Chapter 1 Introduction

1.1 Background

The construction of America's freeway system is nearly complete. The focus of highway initiatives is shifting further into maintenance, rehabilitation, and reconstruction of existing facilities. The work operations that carry out these initiatives require changes to the normal roadway conditions; therefore, measures must be taken to control traffic accordingly. The traffic control needed to delineate the location of the work, inform drivers of maneuvers they must undertake, and provide protection for the vehicle and the work operation, along with the work itself, constitutes a work zone. Work zones continue to become more common on our freeways and should be familiar sights to drivers. Of utmost concern in the planning and execution of work zones is safety for both highway workers and the traveling public. However, despite efforts to improve driver recognition and comprehension of, and responsiveness to work zones, accident rates still run much higher in work zones than elsewhere. Studies have consistently shown that driver inattention and exceeding safe speeds are the most common causes of work zone accidents. For example, on Interstate 81 in Virginia, among the work zone accidents during the years of 1991 through 1994, driver inattention and exceeding the safe speed were the first and second most common driver actions cited on state police accident reports. Driver inattention was cited in 22% of the cases, and in 13%, exceeding the safe speed was cited as the cause of the accident. According to these reports, in 39% of work zone accidents, no driver action was taken. During this same period, the number of work zone accidents on I-81 increased every year. These data clearly indicate a growing need to increase driver awareness of work zones and to control speeds within them.

1.2 Problem Statement

Many efforts to inform drivers of work zones and encourage reduction of their travel speeds already exist and are commonly used. Standard sign layouts are used in common work zone configurations. Changeable message signs and low-power advisory radio broadcasts have been increasingly used in recent years to alert drivers to traffic conditions in advance of work zones. In addition, many techniques, ranging from variations in the traffic control to the threat of law enforcement, are being employed in an attempt to reduce speeds in work zones. The next chapter of this report discusses many of these techniques in detail.

One major area of work zone speed control efforts has been the use of law enforcement. For the past several years, the Virginia Department of Transportation (VDOT) and many other states have deployed state police vehicles in work zones as a deterrent to speeding. Studies, reviewed in the next chapter, conducted on the impact of various forms of police presence have generally shown it to be one of the most effective speed control techniques. However, it is also one of the most expensive, in terms of both personnel and equipment costs. VDOT has recently purchased unmanned, or “drone,” radar transmitters as a low-cost alternative, and supplement, to police presence. These devices emit radar signals that are then received by radar detectors. Obviously, the natural driver response is a reduction in speed, as the driver assumes that police radar is being operated from somewhere nearby, and the drone has served its purpose. However, only limited research has been performed on the effectiveness of unmanned radar, and the studies conducted in work zones have only been in long-term work zones with the same configuration for several days or more. Additionally, VDOT has not studied the impact of its new unmanned radar units nor that of police presence on traffic in work zones. These factors, the unique traffic characteristics of Interstate 81, and the roles that unmanned radar and police presence can play in reducing speeds and accidents render this topic worthy of study.

Interstate 81 has many characteristics that limit the application of results from other studies of unmanned radar and police presence to its work zones. First, radar detectors are illegal in Virginia, unlike states in which past research has been conducted. Unofficial estimates from VDOT and the Virginia State Police indicate that approximately 15% to 25% of the vehicles on Virginia's section of Interstate 81 use radar detectors. Second, truck traffic on Interstate 81 is heavier than on most freeways. The American Trucking Association reports that it is among the top ten trucking routes in the country. Trucks typically constitute thirty to thirty-five percent of the total traffic volume on Interstate 81. Other studies on the effectiveness of unmanned radar have not only been conducted on highways with considerably less truck traffic, but have also revealed that the use of radar detectors is more prevalent among trucks than with cars. Lastly, Interstate 81 traverses rolling to mountainous terrain, considerably more rugged than that of most freeways. The terrain, coupled with the high volume of trucks, creates traffic conditions that are storied among regular drivers of Interstate 81 and are somewhat unique when compared to most freeways. Most of the research on real and simulated law enforcement presence has been conducted on freeways in relatively level terrain.

While work zones are a daily occurrence on Interstate 81, their presence will soon increase tremendously. Virginia plans to widen and reconstruct its 325-mile section of Interstate 81 over the next twenty years. The most heavily traveled sections, in the Bristol and Roanoke-Salem areas, should be under construction in three to four years. Thus, these sections of Interstate 81 constitute the most appropriate locations for research on the effectiveness of unmanned radar and police presence as speed control techniques in work zones, as it is hoped that the results of this research will be applied to work zones on Interstate 81.

1.3 Research Objectives

The goal of this research effort is to determine the effectiveness of unmanned radar and police presence as speed control techniques in work zones. As stated in the previous section, the studies will be conducted on Interstate 81, rendering their results most applicable to work zones on this highway; however, the information gleaned from this research will have some application to all freeways in Virginia, and to sites in other states as well.

The impact of simulated and real police presence on traffic in work zones will be assessed in a quantitative manner using the following measures of effectiveness:

- *Change in mean speed of traffic entering the work zone*
- *Change in standard deviation of speed (speed variance)*
- *Change in percent of traffic exceeding 65 miles per hour*
- *Change in percent of traffic exceeding 55 miles per hour*
- *Change in eighty-fifth percentile speed*

The data collection will be structured so that these measures can be considered for cars and trucks separately, as well as together. Conclusions will be drawn from the data listed above, as well as information gathered in this research effort, on how to best use these speed control techniques to provide the maximum safety benefit. A review of the literature and past research on speed control techniques in freeway work zones, with particular attention paid to studies of unmanned radar and of police presence, lays the groundwork for examining the data collected in this project. Observations, both quantitative and qualitative, made in the data collection effort will provide insight into the results of the data collection as well as capture traffic behaviors that may not be evident from the analysis of the collected speed data. Several types of work zones will be studied in order to maximize the versatility of the data collected and the comparisons among speed control techniques, locations of their deployment relative to the work zone, and work zone configurations.

1.4 Organization of This Thesis

This thesis is organized into six chapters. The first chapter introduces the topic of work zone safety, states the constant need for improvements in the field, and outlines the research objectives. Chapter two presents background on highway work zones and the role speed plays in highway safety. The remainder of the chapter provides an overview of the effectiveness of many common techniques introduced to control speeds in work zones. Chapter three covers the experiment design, data collection methodology, and the factors in the determination of sites selected for study. Testing for statistically significant differences between sites and among the conditions at particular sites, and interpretation of the results are covered in chapter four. Chapter five provides an overview of the impact of work zones on accidents, costs, benefits, and level of service. The sixth chapter includes conclusions and their limitations, and recommendations for further research. This chapter is followed by a list of references used in this report. Appendices include sample traffic control plans, traffic volume information for the study sites, statistical testing of the speed data, and conditions at the study sites.

Chapter 2 Literature Review

2.1 Highway Work Zones

Highway work zones are fundamental components of an infrastructure and can be encountered by motorists at virtually any time and any place in their travels. Performing maintenance, rehabilitation, and reconstruction operations on a highway requires the use of work zones. The work performed within these zones ranges from ordinary maintenance operations, such as pothole patching and shoulder mowing, to replacement of bridges that carry traffic, and construction of adjacent lanes to increase capacity.

A work zone denotes the general location of a work activity or the subject of work-area traffic control. The term *work zone* came into common use when the Federal Highway Administration conducted its first work zone training course in 1974. Through general use over the years, *work zone* has come to mean anything from the actual space in which a construction or maintenance activity is taking place to the entire length of roadway that experiences some impact from the work itself. Thus, work zones can be said to include all upstream (prior to the area of work) signing and any queues that may form as a result of the traffic control necessary for the actual work to proceed. Subsequently, the term *traffic control zone*, also referred to as *temporary traffic control zone*, was created to provide clarification. A *traffic control zone* for temporary traffic control at a work site is the entire section of roadway over which control related to the work operation is exercised and in which any temporary traffic control devices are placed (1). The definition of *work zone*, as used in this paper, corresponds to that of *traffic control zone*. Thus, a work zone begins at the first warning signs relevant to the work operation seen by traffic (typically “Road Work Ahead”), and ends when traffic is restored to its normal routine downstream of the work site.

A *traffic control plan (TCP)* outlines the changes to normal traffic flow needed to allow road work to proceed. This plan can range from elaborate large-scale drawings of the affected area to a short description of the site and corresponding temporary traffic control in paragraph form. The TCP specifies the locations of all traffic control devices, such as signs, cones, drums, and barricades, needed to direct traffic from its usual pattern for the purposes of establishing a work zone. Depending on the nature of the road work, temporary closure of shoulders or lanes may be required. The Manual on Uniform Traffic Control Devices (MUTCD), published by the Federal Highway Administration, contains general guidelines for the layout of work zones (2). Many states have published books, such as the Virginia Work Area Protection Manual, which supplement MUTCD and provide TCPs for common types of work zone configurations (3).

One consideration in the development of a traffic control plan is the speed at which traffic will be traveling through the work zone. The distances between warning signs, length of the transition for a lane closure, and spacing of cones along a closure, among other parameters, are all functions of speed. For example, the faster a motorist travels, the greater the distance must be to allow the driver to recognize, comprehend, and react to messages on signs. It is obvious that the faster traffic travels through a work zone, the higher the safety risk is to both traffic and the work crew itself, and thus the speed of traffic is of paramount concern to those involved in all aspects of planning and implementation of work zones.

2.2 Speeds in Work Zones

The speed at which a motorist elects to drive through a work zone is a function of driver recognition of, comprehension of, and respect for the work zone. A driver's perception of the safe speed is affected by many factors, including:

- temporary traffic control devices (signs, cones, drums)
- placement of the work zone with respect to traffic
- length, or distance, of the work zone
- duration, or amount of time present, of the work zone
- presence of workers and intensity of the work
- speed control techniques that may be in place

All of these factors represent deviations from normal driving conditions. Their existence provides additional information to motorists upon which a perception of the appropriate speed is developed. Of course, in addition to these factors, posted speed limits and advisory speed signs also impact the speed at which a driver chooses to travel in a particular work zone.

In many work zones, the responsible agency (usually a state transportation department) deems it prudent to reduce the speed limit and/or post an advisory speed lower than the speed limit. There are many compelling reasons for speed reductions in work zones, given the hazards of people and equipment present. The slower a vehicle travels, the less momentum it has, and therefore, the lower the magnitude of force dissipated in a collision. In addition, the amount of time available for perception of a hazard and appropriate reaction increases as speed decreases.

Speed variance is also of major concern in work zones. Classic research has shown that as speed variance increases, so do accident rates (4,5). Generally, the greater an individual vehicle's deviation is from the mean speed of its traffic stream, the higher its probability is of being involved in an accident.

The decision on speed reduction in work zones, while there may be traffic hazards present, must be balanced with the notion that reduction in speed limit may cause an increase in the range of speeds traveled through the work zone, and an increase in speed variance as well (6). Additionally, unreasonably low speed limits may lead to an increase in noncompliance. A recent research effort commissioned by the Transportation Research Board developed a rational procedure involving sound engineering judgment which determines the appropriate work zone speed limit (7). The procedure developed in this study yields a recommendation on speed limit reduction based on an assessment of the proximity of the work activity and associated traffic control devices to the traveled way and the factors present within the work area. These factors are made up of physical and geometric conditions that deviate from normal conditions and include:

- presence of workers unprotected by barriers
- uneven pavement edges or dropoffs
- lane width reductions
- horizontal curvatures of lower design speed (such as in lane shifts)
- reduced sight distance
- taper, or lane transition, lengths of lower design speed
- other unexpected conditions

A 1990 study addressed speed change patterns in a work zone on a four-lane section of I-57 near Mattoon, Illinois (8). The study intended to assess where drivers slow down and how well the reduced speeds were maintained through a long work zone. This particular work zone was four miles long, and the project on this section of gentle curves and grades in level to rolling terrain included two sets of bridge deck repairs, shoulder reconstruction, and pavement overlay. At the time of the speed studies, the only active work sites were at the two bridges (about 0.6 mile apart), and a lane closure 1.5 miles in length was in place to cover both. Average daily traffic was approximately 12,000 vehicles per day, with 22% trucks. A regulatory 45 mph work zone speed limit was in place immediately after the transition from two lanes to one lane, with flashers mounted atop the signs to indicate that the reduced speed limit was in effect. The normal speed for this section was 65 mph for cars and 55 mph for trucks.

Along the 1.7 mile study section, speed data were collected at 21 locations. The resulting speed profiles of the vehicles sampled can be placed into the following four groups (listed along with their respective percentages):

1. Considerable speed reduction near the speed limit signs (63%)
2. Considerable speed reduction when nearing the actual work site (11%)
3. No significant speed reduction in the work zone (11%)
4. No particular speed reduction pattern (15%)

The results showed that speed patterns were most affected when vehicles passed speed limit signs, or as they neared the actual work sites. A higher percentage of trucks maintained reduced speeds than did cars. As can be expected, the lowest average speeds occurred at the two active work sites. At the first site encountered, 93% of cars and 90% of trucks exceeded 45 mph, 56% of cars and 20% of trucks exceeded 55 mph, and 6% of cars and 1% of trucks exceeded 65 mph. At the second active site, 65% of cars and 47% of trucks exceeded 45 mph, 32% of cars and 5% of trucks exceeded 55 mph, and 6% of cars and 1% of trucks exceeded 65 mph.

The data collected in this study, are, of course, particular to the work zone studied. Any general conclusions about speed patterns would only be applicable to work zones of similar length and duration. No conclusions about other issues, such as speed variance (at particular locations within a work zone), can be drawn. At the time of this study, no law enforcement or unmanned radar was active in the area.

A study of the speed change patterns was conducted as a part of the previous study discussed (9). Therefore, the work zone characteristics are the same. This paper discusses the average speeds and speeds exceeding threshold levels at various influence points and speed changes between particular influence points. There were a total of thirteen influence points over a span of 8300 feet. These influence points were determined as a function of sign locations, the location of the transition, and the actual work sites themselves.

Rigorous statistical analysis was performed on the collected data. Standard deviations and errors, confidence levels, and ranges of observed data were calculated. However, the main conclusions from this study are somewhat apparent without the statistical analysis. The lowest level of speeds was observed at the actual work spaces within the 1.5 mile lane closure. After passing the work sites, speeds generally increased to previous levels, despite still being within a lane closure governed by a 45 mph speed limit. Vehicles generally traveled 3 to 13 mph slower within the work zone (lane closure) than prior to the beginning of the transition. At the bridges where work was actively pursued, 65% of cars and 47% of trucks were speeding.

The study's authors recommend that placement of speed limit signs pertaining to the work zone be based upon speed reduction profiles. While the logic behind this is simple (place work zone speed limit signs where they will have the highest recognition and compliance), implementation of this recommendation is difficult. Only a small percentage of freeway work zones may be similar enough to that in the study for its recommendations to be followed. Otherwise, the speed reduction profiles can only be assessed after the work zone is in place, which is after the ideal time to implement reduced speed limits. The authors do state that speed profile data should be collected from other work zones to validate their study. Speed variance at particular locations was not addressed, and no active law enforcement was in place during the data collection.

As highlighted by the Illinois study just discussed, drivers determine their speed based more on roadway conditions than on the posted speed limit (10). Therefore, the determination of the work zone speed limit should be based on a rational evaluation of these conditions. The improper setting of work zone speed limits, particularly limits set unreasonably low, or left in place after the work activity is removed, has caused driver respect for work zones and speed limits within them to suffer (11). Generally, mean speeds through work zones, without the presence of speed control techniques, exceed the posted speed limit (6,8,10,11).

Speeding in work zones is part of an overall speeding problem on America's highways. The National Highway Traffic Safety Administration (NHTSA) studied public perceptions on speeding in 1989, soon after the speed limit on rural interstate highways was raised from 55 miles per hour to 65 miles per hour (12). Focus group discussions held by NHTSA revealed that "the public, as a whole, does not view speeding as a serious traffic offense." The participants in the discussions did not recognize their personal safety risks incurred by speeding, and speeding was generally viewed as acceptable behavior as long as the driver maintains control of the vehicle. The NHTSA report concluded that "the public sees speed limits only as guidelines and not laws that will be strictly enforced," and that there is a lack of public support for enforcement of speed limits.

2.3 Speed Control Techniques in Freeway Work Zones

Speed control techniques can play an important role in reducing accidents due to driver inattention and excessive speed by reducing speeds and speed variance. A *speed control technique* is a method employed by a transportation and/or law enforcement agency with the intention of slowing traffic. Several speed control techniques have been studied, and the results of some of these studies are discussed here. The techniques most commonly studied, and used, include (in no particular order):

- Static Signs (such as speeding in work zone fine sign)
- Changeable Message Sign
- Flagging (both MUTCD and ‘innovative’ techniques)
- Lane Width Reduction
- Rumble Strips and Speed Bumps
- Iowa Weave section (lower design reverse curve)
- Transverse Pavement Striping
- Speed Monitoring Display
- Police Enforcement (of various forms)
- Unmanned or drone radar

Lowering vehicle speeds should increase safety by giving drivers more time to react to other drivers’ responses to the work zone and to any queues that may form. Slowing drivers down should increase the amount of time they have available to brake in the event of a queue or other rapid deceleration of traffic. The fact that the majority of work zone accidents (57%) on Interstate 81 in Virginia from 1991 to 1994 were rear-end collisions underscores the importance of proper speed control techniques (13).

Speed control techniques should aim to reduce both speeds and speed variance. The effectiveness of speed control techniques in work zones is measured by comparing data from before and after implementation (control and treatment). Parameters typically used as measures of effectiveness are mean speed, speed variance, percent of traffic exceeding speed limit, and percent exceeding high speed thresholds. This section of the literature review reports on the effectiveness of various speed control techniques other than unmanned radar. The results discussed in this review, unless otherwise noted, pertain to work zones on freeways only. The following subsections discuss commonly used freeway work zone speed control techniques other than unmanned radar and police presence, which will be discussed in the next section of this report.

2.3.1 Flagging

The effects of two types of flagging techniques on speeds in work zones have been studied extensively. These are the flagging procedure according to the Manual on Uniform Traffic Control Devices (MUTCD), and an "innovative" flagging procedure. The latter method augments MUTCD flagging by positioning the flagger next to a speed sign (either regulatory or advisory) and having the flagger point to the speed sign with one hand while flagging with the other. This procedure has also been called the "alert and slow" method. With this "innovative" method, more effort is directed toward alerting motorists to the appropriate speed.

A study was conducted in 1985 at several freeway work zones in Texas, and the two flagging methods were compared (6). Among the three sites studied, flagging according to MUTCD created reductions in the mean speed of traffic of 3 to 7 mph when compared with the null option. Innovative flagging created reductions of 5 to 13 mph. The smallest reductions for both methods occurred at the one urban site considered.

A subsequent report noted implementation considerations and practical limitations to flagging for speed control at freeway work zones (11). The report states that flaggers must be well-trained, properly attired, and relieved frequently, and should be stationed adjacent to speed signs to maximize their effectiveness. This treatment is most effective for short-term (less than one day), short length (less than one mile) lane closures, and was most beneficial on non-limited access highways. Flagging during inclement weather and at night have serious limitations and safety concerns. Additionally, flagging may not be appropriate if "speeds are too high, sight distance is limited, or there is no room for the flagger to stand" at least eight to ten feet away from open lanes.

Research conducted in work zones on Interstate 495 in Wilmington, Delaware in 1987 found less impressive results than did previous studies for both flagging procedures (14). Two work zone configurations were studied on this three-lane section: right lane closed, and left and center lanes closed. In the single lane closure, innovative flagging caused a reduction in mean speed of less than 2 mph, while an increase of over 4 mph was observed with MUTCD flagging. In the double lane closure, the mean speed decreased by approximately 6 mph with innovative flagging, while it increased by over 3 mph when MUTCD flagging was used.

An innovative flagging procedure was tested on a section of Interstate 90 near Sioux Falls, South Dakota (15). The average daily traffic was approximately 9000 vehicles per day with 18% trucks. In addition to using the 'alert and slow' flagging procedure, the flaggers held an 18-inch square sign paddle with their free hand. This paddle was a 45 mph advisory plate, such as the one mounted below the transition sign as described in the previous paragraph. Although previous research on the 'innovative' flagging technique had flaggers standing adjacent to, and pointing at with their free hand, a post-mounted speed sign, the intention was the same: to reduce traffic speeds by directly bringing the drivers attention to the safe speed. Results from this study were similar to those previously conducted on innovative flagging on freeways. The mean speed at the beginning of the transition dropped from 58.9 mph to 43.7 mph with the innovative flagging procedure. At the end of the transition, the mean speed dropped from 57.1 mph to 46.0 mph. The reductions of -15.2 mph at the beginning of the transition and -11.1 mph at the full lane closure were both statistically significant. The flagging procedure used in this test proved highly effective in reducing speeds, comparable to law enforcement in terms of its effectiveness. It is important to note that "the flagger must follow the proper flagging procedure...when using flagging, it is very important that the flaggers be properly trained and motivated in order to achieve maximum effectiveness." Flagger behavior, attitude, and location must be emphasized, and consistency and fatigue monitored, to minimize the hazard for the flaggers and motorists, and to maximize the speed reduction benefits.

Overall, the effect of flagging on speeds in freeway work zones appears to be highly dependent on the flagging technique used. More favorable results were found with the innovative flagging technique than with flagging according to MUTCD. Among the many sites and work zone configurations studied, and variations on the innovative flagging procedure, mean speed reductions over the range of 2 to 15 mph were observed. MUTCD flagging has produced mixed results, with increases in mean speed as high as 6 mph, and decreases of similar magnitude. Additionally, previous research on flagging has not typically presented its effects on speed variance.

2.3.2 Lane Width Reduction

Creation of an effective lane width reduction by “funneling,” or narrowing the available travelway through a work zone, has been employed as a speed control technique. The 1985 Texas study tested effective lane width reductions (LWR) from a lane width of 14 feet to 12.5 feet and to 11.5 feet (6). Reductions in mean speed of traffic for both rural freeway locations were approximately 2 mph for the 12.5 foot travel path; with the 11.5 foot travel path a reduction of about 2 mph at one site was observed, and a reduction of 5 mph was noted at the other rural site. At the urban freeway work zone, the mean speed increased insignificantly, by less than 1 mph, for each reduced lane width studied.

The body of research on LWR as a speed control technique in freeway work zones generally notes minimal reductions in mean speed, and some studies have shown an increase in speed variance (10). This change in variance may be due to a wide range of driver perceptions about shy zones, the distance between a vehicle and objects next to the vehicle’s path. While this speed control option is relatively simple to implement, and a wide range of devices (cones, barrels, pavement marking) can be used, a high level of attention must be paid to proper installation and maintenance. Workers are exposed to traffic during installation and the frequent maintenance task of resetting the devices after being struck by passing vehicles, particularly wideloads (11). Speed reductions have been modest, and considering the possibility of increasing speed variance and the inconvenience imposed on wideloads, this technique has limited application.

2.3.3 Speed Monitoring Display

A speed monitoring display was tested on a section of I-90 near Sioux Falls, South Dakota in advance of a right lane closure (15). This work site was also used for testing the innovative flagging procedure described previously. The display, with sign and radar, was installed approximately 350 feet before the beginning of the transition of the right lane closure. Drivers had passed signs, one mile upstream, that reduced the speed limit from 65 mph to 55 mph. Immediately before measurement of their speeds, drivers had just passed a lane transition symbol sign which had a 45 mph advisory speed plate attached immediately below. This system constitutes a dynamic form of speed control in that a motorist’s speed is measured and displayed by the device.

Speeds were observed before and after display installation at three locations: in advance of the first work zone signs, at the beginning of the transition, and approximately 670 feet later, at the end of the transition. An analysis of variance statistical analysis was performed on the collected data, in part to correct for the differences in the observed mean speeds at the upstream data collection point between the before and after scenarios. Before installation of the speed monitoring display, the mean speed at the beginning of the transition was 59.0 mph, while after installation the mean speed was 54.3 mph. At the end of the transition, the mean speed dropped from 57.8 mph to 54.0 mph. The reductions of -4.7 mph at the beginning of the transition and -3.8 mph at the full lane closure were both statistically significant. It is interesting to note that in the before condition, 0.9% of the vehicles were still in the right lane at the beginning of the transition, while this figure rose to

2.1% when the speed monitoring display was used. This undesirable change may be due to some drivers attention being diverted to identifying and understanding the speed monitoring display. The researchers also noted that the location of the display in close proximity to many other traffic control devices may have reduced its effectiveness, and that this technique should be further studied to determine optimum assembly and optimum location of the display.

2.3.4 Changeable Message Signs

Portable changeable message signs (CMS), also called variable message signs, have been used at work zones to display information on speed, delays, or other downstream conditions for many years. The 1985 Texas study found reductions in mean speed ranging from less than 1 mph to about 5 mph when messages were displayed on a CMS prior to the lane closure (6). Two types of messages were tested; one concerning only speed, and one concerning speed and information about the upcoming work zone. No significant differences in mean speed changes were observed between the two message types. As with the innovative flagging technique, the rural sites experienced greater speed reductions than did the urban site in the study.

In 1986, a study was conducted on Interstate 75 in Kentucky for which the primary focus was to evaluate various means of encouraging motorists to merge at an increased distance before a lane closure (16). However, CMS was studied, and some speed data was collected. Mean speed changes immediately after the sign, placed well before the taper, ranged from an increase of 1 mph to a reduction of 3 mph.

Compared to innovative flagging and proper law enforcement, only modest speed reductions were obtained through the use of CMS (11). The type of message displayed had little effect. While the CMS has a high degree of versatility in terms of weather, lighting, and other environmental conditions, it also has high service requirements and leasing/operating costs.

A study was conducted in 1992 and 1993 at several freeway work zones in Virginia (17). This study applied a new twist: responsiveness to traffic. Its intention was to assess the effectiveness of CMS on speeds in work zones, particularly targeting vehicles traveling higher than the posted speed limit. All sites studied had normal speed limits of 65 mph which were lowered to 55 mph for the work zones. The speed control device used in this study consisted of a radar-controlled changeable message sign, which upon sensing the speed of an approaching vehicle to be above the speed limit, displayed a message to that effect. Thus, a dynamic form of speed control signing was developed. The following four messages were tested:

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

Speeds were observed at three locations at each site: immediately before the work zone (station 1), just after the full lane closure (station 2), and just before the end of the work zone (station 3). Three speed profile characteristics, using an analysis of variance procedure, were evaluated: average speed, 85th percentile speeds, and speed variances. In addition, odds ratios for vehicles speeding in the before condition (no CMS) and after condition (CMS in use) were calculated. The significance levels of the different messages varied among the three measures of effectiveness. According to the study report, “when directly compared, there were no significant differences between the four messages with regard to their effect on high speed vehicles as well as the whole population.” However, the study’s authors presented general conclusions comparing the four messages, and recommended “you are speeding slow down” for further implementation. Since the primary quantitative form of evaluation was the use of odds ratios, and not reductions in mean

speed, comparison with results of other speed control technique studies is difficult. For example, average speeds before and after CMS installation are reported only at each site, and not overall. However, a study of these data reveal reductions in average speeds through CMS, using the recommended message of “you are speeding slow down,” in a range (among the seven sites) of -1.4 mph to -4.6 mph at station 1, -3.5 mph to -6.6 mph at station 2 (nearest the actual work), and -3.3 to -9.3 mph at station 3. In these tests, the changes in speed variance produced by the CMS ranged from +4.5 mph to -15.0 mph at station 1, +3.1 mph to -14.7 mph at station 2, and +1.6 mph to -20.3 mph at station 3.
At a 95% confidence level, all of the messages produced statistically significant reductions in average speeds of vehicles traveling faster than 59 mph in a freeway work zone posted at a speed limit of 55 mph, when compared to standard static signing. Overall, the CMS has some speed reduction potential in freeway work zones, as well as the likelihood (but not guarantee) of reducing speed variance.

The recommendations on the best use of responsive CMS as a speed control device in work zones state that the threshold speed for activation should be set at 3 mph over the posted speed limit. The CMS should be placed just before the beginning of the actual work activity area, but unobstructed by other signs and such that it can obtain as much of the driver’s attention as possible. The effectiveness of the CMS was studied for periods of up to one week. Further research recommendations from the authors include assessment over longer periods, as well as suggestions for further testing of CMS effectiveness, such as: when used only during critical periods in a long-term project (such as when conditions or work zone geometrics change), periodical changing of messages, various reduced speed limits, day or night operation (only daytime operation was tested), and work zone length and type.

2.3.5 Rumble Strips

Another speed control device that has been tested and deployed in work zones is a portable rumble strip or series thereof, or speed bumps. However, most of the studies of portable rumble strips in work zones and their effect on traffic have been conducted on two-way two-lane roads. Such studies have shown that portable rumble strips had only minimal effect on speeds. One such study showed a reduction in mean speed of less than 2 mph (6). One study conducted in a freeway work zone utilized a series of portable rumble strips at decreasing spacing as traffic approached a lane closure (16). The stated purpose of the study was to provide additional motivation for drivers to merge into the open lane before the lane closure. While researchers noted some decrease in mean speed, due to the analysis methodology used, as speed measurement was not a primary focus of the effort, the effect of the rumble strips on speed could not be conclusively determined.

Rumble strips have been primarily tested and used on two-way two-lane rural roads. This may be due in part to the possibility of drivers swerving to avoid the devices on multilane highways. The studies conducted on two-lane roads have not shown consistent reductions in speed or speed variance upon installation of the rumble strips. An FHWA report recommends that rumble strips be used only for unusual situations (18).

2.3.6 Summary: Past Research on Common Speed Control Techniques

Table 2.1 presents a summary of the effectiveness of speed control techniques in freeway work zones just discussed, as determined by previous research.

Table 2.1 Mean Speed Changes For Various Techniques

Sources: (6,10,11,14,15,16)

Speed Control Technique	Change in Mean Speed
Flagging (MUTCD)	**-7 to +6 mph**
Flagging (Innovative)	**-15 to -2 mph**
Lane Width Reduction	**-5 to 0 mph**
Speed Monitoring Display	**-5 to 0 mph**
Changeable Message Signs	**-6 to +1 mph**

The speeds referred to in Table 2.1 are measured at or near the beginning of the constriction on traffic, such as the beginning of a lane closure, shoulder closure, or temporary detour. There are many reasons why changes in mean speed of traffic are expressed in ranges. As is the case with the data collected for this report, the study environments of previous research on speed control techniques in work zones covered a wide range of work zone types, configuration, and traffic volumes. Data collection for studies on speed control methods typically occurs at several work zones covering such a range of parameters. Changes in mean speed, as well as other measures of effectiveness, that can be expected from deployment of a work zone speed control technique vary depending upon physical characteristics of the particular work site. The impact of these physical characteristics on traffic patterns is reflected in the range of speed changes among sites studied.

2.4 Police Presence and Unmanned Radar Techniques

The presence of police, and the threat of it, have been commonly used to encourage drivers to slow down in work zones. These techniques can take many forms, such as a patrol car stationed strategically in or near a work zone, a patrol car circulating through the work zone, or the deployment of an unmanned radar transmitter to simulate police presence. An enforcement strategy should maximize its speeding deterrent capabilities and increase a driver's perception of risk of apprehension for violation of traffic laws.

Radar detectors are used by some drivers in an effort to identify enforcement measures (radar) and react accordingly. Radar detector use is widespread and varies among types of vehicles and type of highway. A 1990 study conducted by the Insurance Institute for Highway Safety found that on Interstate highways in Maryland, eleven percent of the vehicles were equipped with radar detectors, and in Virginia the comparable figure was fourteen percent (12). This study also found that vehicles with radar detectors had a higher rate of exceeding the speed limit than did vehicles without radar detectors. A study conducted on Interstate 75 in Kentucky in 1987 found that forty-two percent of trucks and eleven percent of cars carried radar detectors (19). Unofficial estimates from the Virginia State Police place radar detector use on Interstate 81 at fifteen to twenty-five percent. While radar use does not affect all drivers directly, it does reach a significant percentage of traffic.

In 1991, the National Highway Traffic Safety Administration (NHTSA) developed guidelines for law enforcement agencies pertaining to the use of unmanned, or drone, radar installations as a speed limit enforcement strategy (12). The NHTSA report emphasized that drone radar should be a component of an agency's overall traffic law enforcement plan. According to NHTSA, a policy on drone radar use should include the following components:

- Drone radar must be a part of an agency's speed enforcement efforts
- Selection of a site for drone radar use should be based on problem identification
- The drone radar unit and its use must comply with Federal Communications Commission (FCC) rules
- The drone radar must be under local control and supervision
- The drone radar program should be evaluated

The NHTSA report states that "drone radar can be viewed as an additional tool available to the law enforcement community" to increase the public perception of apprehension. "Caution must be exercised, however, so that agencies do not embark upon a policy of widespread and unlimited use of drone radar. Such a practice would defeat the purpose of its selective and controlled use and would also constitute a violation of FCC rules." Deployment locations should be determined selectively to provide the greatest benefit and maintain the effectiveness of the technique. Three types of sites are recommended for consideration by NHTSA:

- Locations with high accident rates in which speeding and speed-related violations are commonly contributing factors to accidents
- Construction and maintenance work zones

- Roadway locations not suitable for other means of speed limit enforcement, such as in urban areas where shoulders are used as travel lanes and thus are not safe locations for apprehension

The use of drone radar considered in this study falls into the second of these three categories, as the Virginia Department of Transportation intends to reduce speeding in work zones. This section of the report reviews past studies on various forms of police presence and unmanned radar use.

2.4.1 Police Presence

The presence of a police patrol car as a speed control technique was studied in three freeway work zones in 1985 (6). At two rural sites, a stationary patrol car with lights and radar off was placed on the side of the road, highly visible to traffic. At an urban site, in addition to the above strategy, the effects of a stationary patrol car with emergency lights on, and a stationary patrol car with radar on, were also studied. The cars were typical state police / highway patrol marked cars. This study used the typical two-station layout seen in most other work zone speed control studies, and the reported data reflect drivers' immediate responses to the speed control method (speeds at station 2).

At the rural freeway site with a left lane closure, the mean speed of traffic was reduced by 9 mph, from 60 mph to 51 mph, when a stationary patrol car without lights or radar in operation was present. During the study period, traffic volumes ranged from 900 to 1400 vehicles per hour, with 10% trucks, and the speed limit had been reduced from 55 mph to 45 mph for the work zone. Another rural freeway site with similar traffic characteristics and both shoulders closed was studied. When the stationary patrol car with lights and radar off was deployed, a reduction in mean speed of 5 mph, from 56 mph to 51 mph, was observed. The speed limit at this site had also been reduced from 55 mph to 45 mph for the work zone. An urban freeway site where the work zone traffic control consisted of lane shifts onto a temporary detour, with no reduction in the number of lanes, was studied employing three types of police presence. A stationary patrol car with lights and radar off caused a reduction in mean speed of 3 mph, from 60 mph to 57 mph. When the car's lights were on, the mean speed reduction was 4 mph, and when lights and radar were on, the mean speed decreased by 6 mph. This site had volumes ranging from 1300 vph to 1700 vph, with a 20% truck composition during the study.

In summary of the 1985 Texas study, reductions in mean speed of 3 mph to 9 mph were observed when law enforcement was present at the beginning of the work zone. The reduction varied from site to site, and among work zone types. At the site where several forms of police presence were tested, the greatest benefit was realized when the patrol car was positioned in a location clearly visible to oncoming traffic, with lights and radar on. The results presented by the study did not explore effects on cars and trucks separately, nor did the study examine the issue of speed variance.

A subsequent study considered effectiveness and implementation concerns of many speed control techniques (11). Relatively large reductions in speeds are possible when a patrol car is exclusively devoted to a work zone, when compared to other speed control methods. However, this method has a relatively high cost in its need for a trooper and a vehicle to be present during its use. In Virginia, this cost concern is further exacerbated by the fact that troopers perform the work in addition to their regular duties and are therefore paid at overtime rates. A high level of coordination and cooperation among many people from the highway agency and police force is required for successful deployment.

The greatest effectiveness was achieved by visibly stationing a patrol car near a speed sign. For night operations, it is recommended that the patrol car's overhead emergency lights be in operation to increase effectiveness; during the day, the impact of lights is negligible. It is also interesting to note that a circulating patrol car, also studied in the previous Texas study, was ineffective in reducing traffic speeds. The study's authors state that some citations must be issued to maintain long-term effectiveness. However, the patrol car is effective only when in place, so attempts to pursue violators should be reserved for the most egregious offenders. Other points raised by the study in order to maximize effectiveness are to have the trooper present as much as possible, particularly for long-term projects, and to frequently vary the patrol car's location within the work zone.

2.4.2 Unmanned Radar

A study on unmanned radar installations was conducted along a six-lane urban section of I-75 in northern Kentucky in 1987 (19). The thirteen-mile highway was broken into sections for the purposes of the study. Section 1 was nine miles in length, speed limit 55 mph, and had six unmanned radar units providing coverage over approximately half of this nine-mile section. Section 2 was four miles long, and due to alignment constraints, it had a speed limit of 50 mph. Nine unmanned radar units provided full coverage to this section.

Speed data were collected with radar units on and off, at day and at night, and in each lane. In section 1, as described above, the average speed was reduced approximately 2 mph with radar on, while in section 2, no significant reduction occurred. A similar trend was noted with 85th percentile speeds when radar was active (reduced by 1.4 mph at section 1 and by 0.2 mph at section 2).

Average speed reductions were comparable among the lanes, but average speed reductions were slightly greater at night (1.9 mph) than during the day (1.3 mph) with radar on. However, at both sites, significant reductions in the numbers of vehicles exceeding certain speeds (i.e., 65 mph, 70 mph, 75 mph) were observed with radar on. In addition, a slight reduction in the standard deviation of observed speeds (and thus the speed variance) occurred at both locations. In all lanes, and at all times of day, a reduction in the standard deviation of observed speeds (ranging from 0.1 mph to 0.3 mph) was observed between radar off and radar on conditions.

In this study, an effort was made to capture the effect of radar detectors (legal in Kentucky). It was observed that 42% of trucks and 11% of cars had radar detectors. As expected, the unmanned radar had a tremendous impact on those vehicles. Among the vehicles that had radar detectors, average speeds decreased by 2.1 mph. A more significant reduction in the percent of these vehicles exceeding high speeds occurred. For example, the percent of vehicles exceeding 65 mph in the 55 mph speed limit section dropped from 36.4% to 19.8% among those with radar detectors. The overall traffic stream saw a reduction from 28.6% to 26.3%.

While this study provides much information on the use of unmanned radar installations, the use of such equipment in work zones was not covered. The issues of supplementing the unmanned radar with live law enforcement, as well as moving the locations of the units, were also not addressed. This study did provide good information on the percent of drivers exceeding threshold speeds and on speed variance, and concluded that unmanned radar units may be more effective in reducing the speeds of the fastest drivers than in reducing overall average speeds. The study concluded that drone radar “was an effective means of reducing the number of vehicles traveling at very high speeds, decreasing the speed variance between vehicles and perhaps reducing accidents.”

A study of the effect of unmanned radar on traffic in a work zone was conducted on southbound I-57 near Mattoon, Illinois, and the work zone layout and characteristics are the same as in other studies conducted at this work site as described in the previous section (20). The regular speed limits of 65 mph for cars and 55 mph for trucks were reduced to 45 mph for all vehicles immediately after the end of the transition from two lanes to one.

This effort is the first attempt to assess the effects of drone radar specifically in work zones. The following experiments, using drone radar units, were conducted:

1. Use of one unit to evaluate immediate (a few minutes) impact on speed
2. Use of one unit to evaluate short-term (over one hour) impact on speed
3. Use of two units to evaluate short-term (over one hour) impact on speed

Experiment one was conducted in September of 1989, and experiments two and three were conducted in June of 1990. During the experiments, the citizens band (CB) radio was monitored in order to gain additional insight about the awareness of the unmanned radar among drivers. To assess the effects of the radar, speed data were collected with radar off (before) and then radar on (after) in each experiment. In the first experiment, radar units were set up immediately before the first work zone signs (station 1) and near the actual work site (station 2). In the second and third experiments, designed to allow time for word of the radar to circulate among drivers, radar units were set up at three locations: prior to the first work zone signs (station 1), at the actual work site (station 2), and at the end of the work zone (station 3). Before and after data analysis was performed, for cars and for trucks, on average speeds, standard deviations of these, and percent exceeding threshold speeds (45, 50, 55, 60, 65, 70, and 75 mph).

In experiment 1 (immediate effect), before and after speeds were measured near each radar unit. At station 1, average speeds for cars were 75.1 mph (before) and 73.8 mph (after), while for trucks, average speeds were 64.8 mph (before) and 64.5 mph (after). At station 2, average speeds for cars were 63.8 mph (before) and 54.3 mph (after), while for trucks, average speeds were 58.5 mph (before) and 48.3 mph. This experiment showed that the immediate impact of drone radar usage is significant reductions in average speed within the work zone. Average speeds dropped 1.3 mph for cars and 0.3 mph for trucks at station 1, which do not constitute significant reductions. However, at station 2 (within the work zone), the average speed was reduced by 9.5 mph for cars and 10.2 mph for trucks. The standard deviations of speeds at station 2 did not change significantly for cars (12.4 mph before, 12.3 mph after) or trucks (8.6 mph before, 10.1 mph after).

In experiment 2 (short-term effect of one drone radar unit), the unit was operating at station 2. With cars, no reduction in average speed occurred over the two-hour radar operation window as compared with no radar. With trucks, the average speed dropped 1.2 mph from the before condition to the after. These reductions were not significant. Changes in standard deviations of speeds were not significant for cars (9.2 mph before, 9.4 mph after) or trucks (7.5 mph before, 7.0 mph after).

In experiment 3 (short-term effect of two drone radar units), units operated for about three hours near stations 2 and 3. The results of this test were broken into each of the three hours. At station 2, the changes in average speed for cars, from the before condition, were -1.8 mph for the first hour, 0.0 mph for the second hour, and +2.6 mph for the third hour. For trucks, the respective changes were -4.3 mph, -1.9 mph, and -1.1 mph. At station 3, the changes in average speed for cars, from the before condition, were -3.4 mph for the first hour, -2.6 mph for the second hour, and -0.1 mph for the third hour. For trucks, the respective changes were -4.0 mph, -4.7 mph, and -3.6 mph. At station 2, the standard deviations of speeds for cars were 9.6 mph for hour 1, 12.2 mph for hour 2, and 9.7 mph for hour 3, compared with 9.2 mph with no radar. For trucks, the respective figures were 6.6 mph, 9.9 mph, and 6.6 mph, compared with 7.5 mph with no radar. At station 3, the standard deviations of speeds for cars were 9.9 mph, 11.6 mph, and 10.2 mph, compared with 10.2 mph with no radar. For trucks, the respective figures were 7.9 mph, 8.1 mph, and 7.2 mph, compared with 9.7 mph with no radar. In this experiment, the percentage of high speeders was also reduced. For example, in the first hour, the percentage of cars exceeding 55 mph dropped from 34% to 27% at station 2, and from 80% to 58% at station 3. For trucks, the respective figures are 11% and 2%.

The overall results show that drone radar, when used for very short-term situations, can cause significant reductions in average speeds. However, as time passes, and the units remain stationary and in operation, these effects seem to taper off. From experiment 1, it was learned that the operation of drone radar within the work zone can cause reductions in average speeds of approximately 10 mph upon activation. Experiments 2 and 3 showed that over the next couple of hours, the average speeds creep toward the control (no radar) speeds (more so with cars). Monitoring of CB radio transmissions showed that, in experiment 2, some drivers had figured out by whom and from where the radar was being activated. Within 30 minutes of the start of this experiment, drivers were advising each other "of the absence of active speed limit enforcement, and they may not have felt threatened by the radar transmission." The third experiment, using two drone radar units spaced one mile apart, proved more difficult for drivers to figure out. Many CB conversations centered on determining where the radar was coming from, and how many radar units were present. Drivers found it much more difficult to determine whether the radar was from law enforcement or merely a drone in the two-unit experiment. Greater speed reductions, consistently for trucks but less so for cars, were achieved in experiment 3 than in experiment 2. By hour three, the average speed of cars had increased over the control condition, while among truck drivers, speeds were still significantly lower. This may be somewhat explained by the fact that use of radar detectors and CB radios is much more common in trucks than in cars. For example, Pigman's study on I-75 in Kentucky found that 11% of cars used radar detectors, compared with 42% of trucks.

The conclusions that can be drawn from this study are that drone radar is highly effective immediately after activation, and that over the long-term when drivers cannot determine its source, it is somewhat less effective. According to this study, the units should be stationed "to provide maximum threat of police presence...drone radar should 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 drone." The two-unit radar experiment caused significant reductions in the percentage of vehicles exceeding higher speeds, particularly among trucks.

A study of unmanned radar transmissions was performed at eight highway work zones in Texas in 1990 (21). These work zones ranged from shoulder closures to lane closures to temporary detours. Speed data were collected at three stations at each site: one immediately prior to the work zone signs, another at the beginning of the transition (in case of lane closure) or the point of constriction, and lastly, approximately 500 feet beyond the transition. The range of the radar transmissions was approximately 1000 feet prior to the transition or constriction, between stations 1 and 2. It is important to note that in this study, no visible law enforcement was present.

This study had two objectives: to determine the effect of radar signals on speed characteristics, and to document erratic behavior in the influenced area. The results of the study showed that the differences in average speeds (at station 3) between radar off and radar on conditions ranged from 0.0 mph to -1.6 mph among the eight work zones, however, the reductions were statistically significant at the 0.05 level at only two of the sites. The differences of the standard deviations of the observed speeds with radar off and radar on ranged from -0.2 to +0.8 mph, and again, these were statistically significant at only two of the eight sites included in the study. As a measure of how much drivers slow down for work zones, the differences between the radar off and radar on average speed changes from station 1 to station 3 ranged from -0.2 mph to -4.5 mph, with four of these differences being statistically significant. The differences in standard deviations of the speed changes between radar off and radar on ranged from +0.1 mph to +2.0 mph, suggesting that the range of driver reactions (speed reductions) to work zones is greater with radar on. The greatest effects of the radar transmissions were on trucks and on high speeders, which agrees with previous studies. The level of radar detector ownership is relatively high among these groups.

The authors state that because of the generally small reductions in speed observed with unmanned radar operations, “there is no way of discerning...how the site specific factors (traffic volume, work zone type, work speed limit) considered in this study influence the effectiveness of radar transmissions at work zones.” It is also concluded that, contrary to previous research, radar transmissions do not necessarily result in reductions in speed variance. On the issue of vehicle conflicts, due to driver reactions to the radar transmissions, observers noted the greatest increases in vehicle conflict rates at the sites where the differences between average speed in the work zone and the work zone speed limit were greatest. This may point to work zone speed limits being set too low at some locations.

Overall, this research produced similar results to those noted by Benekohal et al. (1990) in Illinois. Mean speeds in the work zone were reduced by 0.0 mph to 2.8 mph. In addition, a small increase in erratic driving maneuvers and vehicle conflicts was observed with the unmanned radar on. At the freeway sites, vehicle conflict rates increased by anywhere from less than 1% up to about 40%. However, in contrast to Benekohal’s study, standard deviation (and therefore, variance) of speeds did not necessarily decline with the use of unmanned radar. In this study, the changes in standard deviation of speeds when the unmanned radar was active when compared with the control (radar off) condition range from an increase of 0.7 mph to a decrease of 0.4 mph. While Benekohal’s study generally found that speed variance was reduced, it is not apparent why Ullman’s study showed less consistent changes in speed variance. However, the author has suggested that speed variance may be reduced due to the impact of unmanned radar units on high-speed vehicles (many of which carry radar detectors), causing the greatest speed reductions among the fastest vehicles.

This study shows that one can expect reductions in mean speeds with the use of one unmanned radar unit in a work zone of 2 to 3 mph, after the initial effect of activating the unit has worn off. However, it is important to note that the effect of the unmanned radar was greater, and longer lasting, on trucks than cars, and greater on high-speed vehicles than the entire driving population. In this study, the use of two unmanned radar units within a work zone, or a combination of unmanned radar and live radar, was not examined.

The authors of this report state that "since only a couple of studies of these types of devices have been performed to date, additional research and demonstration of their use at work zones will be necessary before a conclusion as to their applicability and effectiveness at work zones can be made." They also state that "there is no way of discerning, either statistically or through engineering judgment, how the site-specific factors considered in this study influence the effectiveness of radar transmissions at work zones."

2.4.3 Summary: Past Research on Police Presence and Unmanned Radar as Speed Control Techniques in Freeway Work Zones

There are many conclusions that can be drawn from the body of research on unmanned radar to date. The use of one unmanned radar unit is most effective in reducing speeds within the first few minutes of operation, with expected reductions in mean speed of approximately 10 mph. However, with time, as some drivers (particularly those with CB radios or radar detectors) figure out the nature of the radar, some of the initial speed reduction is lost. After an hour or more, one can expect minimal reductions in mean speed, in the neighborhood of 2 mph to 3 mph. The use of two units within a long work zone (perhaps one mile or more) has a greater and longer lasting effect than the use of one unit. With two units, it seems that drivers have more difficulty locating the source of the transmissions, as well as determining the nature (unmanned or 'live') of the transmission. The impact of unmanned radar on speed variance has not conclusively been determined.

While some research has shown minor, but consistent, reductions in variance, other studies have not shown consistency in this area.

Analysis of the speed data collected in the previous research shows that there is a greater impact of unmanned radar on the speeds of trucks than on cars, and on high-speed vehicles than on the entire vehicle population. This stands to reason considering that high-speed and commercial drivers are more likely to use radar detectors than the entire population. Drivers who speed excessively would have the obvious need for detection of radar in hopes of reducing the possibility of receiving a speeding ticket. Truckers are typically working against the clock and are paid according to the mileage covered. One effort that studied the changes in driving behavior when unmanned radar was used showed increases of up to 40% in erratic maneuvers and vehicle conflicts. However, past research does not provide conclusive information on the impact of site-specific work zone parameters (such as speed limit, type of work, highway alignment, traffic volume, and the percentage of heavy vehicles in the traffic stream) on the effectiveness of unmanned radar.

Many issues relating to the use of unmanned radar in work zones have not been addressed. These include assessing the mixing of unmanned radar with live law enforcement, the effect of frequent relocation of the transmitter within the work zone, attempting to determine the optimum transmitter location, the impact in short-term (less than twelve-hour) work zones, and the impact in mobile lane closures. This research effort addresses some of these issues, including mixing with live law enforcement, varying transmitter location, and the impact in short-term work zones. The next chapter details the methodology used in conducting research on unmanned radar as part of this effort.

Chapter 3 Methodology

3.1 Work Zone Parameters

A wide range of work zone types and speed control configurations dominate the highway construction and maintenance activities a motorist encounters on a freeway. Work zones can range from a mowing operation that requires two signs as the only temporary traffic control, to a detour that may require traffic to be routed onto the lanes in the opposing direction or off the freeway altogether (3).

Work zones can be classified into the following four categories:

- No change in the available travelway (such as a mowing operation)
- Shoulder closure (such as for guardrail maintenance or pavement widening)
- Lane closure (such as for a pothole patching or lane resurfacing operation)
- Freeway closure (such as a sinkhole repair operation for which traffic must be rerouted onto parallel facilities)

Other parameters can be used to categorize work zones. For example, the type of device delineating the lane or shoulder closure can range from cones (highly flexible upon impact) to concrete barrier, virtually impenetrable by traffic. The type of device used is a function of the duration of the work zone, the type of activity in the work zone, and the speed for which it is designed.

Lane and shoulder closures can also be classified as mobile or stationary. A mobile lane closure is commonly used in pavement marking operations where the entire work zone can move as a function of time. This type of closure has no cones, drums, or barriers other than the train of vehicles that follows the actual work vehicle. These following vehicles carry signs and electronic flashing arrow boards to inform motorists of the closure, as well as “crash cushions” which serve as impact attenuators in the case of an inattentive driver encroaching on the work zone. On the other hand, a stationary closure uses devices that delineate the work zone and typically remain stationary for the duration of the work zone, in addition to warning signs erected upstream of the closure.

A wide range of conditions were considered for study. These conditions include different types of work zone configurations, and locations and operational schemes for the speed control techniques. The study sites selected, and the related reasons, are explained in later in this chapter. However, the work zone conditions that are most relevant to the reconstruction of Interstate 81 are those where a lane must be closed, and those where a shoulder is closed using a concrete barrier. The former of these conditions is the most common work zone encountered and also has the most extensive accident history, while the latter will be the most frequent work zone configuration used when Interstate 81 is widened in the coming years.

3.2 Unmanned Radar Units

Unmanned, or drone, radar units provide the threat of law enforcement as a deterrent to speeding. The only vehicles directly influenced by this technique are those with radar detectors that receive the transmitted beam. It is arguable that more than the estimated 25% of vehicles on Interstate 81 that have radar detectors will be impacted, however. Some drivers, when passed by a vehicle that visibly has a radar detector, may choose to follow that vehicle at a “comfortable” distance. This distance may be from hillcrest to hillcrest, perhaps thousands of feet, so that if a state trooper decides to pursue the speeding vehicle with the radar detector, the driver following will be far enough behind as not to get “caught.” This driving technique provides the “benefit” of having a radar detector, namely the ability to speed and be aware of troopers (or drones) operating radar, while being far enough upstream of the vehicle with the radar detector so that the driver following can reduce speed before reaching the radar signal.

In April 1996, the Virginia Department of Transportation purchased several unmanned radar units (Checkpoint Model 2A, marketed by PM Design Labs of North Carolina) for use in and near work zones. The drones emit a continuous X-band (10.515 GHz - 10.525 GHz) radio signal. The unit has an effective range of up to 2500 feet in each direction, depending on the terrain and highway alignment. The unit is about seven inches long in its greatest dimension, and weighs about two pounds. It is gray-colored, and blends in well with metal sign posts and guardrail, and has magnets for mounting onto these surfaces. For the purposes of the study, the unmanned radar unit was mounted on a guardrail or metal sign post on the right shoulder of the directional lanes in which the work zone was located. The location in relation to the work zone for each site is noted on the site summaries in Appendix D.

3.3 Police Presence

As noted in the problem statement, the Virginia State Police have been employed by VDOT in an effort to encourage drivers to reduce their speeds and increase their alertness in work zones. Typically, this arrangement involves the use of funds allocated to the particular construction or maintenance project in which police presence is desired. VDOT uses these funds to pay the state police on a per-hour basis for providing a trooper on the project for a prescribed time period (typically the hours in which work is actively pursued). To avoid shifting resources away from other responsibilities, troopers are asked to volunteer to work overtime to be assigned to the highway work zone. The overtime pay rate and benefits are figured into the price that VDOT pays the state police to provide their services.

The service provided by the state police consists of a trooper present in the work zone during the requested time period. The presence of the vehicle and the operation of radar, at the trooper’s discretion, are intended to slow down traffic. However, the trooper also has discretion to apprehend violators and pursue reckless drivers as necessary. For the purposes of this study, the police vehicle was located on the right shoulder, visible to traffic, with radar in continuous operation, at a location relative to the work zone as described in the site summaries in later in this chapter. The radar signal is of the K-band (24.050 GHz - 24.250 GHz) and the Ka-band (34.200 GHz - 35.200 GHz) varieties. The police vehicle was a standard marked patrol car, a Ford Crown Victoria painted in shades of blue and gray with the words “STATE POLICE” and the state seal displayed prominently on the side. The type of vehicle used and its placement in this study are typical of state police presence in work zones on Interstate 81.

3.4 Data Collection Methodology

At a typical site, there were two conditions for which speed data were collected: one with radar off and one with radar on, in order to account for changes in speed due to the work zone itself, rather than the radar device. Additionally, the speed control technique, or condition, of police presence was considered when it could be arranged. Prevailing conditions, such as the speed limit, work activity, and weather at the time of data collection, were recorded. This information can be found in Appendix D. For each condition tested, data was collected at two points, or stations: one several hundred feet upstream of the influence zone of the radar device, (referred to as station 1), and one about 500 to 1000 feet into the influence zone (station 2). These locations were typically about 3000 feet apart. Placement of the radar device was varied among sites and conditions. A sign post or a guardrail beam on the right shoulder was the typical mounting location. As discussed in Section 3.4.2, each measured speed collected in this manner is accurate within 2.1 mph.

3.4.1 Sample Size

In each spot speed study, sufficient data was collected to ensure results at a 95% confidence level. The procedure from the Manual of Transportation Engineering Studies (22) for determining required sample sizes for spot speed studies was used. The equation is as follows:

$$N = (S \times K / E)^2 \quad \text{where} \tag{1}$$

N = *minimum sample size of desired speeds*

S = *estimated standard deviation (mph)*

K = *constant corresponding to the desired confidence level*

E = *permitted error in the average speed estimate (mph)*

A typical value used for *S*, for freeways, is 5.0 mph. The rolling terrain of Interstate 81 and its relatively high percentage of heavy vehicles result in a wide range of speeds. Therefore, the typical standard deviation of speeds on Interstate 81 may be higher than the average value for freeways of 5.0 mph as given by the manual. Based on the standard deviations from other studies, and to generously estimate sample size, a value of 7.0 mph will be used for *S* in equation 1. For a 95.0% level of confidence, $K = 1.96$. *E* reflects the precision of the observed speeds and is the maximum tolerance for errors in the data collection process. The manual states that typical values for *E* range from 1.0 mph to 5.0 mph. For the speed study technique used in this study, a value of 2.1 mph will be assumed for *E*, based on the calculations in the following subsection. Thus, the minimum sample size at the 95% confidence level, according to equation 1, is:

$$N = [(7.0)(1.96)/(2.1)]^2 = 42.68 = 43$$

To allow for the possibility of the standard deviation of speeds being higher than expected, minimum sample sizes of 50 for each condition of each experiment were used. The typical sample size ranges from 75 to 100 vehicles.

3.4.2 Data Collection Procedure

Radar and sensors were considered as instruments to collect speed data. However, the use of radar could possibly bias the data as drivers with radar detectors may respond to the signal and reduce their speeds, obviously an undesirable situation in a scientific experiment. The use of sensors proved infeasible due to the need for portability and quick setup. Therefore, data was collected using time-distance methods.

A person stationed off the road (inconspicuous to traffic) used a stopwatch and a measured distance at each station to determine speeds. Distance was measured by establishing two fixed points, or markers, along the road, and then using a measuring wheel off to the side to determine the distance. The time required for a vehicle to pass the two points was measured with a stopwatch. The time for each vehicle was recorded on paper for later calculation by dividing time into distance to obtain spot speed. To determine the error in this process, one must consider the distance of the "speed trap," the precision of the stopwatch, and human reaction time for stopping and starting the stopwatch. For example, a distance of 250 feet, stopwatches registering in hundredths of a second, and an assumed average reaction time variation of 0.10 seconds will yield speeds with an accuracy of within 3.1 feet per second, or 2.1 mph. Therefore, each measured speed was assumed to be within 2.1 mph of its true value. This level of accuracy is comparable to those of radar and sensors.

Upon setup of the two speed traps, the proper operation of the drone radar unit was checked using a radar detector. VDOT and the Virginia State Police have an agreement in which a radar detector, owned by VDOT, can be legally used in a state vehicle exclusively for this purpose.

Several strategies were employed to minimize errors and inconsistencies in the data collection process. Specifically, these strategies include:

- The speed traps employed at each data collection station were of the same length or approximately so. The length of the speed traps was in the range of 200 to 300 feet and a function of the availability of markers to distinguish the beginning and ending points.
- A systematic sampling procedure, sampling every *n*th vehicle, was employed to ensure the randomness of the sample. The value of *n* was determined in the field as a function of the time required to complete the recording of an individual observation.

- The time to conduct a particular study, for example a sample of 100 vehicles for the off phase and 100 vehicles for the on phase, typically took two to three hours. To minimize any effects of changes in traffic volume that may occur during the sampling period, the samples were collected in a mixed order. For example, the rotation may be 50 off, 50 on, 50 off, 50 on, for a given site.
- To minimize the possibility of errors due to differences in individual collectors' reaction times, the collectors were rotated between stations in a manner similar to that described above for changes in traffic volume.
- Ideally, the data collection effort should be as inconspicuous to traffic as is practical while ensuring accurate data collection. While the speed traps were being set up, the data collectors wore appropriate work zone attire, namely hardhats and orange vests for safety reasons. After setting up but before starting the data collection, the collectors removed their hardhats and vests and stood behind the deflection zone of the guardrail in a fill section, and behind the ditch line in a cut section. The data collection personnel were stationed about twenty feet away from moving traffic.

The patterns of individual vehicles, in addition to a random sample, can be analyzed by "tracking" through the work zone. This was accomplished by each person having a walkie-talkie so that the person located at station 1 could inform the data collector at station 2 as to which vehicles to sample. This also allows for analysis on cars and trucks (tractor-trailers) separately, as well as together.

To broaden the statistical analyses of the speed data, all vehicles were grouped into the categories of "cars" and "trucks." For the purposes of this study, any vehicle with the acceleration characteristics of vehicles other than cars were considered trucks. Therefore, the category of cars includes cars, pickup trucks, vans, and motorcycles. Vehicles classified as trucks include trucks of three axles or more, including tractor-trailers, as well as recreational vehicles and buses.

The greatest drawback to this data collection scheme was the need for ‘live’ bodies to be present during the data collection phase. However, it has been noted anecdotally that some drivers slow down when approaching road tubes. This plan allowed for relatively inconspicuous collection of traffic data (as opposed to the use of road tubes), and thus a high level of confidence in accurate and unbiased samples. One of the data collectors had to be a VDOT employee. This was due to the fact the radar detector used to verify operation and determine the range of the unmanned radar, under the agreement between the department of transportation and the state police, can only be used in a VDOT vehicle. Only VDOT employees can legally operate VDOT equipment; therefore, a VDOT employee was always part of the data collection team. However, this scenario also presented one of the problems in scheduling data collection, namely the commitment of an employee’s time to the data collection effort.

3.5 Site Selection Considerations

The initial intent of this study was to collect data among a wide range of work zone types and roadway conditions. However, as data collection efforts progressed, it became clear that many factors, both within the control of the investigators and external to the study, would affect the site selection process. The availability of work zones suitable for study, coordination required to make data collection possible, and the data collection method itself limited the number and range of sites studied.

A work zone of a given type had to be planned for one location for at least four hours at a time to be suitable for study under the data collection method selected. Thus, mobile lane closures could not be studied as a part of this effort. During the data collection period, stationary work zones, particularly lane closures, did not occur as frequently and for as long as had been anticipated. In recent years on Interstate 81, there were more bridge deck overlay projects, and more sections repaved during the day, than during the time allotted for this effort. In the late summer and early fall of 1996, no such bridge work, and relatively little repaving during the day, took place. Additionally, in 1996, the Virginia Department of Transportation (VDOT) shifted more road work to nighttime hours, when traffic volumes are lower, thus reducing the inconvenience to travelers and total user costs associated with work zones. Most of the repaving work on I-81 in Virginia in 1996 was performed at night. An effort was made to collect data in one of these situations; however, data collection proved too difficult without daylight. Identification of the vehicles approaching station two that had been timed upstream at the first station was nearly impossible at night. Therefore, the reduced availability of work zones and the limitations of the data collection method both affected the sites selected.

Work zones that were not in one place for more than a few days were the most desirable for study, as past research on the effectiveness of unmanned radar had taken place in long-term work zones in which the configuration did not change. Thus, sites 1 and 3, in which the lane closures were in place for just one day, were selected for study. Site 2, while a long-term construction zone, was selected for study because of its similarity to the type of work zones anticipated in the future widening and reconstruction of Interstate 81. This site involved a left shoulder closure of approximately one-half mile using safety-shaped concrete barrier service, and lane width reductions from twelve to eleven feet. This configuration will be prevalent when widening takes place in the median of the highway, and will be in place for several months at a time. Therefore, site 2 was highly relevant in terms of future work zone applications on I-81. Due to the police patrol employed periodically by VDOT at the site, which will likely be used in the future widening projects, it was also included in the study as a speed control technique.

It is important to consider that data collection in the “real world” is quite different from conducting a completely controlled experiment in a laboratory. Many factors that affect driver behavior, and therefore the data collected, cannot be accounted for or factored out of the field experiments. For this study, the highway was the laboratory, comprised of three key components: the highway itself, the vehicle, and the driver. Obviously, the highway is the only component of the experiment over which a significant degree of control can be exercised. Features that can be controlled are those of the work zone, including, but not limited to, the physical location and layout of the work zone, signs that provide advance warning to drivers of the conditions ahead, and the speed control techniques applied. Vehicles and their drivers constitute elements of the experiment that factors external to the data collection effort impact. In an effort to maximize control of the conditions on the highway, all studies took place in good weather and on dry pavement. Extreme conditions, such as work zones that occurred on steep extended grades or those where the location of ramps may have significantly impacted traffic flow, were not selected as study sites.

3.6 Site Descriptions

Based on the factors described in the previous section, three sites, covering six days of data collection, were studied. Table 3.1 provides a summary of all sites. More information on the traffic conditions during the studies at each of the sites is provided in appendix B.

Site 1 was located on Interstate 81 northbound in Botetourt County between exits 156 and 162. Data was collected on two consecutive days at this rural location. This site is referred to as sites 1A and 1B throughout this report to distinguish between the configurations used on each day. Site 1A was a left lane closure, while site 1B was a right lane closure in the same location on the next day. The sites were part of a fourteen-mile pavement rehabilitation project that lasted about eighteen months. However, the work zones on this project were set up and taken down on a daily basis as work occurred throughout the project, and the lane closures studied were in place only for the days of the studies. Additionally, the speed limit was lowered to 55 miles per hour (mph) during the prosecution of the work. A diagram of the temporary traffic control at this site can be found in Appendix A.

Site 2 was located on Interstate 81 northbound between exits 140 and 141 in Roanoke County. This long-term work zone was in place for replacement of narrow, deteriorating bridges over Mason Creek with wider structures. Specifically, this project had been underway for about thirteen months at the time of the studies. Data was collected on three separate days at this suburban site. The traffic control and work zone configuration, a left shoulder closure with concrete barrier, and lane width reductions of one foot for each lane were the same on each of the three days. Additionally, the speed limit had been reduced to 55 mph for the duration of the project, due to the concrete barrier and narrow lanes. The figures in this chapter refer to sites 2A, 2B, and 2C to distinguish between the various speed control techniques and configurations studied on each day. Study sites 2A and 2B were located immediately before the beginning of the barrier, while study site 2C was about one-half mile upstream of 2A and 2B so that two different drone radar locations could be studied. It is important to note that police presence is common at this work zone and that most drivers may expect it. The typical hours of police patrol as designated by VDOT were 7:00 am to 7:00 pm, Monday through Saturday. The troopers were given latitude to patrol the work zone in any manner they wished, varying their locations, operation of radar, and level of enforcement as they saw fit. Therefore, regular commuter traffic was exposed to police patrol and law enforcement on a daily basis.

Site 3 was located on Interstate 81 southbound between exits 162 and 167 in Botetourt County. The work at this rural location consisted of milling and resurfacing the left lane, requiring a left lane closure. This work was part of the annual paving schedule, and the work zone had not been in place prior to the day of the study. At this site, the 65 mph speed limit had been left in place. A diagram of the temporary traffic control used at this site can be found in Appendix A.

Tables that summarize the data collected at each site and figures that describe the prevailing conditions on each day of data collection, as well as diagrams of the sites, showing locations of the work zones, speed control techniques, and data collection stations can be found in Appendix D. The next chapter of this report presents a statistical analysis of these results, and tables that summarize the results of the analyses.