.624	.229	.092	.754	.322	.121
	With CMS	.747	.278	.109	.588	.196	.078	.322	.052	.011

Table 28. Probability of Speeding Table - I-81 North Bristol

		Probability of Speeding Station 1			Probability of Speeding Station 2			Probability of Speeding Station 3		
		Any amount	>5mph	>10mph	Any amount	>5mph	>10mph	Any amount	>5mph	>10mph
Week1	No CMS	.698	.234	.062	.624	.203	.068	.461	.058	.008
	With CMS	.622	.208	.06	.442	.147	.043	.274	.041	.006
Week2	No CMS	.698	.234	.062	.624	.203	.068	.461	.058	.008
	With CMS	.762	.338	.124	.421	.111	.036	.434	.011	.003
Week3	No CMS	.698	.234	.062	.624	.203	.048	.461	.058	.008
	With CMS	.732	.298	.102	414	.05	.007	.403	.013	.003

Table 29. Probability of Speeding Table - Rte 19 North Lebanon

		Probability of Speeding Station 1			Probability of Speeding Station 2			Probability of Speeding Station 3		
		Any amount	>5mph	>10mph	Any amount	>5mph	>10mp h	Any amount	>5mph	>10mp h
Week1	No CMS	.662	.287	.156	.512	.112	.045	.541	.164	.062
	With CMS	.657	.198	.111	---	---	---	---	---	---
Week3	No CMS	.662	.287	.156	.512	.112	.045	.541	.164	.062
	With CMS	.634	.199	.135	.418	.086	.035	.476	.061	.036
Week5	No CMS	.662	.287	.156	.512	.112	.045	.541	.164	.062
	With CMS	.632	.266	.151	.428	.076	.02	.485	.052	.02
Week7	No CMS	.662	.287	.156	.512	.112	.045	.541	.164	.062
	With CMS	.653	.219	.178	.436	.104	.037	.475	.078	.03

Table 30. Results of ANOVA - Probability of Speeding (Whole Population Data)
(Compare Ps with Sign for All Weeks)

	Station 2 (Hypothesis 29)			**Station 3 (Hypothesis 30)**		
	F	**Significance of F**	**Significant Difference? (yes/no)***	**F**	**Significance of F**	**Significant Difference? (yes/no)***
81 South Bristol	21.62	.0012	YES	10.392	.0001	YES
81 North Bristol	31.25	.0205	YES	37.13	.0097	YES
19 North Bristol	.493	.112	NO	.346	.062	NO

* Yes - reject null hypothesis
No - do not reject null hypothesis

Table 31. Tukey-HSD Test for Multiple Comparisons for Probabilities of Speeding with the Sign for Different Weeks - I-81 South Bristol (Positive mean differences indicate decrease in probabilities. Negative mean differences indicate increase in probabilities)

Week	Compared with				
		Significant Difference? (yes/no)*	**Mean Difference in Probabilities**	**Significant Difference? (yes/no)***	**Mean Difference in Probabilities**
Week1	**Week3**	NO	.0088	YES	.021
	Week5	YES	.0202	NO	-.012
	Week7	YES	.099	YES	.16
Week3	**Week5**	NO	-.011	YES	-.033
	Week7	YES	.091	YES	.137
Week5	**Week7**	YES	.079	YES	.171

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 32. Tukey-HSD Test for Multiple Comparisons for Probabilities of Speeding with the Sign for Different Weeks - I-81 North Bristol (Positive mean differences indicate decrease in probabilities. Negative mean differences indicate increase in probabilities)

Week	Compared with				
		Significant Difference? (yes/no)	**Mean Difference in Probabilities**	**Significant Difference? (yes/no)**	**Mean Difference in Probabilities**
Week1	**Week2**	YES	.024	NO	-0.011
	Week3	YES	.031	YES	-0.17
Week2	**Week3**	NO	.0072	YES	-0.104

* Yes means reject null hypothesis
No means do not reject null hypothesis

Table 33. %Reductions in Ps With and Without Sign - I-81 South Bristol

Week During Which Data Were Collected	Speed Reductions From Station 1 to Station 2			Speed Reductions From Station 1 to Station 3		
	%Reduction in Ps without Sign	%Reduction in Ps with Sign*	% of Population influenced	%Reduction in Ps without Sign	%Reduction in Ps with Sign*	% of Population influenced
Week 1	15.93	26.67	10.67	-1.66	27.62	29.28
Week 3		38.58	22.65		40.95	42.61
Week 5		31.69	15.76		27.88	29.54
Week 7		52.66	36.73		52.88	54.54

* - Only Standard MUTCD Signs

Table 34. %Reductions in Ps With and Without Sign - I-81 North Bristol

Week During Which Data Were Collected	Speed Reductions From Station 1 to Station 2			Speed Reductions From Station 1 to Station 3		
	%Reduction in Ps without Sign*	%Reduction in Ps with Sign	% of Population influenced	%Reduction in Ps without Sign*	%Reduction in Ps with Sign	% of Population influenced
Week 1	10.53	28.67	18.14	33.88	49.57	15.69
Week 2		44.77	34.24		57.34	23.46
Week 3		43.51	32.98		34.04	0.16

*-Only Standard MUTCD Signs

Table 35. %Reductions in Ps With and Without Sign - Rte 19 North Lebanon

Week During Which Data Were Collected	**Speed Reductions From Station 1 to Station 2**			**Speed Reductions From Station 1 to Station 3**		
	%Reduction in Ps without Sign*	**%Reduction in Ps with Sign**	**% of Population influenced**	**%Reduction in Ps without Sign**	**%Reduction in Ps with Sign***	**% of Population influenced**
Week 3	22.74	33.95	11.21	18.42	24.84	6.42
Week 5		31.96	9.22		23.11	4.69
Week 7		32.92	10.18		27.16	8.74

* - Only Standard MUTCD Signs

Results of Confidence Band Analysis

Confidence bands were computed at a 95% confidence level for speed reductions of the vehicles exceeding the speed limit in response to the CMS. They were computed for both reductions from stations 1 to 2 and 1 to 3. The results are shown in Tables 36-38.

Table 36. Lower and Upper Limits of 95% Confidence Band for Speed Reductions Using Camera Data - I-81 South Bristol

Week During Which Data Were Collected	Speed Reductions from Station 1 to Station 2			Speed Reductions from Station 1 to Station 3		
	Mean km/h *(mph)*	Lower Bound for Mean km/h *(mph)*	Upper Bound for Mean km/h *(mph)*	Mean km/h *(mph)*	Lower Bound for Mean km/h *(mph)*	Upper Bound for Mean km/h *(mph)*
Week 1	9.21 *(5.73)*	8.44 *(5.25)*	9.98 *(6.21)*	8.51 *(5.29)*	7.73 *(4.81)*	9.28 *(5.77)*
Week 3	10.96 *(6.82)*	10.34 *(6.43)*	11.59 *(7.21)*	10.47 *(6.61)*	10 *(6.22)*	11.26 *(7)*
Week 5	11.43 *(7.11)*	10.77 *(6.7)*	12.09 *(7.52)*	11.06 *(6.88)*	10.4 *(6.47)*	11.72 *(7.29)*
Week 7	11.4 *(7.09)*	10.69 *(6.65)*	12.11 *(7.53)*	9.66 *(6.01)*	8.94 *(5.56)*	10.4 *(6.46)*

Table 37. Lower and Upper Limits of 95% Confidence Band for Speed Reductions Using Camera Data - I-81 North Bristol

Week During Which Data Were Collected	Speed Reductions from Station 1 to Station 2			Speed Reductions from Station 1 to Station 3		
	Mean km/h *(mph)*	Lower Bound for Mean km/h *(mph)*	Upper Bound for Mean km/h *(mph)*	Mean km/h *(mph)*	Lower Bound for Mean km/h *(mph)*	Upper Bound for Mean km/h *(mph)*
Week 1	14.07 *(8.75)*	13.46 *(8.37)*	14.68 *(9.13)*	17.35 *(10.79)*	16.69 *(10.38)*	18 *(11.2)*
Week 2	14.34 *(8.92)*	13.64 *(8.48)*	15.05 *(9.36)*	17.83 *(11.09)*	17.09 *(10.63)*	18.57 *(11.55)*
Week 3	12.3 *(7.64)*	11.59 *(7.21)*	12.97 *(8.07)*	15.9 *(9.89)*	15.12 *(9.4)*	16.69 *(10.38)*

Table 38. Lower and Upper Limits of 95% Confidence Band for Speed Reductions Using Camera Data - Rte 19 North Lebanon

Week During Which Data Were Collected	**Speed Reductions from Station 1 to Station 2**			**Speed Reductions from Station 1 to Station 3**		
	Mean km/h *(mph)*	**Lower Bound for Mean km/h *(mph)***	**Upper Bound for Mean km/h *(mph)***	**Mean km/h *(mph)***	**Lower Bound for Mean km/h *(mph)***	**Upper Bound for Mean km/h *(mph)***
Week 1	14.37 *(8.94)*	13.49 *(8.39)*	15.23 *(9.47)*	13.78 *(8.57)*	12.94 *(8.05)*	14.62 *(9.09)*
Week 3	16.42 *(10.21)*	15.44 *(9.6)*	17.4 *(10.82)*	15.94 *(9.91)*	14.95 *(9.3)*	16.92 *(10.52)*
Week 5	16.8 *(10.45)*	15.97 *(9.93)*	17.6 *(10.97)*	19.18 *(11.93)*	18.33 *(11.4)*	20.04 *(12.46)*
Week 7	15.08 *(9.38)*	14.12 *(8.78)*	16.05 *(9.98)*	14.77 *(9.19)*	13.79 *(8.58)*	15.76 *(9.8)*

Effect of Length of Work Zone

The lengths of the work zones and the corresponding speed reductions from station 1 to station 3 are shown in Table 39. Also the graph plotting the speed reductions for each length is shown in Figure 17. The correlation coefficient between these two quantities (length and speed reduction) was computed to be -0.733. Though this is not a very strong correlation in statistical terms, it indicates the general trend where longer work zones cause comparatively lesser speed reductions. In other words, if the length of the work zone is significant then the drivers are not maintaining their speed reductions and tend to speed back up. This result indicates that very long work zones might warrant the inclusion of a second CMS with radar unit, to sustain speed reductions and maintain lower speeds throughout the entire stretch of the work zones.

SUMMARY OF RESULTS

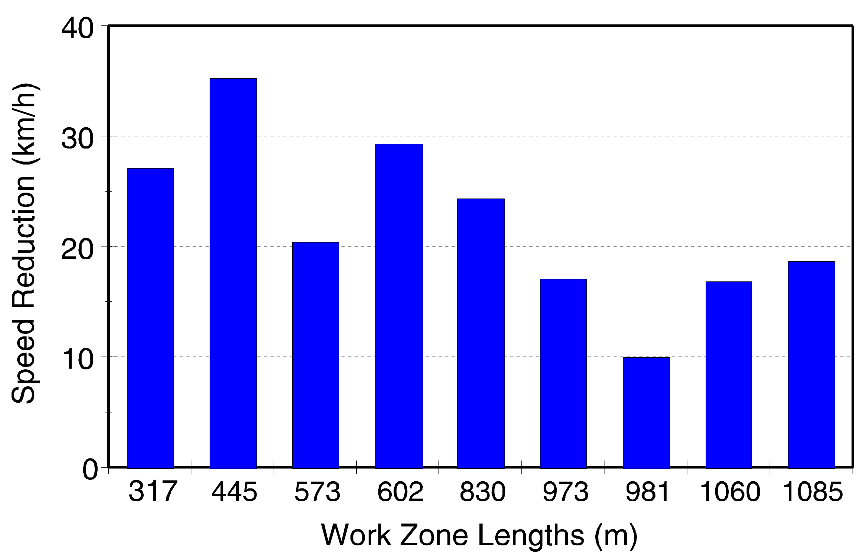
- The presence of the data collection team caused marginally lower speeds (0.8 - 3.2 km/h [0.5 - 2 mph]) than speeds recorded when the data collection team was not present at all three sites. This, however, did not negate the result on the effectiveness of the CMS. The speed reduction at each site varied from 12.81 km/h to 14.47 km/h (8 to 9 mph).

- The effect of the data collection team in lowering vehicle speeds was more pronounced at the primary highway site (3.3 km/h [2 mph]) than on the interstates (0.8 - 2.4 km/h [0.5- 1.5 mph]).

Table 39. Effect of Length of Work Zone on Speed Reductions

Site	Length of Work Zone (Station 1 to Station3) *m (feet)*	Speed Reduction (Station 1 to Station 3) km/h *(mph)*
I-81 South RockBridge*	317 *(1044)*	27.06 *(16.83)*
I-64 East Covington*	445 *(1466)*	35.22 *(21.9)*
I-64 East Short Pump*	573 *(1884)*	20.37 *(12.67)*
I-81 North Abingdon*	602 *(1980)*	29.25 *(18.19)*
I-81 South Abingdon*	830 *(2730)*	24.31 *(15.12)*
I-81 North Bristol	973 *(3202)*	17.03 *(10.59)*
I-81 South Bristol	981 *(3227)*	9.95 *(6.19)*
I-64 East Shadwell*	1060 *(3487)*	16.82 *(10.46)*
I-81 North Bristol *	1085 *(3568)*	18.64 *(11.59)*
Route 19 North Lebanon	1523 *(5010)*	15.68 *(9.75)*

* Results obtained from first phase of study



Note: Only week 1 data are used here.

Figure 17. Impact of length of work zone on speed reductions.

- Paired T-tests of the camera data to determine if there were speed reductions between stations 1 and 2 and stations 1 and 3 revealed highly significant reductions. (12.8 km/h [8 mph] on the interstates and 16.1 km/h [10 mph] on the primary road)

- T-tests on the effect of duration of exposure showed that the speed reductions were still significant after seven weeks of exposure.

- No specific relationship was found between duration of exposure and amount of speed reduction.

- No significant differences were found between the speed reductions of the four vehicle types (cars, pickups & vans, trucks & buses, tractor trailers).

- None of the four vehicle types showed any significant loss of effectiveness of the CMS over the long term.

- T-tests on the whole population comparing data with the CMS and without the CMS showed significant reductions of average speeds and percentage of vehicles speeding by any amount in all cases (both stations 2 and 3 for all three sites). In most cases speed variance, 85th percentile speeds, and percentages of vehicles speeding by 8.04 km/h (5 mph) or more and 16.08 km/h (10 mph) were also reduced with the introduction of the CMS with radar.

- The probabilities of speeding were significantly lower with the sign than without the sign at all three of the work zone sites.

- The tests on effect of duration of exposure on probabilities of speeding indicated significant differences only at the interstate sites. On the primary highway the tests showed that there was no difference in probabilities among the four weeks of data collection (collected over a seven week period). At the interstates most of the significant differences showed a decrease in probabilities of speeding over the long term, implying increasing effectiveness of the CMS.

- The confidence bands (at 95% confidence levels) predicted mean speed reductions up to within ±0.64 km/h (0.4 mph) to ±0.804 km/h (0.5 mph) off the mean giving a confidence band of approximately 1.61 km/h (1 mph). This is a fairly accurate estimate of the exact mean reduction of the population and therefore gives a good idea of expected driver behavior in response to the CMS with radar. The confidence bands for the speed reductions at the interstate sites ranged from 7.7 km/h to 18.7 km/h (4.8 mph to 11.6 mph) and from 13 km/h to 20.1 km/h (8.1 mph to 12.5 mph) at the primary highway.

- Correlation analysis between length of the work zone (between stations 1 and 3) and speed reductions (between stations 1 and 3) yielded a coefficient of -0.733. In other words the data reflects (though not with high statistical significance) the fact that in longer work zones drivers have a tendency to increase their speed toward the end of the work zone.

CONCLUSIONS

The results of the Phase II study substantiate the results of the Phase I study that the CMS with radar is effective in reducing the speeds of speeding drivers in a work zone for short durations (one week or less).

In addition, the results of this study indicate that the CMS with radar remains an effective speed control technique even when used for prolonged periods of time (up to seven weeks). The results also indicate all vehicle types behaved similarly with regard to speed reductions. Also, no single vehicle type seemed to disregard the CMS over the long term when studied separately.

The results of this study also give some support to the results of the Phase I study that speed variances tend to reduce with the introduction of the CMS in the work zone.

The results indicate that there is a tendency for drivers to speed back up in long work zones. This indicates that in very long work zones (approximately longer than 1060 m [3500 ft]), the introduction of a second CMS might be required so speed reductions could be maintained through out work zone.

Driver behavior within a work zone is influenced by several factors, like MUTCD signing, geometry of the work zone, type and intensity of construction activity in the work zone, etc. Though it is possible to isolate the impact of the CMS to a large extent by carrying out before and after types of analysis, complete isolation is not always possible. This needs to be kept in mind while interpreting results from several sites.

Given the high costs involved in having law enforcement officers around the clock at the work zone sites and the increasing need to make work zones safer for construction and rehabilitation work, the CMS with radar is indeed a very effective device for controlling speeds and speed variances both in short term and long term work zones.

RECOMMENDATIONS

Based on the results of this Phase II study and the results obtained by the Phase I study, it is strongly recommended that, whenever feasible, Changable Message Signs with radar be used to control speeds at work zones for both short term and long term projects.

Though this project studied the impact of the length of the work zone on speed reduction, a correlation of only 73% was observed between these two factors, which is not very conclusive. More specific research studies are recommended where the speeds of a vehicle that is detected by the sign to be exceeding the speed limit are obtained at different points within the work zone and analyzed to study how speed reductions vary with increasing distance from the CMS. Also it is recommended that studies be carried out in longer work zones with one CMS and two CMSs, and the results compared to look into the pros and cons of introducing a second CMS in long work zones.

This project tried to isolate the impact of the CMS alone. It is felt that the CMS with a radar can prove to be highly effective if used in combination with one or more speed control techniques like a circulating police car, effective lane width reduction or use of flaggers to signal drivers to lower their speed. On the other hand, the use of multiple speed control techniques can confuse drivers and result in lack of effectiveness. More detailed studies to determine the most effective combination and most cost effective solution are recommended.

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