4.3 Effectiveness of Speed Control Techniques by Site

4.3.1 Effects at Site 1

Site 1 was located in a pavement rehabilitation project spanning fourteen miles for which the locations of the work zones changed daily. The speed limit was reduced to 55 mph when work was underway. Since the closures were on consecutive days in the same location, this site offered an opportunity to compare the effects of unmanned radar in a left lane closure and right lane closure in a short-term work zone. While police patrol existed sporadically throughout the fourteen-mile project, law enforcement was not a factor in this particular work zone. As explained below, desirable changes in all measures of effectiveness were observed.

Between observation stations (as traffic approached the left lane closure) the mean speed of traffic increased by 0.1 mph with the radar off, while it decreased by 1.4 mph with the radar on. Interestingly, a greater effect was observed as traffic approached the right lane closure. The mean speed of traffic decreased by 0.3 mph with the radar off, while it decreased by 2.6 mph with the radar on. As indicated in Table 4.2, the speed reductions in both work zone configurations with radar on were highly significant. While the difference in speed reductions between the two configurations with radar on was not statistically significant, some physical differences exist which may explain the greater speed reductions observed in the right lane closure. First, the shy zone, or clear zone, available to drivers is less in a right lane closure than in a left lane closure. The face of the guardrail on the left shoulder is approximately five feet from the edgeline of the lane, while the right shoulder is ten feet wide in the presence of guardrail. In each closure the lane width was about ten feet, as the normal twelve-foot lane is reduced to allow sufficient room for the paving machine in the closed lane and for the cones which serve as traffic control devices. Therefore, drivers in the left lane (right lane closure) had an open travelway of about fifteen feet, while in the opposing scenario the respective value is twenty feet. The narrower shy zone in the right lane closure may encourage drivers to slow down further. A related consideration which may explain the lower speeds in the right lane closure is that a driver in the open left lane must look across the vehicle to determine distance from cones and from the work itself. When the right lane is open, the traffic control devices and work area are on the drivers' left side, making these items more easily visible, providing a greater level of comfort and safety. The higher comfort and safety levels existent in the left lane closure may lead to drivers being comfortable traveling at a higher speed than in a right lane closure, where speed reductions are greater.

While the changes in the other measures of effectiveness which occurred were positive from a safety standpoint, they were generally not as significant as the changes in mean speed. Desirable changes in standard deviation of speed, as a measure of speed variance, did occur. It can be seen from Table 4.5, in the left lane closure, that the standard deviation increased by +0.4 mph between observation stations with the radar off, while a negligible increase of +0.1 mph occurred when the radar was on. In the right lane closure, the respective values were +0.1 mph and 0.0 mph. Thus, in both configurations, speed variance increased by a smaller amount when the unmanned radar was active than when no speed control technique was applied.

Greater reductions in percent of traffic exceeding the speed limit occurred between observation stations when the radar was on than when it was off. Taking data from Table 4.7, in the left lane closure, the percent of traffic exceeding 55 mph approaching the lane closure decreased by 4% with radar off, and by 10% with radar on. In the right lane closure, the respective values were 2% and 22%. The 22% decrease in percent of traffic speeding entering the right lane closure with radar on was highly significant.

Desirable reductions in eighty-fifth percentile speed also occurred with the use of unmanned radar. As indicated in Table 4.8, in the left lane closure, the eighty-fifth percentile speed increased negligibly (+0.2 mph) between observation stations with radar off, while with radar on a decrease of -0.9 mph was noted. In the right lane closure, a decrease of -0.9 mph occurred with radar off, while a decrease of -3.4 mph occurred with radar on.

At site 1, when unmanned radar was used, statistically significant reductions in mean speed occurred in both configurations. A statistically significant reduction in percent of traffic exceeding the speed limit was observed in the right lane closure, while in the left lane closure the reduction fell just short of being statistically significant. Generally, unmanned radar had greater effects on speeds in the right lane closure, for reasons previously discussed. In both configurations, greater speed reductions, smaller increases in speed variance, greater reductions in percent of traffic exceeding the speed limit, and greater reductions in the eighty-fifth percentile speed occurred when the speed control technique was applied.

4.3.2 Effects at Site 2

Site 2 consisted of a bridge widening and replacement project and the necessary approach work. The configuration of this work zone, consisting of a left shoulder closure using concrete barrier, had been fixed for approximately three months when data collection took place. Police presence and enforcement of the reduced speed limit (55 mph) were common at this site. These circumstances allowed an assessment of traffic behavior when police presence was expected, and a comparison of police presence with unmanned radar. Additionally, this type of traffic control will be commonplace when Interstate 81 is widened. Speed data were collected immediately before the beginning of the barrier under three conditions: no speed control, unmanned radar in operation, and a police vehicle stationed on the shoulder with radar on. Speed data were also collected six-tenths of a mile before the barrier with unmanned radar on and no speed control (radar off); however, station two was located immediately before the speed limit reduction, which may also have affected speeds.

In the scenario where speed control techniques were applied immediately before the barrier, between observation stations, the mean speed of traffic decreased by 2.0 mph with no speed control technique applied. With unmanned radar the reduction was 2.8 mph, while a police vehicle parked on the shoulder with lights off and radar on saw the mean speed decrease by 2.9 mph. All of these reductions were highly significant. Police patrol was typically provided at this site twelve hours daily (and on occasion when night operations were pursued). Due to the expectation of police presence by most drivers at this work zone, the mean speed dropped significantly even without any speed control technique. The reductions observed with unmanned radar and with police presence were nearly identical.

The standard deviation of speed, as traffic entered the work zone, decreased by 0.4 mph when no speed control technique was applied. Both when the unmanned radar was on and when the police car was present, a reduction of 0.7 mph occurred. The identical reductions experienced with unmanned radar and with police presence fell just short of being statistically significant. Speed variance decreased somewhat without speed control techniques, due at least in part to the expectation of law enforcement; however, greater decreases were observed with each of the speed control techniques.

Significant reductions in percent of traffic exceeding the speed limit were observed in all three conditions as traffic entered the work zone. With no speed control technique, the decrease was 15%, while with police presence a 17% decrease was observed. Both of these reductions were statistically significant. When unmanned radar was applied, the decrease in percent of traffic speeding was 21%, which was highly significant.

In all conditions studied, reductions in the eighty-fifth percentile speed occurred as traffic entered the work zone. When speed control techniques were not applied, the decrease was 2.0 mph. However, with unmanned radar, the decrease was 5.0 mph, and with police presence the decrease was 4.7 mph. While testing for statistically significant differences was not performed on these data, it is evident that considerably greater reductions in eighty-fifth percentile speed occurred with speed control techniques than without. This may be due in part to the relatively high probability of the fastest speeders using radar detectors, as explained in Section 2.4.

When the unmanned radar unit was placed 0.6 mile before the shoulder closure, the second observation station fell next to the speed limit reduction. Although drivers may have been reacting to the speed limit signs, these signs were present during both the radar on and radar off phases of data collection. Thus, comparisons between the radar off and radar on conditions can be made. Negligible changes occurred between observation stations in the mean speed of traffic. The standard deviation of speed decreased by 0.5 mph between stations with radar off. With radar on, a decrease of 0.8 mph was noted, which was statistically significant. As with the difference in mean speed changes, differences in percent of traffic exceeding the speed limit and in the eighty-fifth percentile speed between radar off and radar on conditions were small and insignificant.

At this site, desirable changes did occur with all measures of effectiveness upon the introduction of speed control techniques. However, desirable changes of a lesser degree occurred without speed control techniques, presumably due to the expectation of police presence. The data also reveal that limited substitution of unmanned radar for live law enforcement caused no adverse impact on speed patterns at this site.

4.3.3 Effects at Site 3

Site 3 was a 1.6 mile-long lane closure for work on the annual paving schedule. This left lane closure was in place for one day, and the speed limit remained at 65 mph. Unmanned radar, placed immediately before the beginning of the lane closure taper, provided the speed control technique at this site. No law enforcement was present. As can be seen below, desirable changes occurred in all measures of effectiveness at this short-term (one day) work zone.

Between observation stations, the mean speed of traffic decreased by 0.8 mph with the radar off, and by 3.1 mph with the radar on. As with the application of unmanned radar at sites 1 and 2, a highly significant reduction in mean speed occurred at site 3. A small decrease in mean speed occurred without speed control techniques at this site. At site 1A, with the same work zone type and configuration in similar terrain, a negligible increase of +0.1 mph occurred with radar off, and a decrease of 1.4 mph was measured with radar on. At site 3, the respective figures are 0.8 mph and 3.1 mph. Two possible reasons for the differences between sites arise. It is possible that when the speed limit has not been reduced from 65 mph to 55 mph, drivers perceive a need for a greater reduction in their speeds due to the work zone. This observation, however, must be tempered with the fact that at site 3, the initial mean speed was approximately 63 mph, while at site 1A the respective value was about 57 mph. Traffic traveling at 63 mph may have been more compelled to slow down due to the work zone than traffic traveling 6 mph slower, regardless of speed limit. Another possible reason for the differences in mean speed changes is that at site 1A, the unmanned radar unit was placed about one half-mile upstream of the lane closure taper, while at site 3 the radar unit was located about 500 feet ahead of the taper. The observation stations move with respect to the radar units. The two different radar locations were purposefully chosen to assess the effectiveness of unmanned radar at multiple locations relative to the beginning of the closure. However, it cannot be conclusively stated that either the difference in speed limits or in radar location accounts for the difference in mean speed changes between sites 1A and 3 without further studies.

Among the three sites, the most dramatic change in speed variance occurred at site 3. With no speed control, the standard deviation of speed decreased by 0.3 mph as traffic entered the work zone, while a decrease of 0.8 mph occurred with radar on. The latter reduction fell just short of being statistically significant. At this site a much greater reduction in speed variance occurred with radar on than with radar off.

The percent of traffic exceeding the speed limit decreased by 11% between observation stations with radar off, while a decrease of 27% was noted with radar on. The 27% reduction was highly significant. While the percent of traffic speeding decreased somewhat without unmanned radar, a highly significant reduction occurred when radar was applied at this site.

A large additional reduction in eighty-fifth percentile speed was observed with radar on at this site. With radar off, a decrease of 0.6 mph occurred as traffic entered the work zone, while with radar on, the figure of the reduction was 4.5 mph. Thus, an additional reduction in eighty-fifth percentile speed of about 4 mph was observed when unmanned radar was operational.

At site 3, when unmanned radar was used, a highly significant reduction in mean speed occurred. A greater reduction in standard deviation of speed occurred with radar on than with radar off; the reduction fell just short of being statistically significant. A highly significant reduction in percent of traffic exceeding the speed limit occurred with radar on. Considerably greater reductions in mean speed, speed variance, percent of traffic exceeding the speed limit, and eighty-fifth percentile speed occurred when the speed control technique was applied at this site.

In all cases, it is important to note that statistical significance is not synonymous with practical significance. While changes between conditions may meet criteria for statistically significant differences, such differences may not be significant when from a traffic engineering standpoint. The practical value of the changes in the traffic stream induced by the use of drone radar should be assessed using sound traffic engineering judgment.

Chapter 5 Additional Impacts of Highway Work Zones

5.1 Costs, Benefits, and Levels of Service of Work Zones

In addition to changes which occur in traffic speed characteristics, work zones also affect the efficiency of the highway system. Economic and operating levels of service perceived by a motorist changes when a work zone is encountered. Costs may be incurred by motorists (users) in the form of lost time due to reduced speeds, delays, and potential changes in accident rates and characteristics. The responsible agency, usually a state department of transportation (owner), faces costs in the installation and maintenance of traffic control devices in addition to the expense of the maintenance operation itself. However, the owner reaps benefits due to the deferral of major maintenance efforts, such as rehabilitation and replacement, which can be forestalled through regular performance of minor or ordinary maintenance tasks. Reduced speeds in work zones translate into the user benefit of improved safety. This chapter includes a general discussion of work zone accident costs and characteristics with application to the sites studied, an examination of user costs and benefits, and level of service using data from the work zones studied, and an overview of owner costs and benefits associated with work zones.

5.2 Work Zone Accidents

Prevention of accidents is of utmost concern in improving safety in work zones. Accidents are a major component of user costs associated with highway travel. Much research has been done on work zone accidents, typically in the form of an analysis of a state's accident record database. The presence of work zones increases with the passage of time and the shifting emphasis from new construction to maintenance of existing highways; however, the level of safety in work zones appears to be decreasing. There were 647 fatalities nationwide in work zones in 1992, in 1993 the figure was 762, and in 1994, 833 people were killed in highway work zones. Within Virginia, a similar trend exists. Seven fatal work zone accidents occurred in 1992, the next year there were eight, and in 1994 an alarming twenty-two fatal accidents occurred in work zones. As stated in the introduction to this thesis, the number of accidents in work zones on Interstate 81 in Virginia has been steadily increasing. Five of the sixty-eight work zone accidents on I-81 from 1991 through 1994 were fatal. Two opposing forces drive the occurrence of work zone accidents. Due to the increasing volume of maintenance and reconstruction activities on our highway system, work zones are becoming more prevalent with time. Thus, it stands to reason that motorists' exposure to work zones is also increasing every year. In logical opposition, the increased exposure should lead to increased awareness of and familiarity with work zones among drivers, thus reducing the possibilities of accidents caused by drivers. An overview of the data suggests that a worsening safety problem in work zones does exist.

5.2.1 Work Zone Accident Characteristics and Rates

A report published in 1995, which reviewed accident studies from several states, presented the following findings as common problems (24):

- Rear-end collisions constituted the most prevalent accident type
- Attempts to reduce speeding problems were often ineffective
- Work zone traffic control was set up improperly

These three problem areas are all focuses of research and education efforts. Rear end collisions usually occur when a queue exists upstream of the merging area (in the case of closed lanes). Many research initiatives are developing methods to provide drivers with timely information about backups. While many techniques are available to control speeds in work zones with varying degrees of success (see Chapter 2), the search for new methods and studies of their effectiveness is ongoing. Concerning the issue of traffic control, standards for the use of placement of traffic control devices continue to evolve, and project owners continuously educate personnel on proper traffic control at work zones.

Despite the commonality of problems associated with work zone accidents, a review of the literature reveals that when comparing accident rates of work zone and normal (non-work zone) conditions, for a particular highway segment, results vary widely. For example, a study of accidents on Interstate 495 in Virginia from 1973 through 1975 reported an accident rate increase of 119% in work zones (25). An analysis of accidents on the Chicago Area Expressway System over a six year period (1980-1985) found an accident rate increase of 88% in work zones (26). However, a study of accidents in New Mexico from 1983 through 1985 found an accident rate increase of only 26% in work zones (27). This study also reported results by highway system: Interstate (33%), Federal-aid primary (17%), and Federal-aid secondary (23%). A study by Graham et al. (1977) considered 79 work zone locations in seven states and found an average accident rate change of +7.5% in work zones (the range among the states varied from -3.4% to +37.6%) (10). A more recent report published by FHWA (1989) examined work zone costs on rural four-lane freeways in ten states around the nation (28). Accident statistics for twenty-five sites with single lane closure temporary traffic control (such as with sites 1 and 3 of this study) were examined. Accident rates increased by an average of 47% during the periods of construction at these work zones. A recent analysis of work zone accidents in Indiana from April to November of 1993 revealed similar trends (29). Among the projects whose accident records were studied were nine projects on four lane Interstate highways in which single lane closures were used for traffic control. When accident rates in these work zones were compared with data for the same period in the five previous years, a mean change of +33% was noted. The results of the studies discussed above are summarized in Table 5.1. The table clearly illustrates that accident rate changes due to work zones can vary widely; however, an increase in accident rate is typical in work zones.

Table 5.1 Accident Rate Changes Due to Work Zones on Freeways

Study Site and Source	Study Period	Accident Rate Change
Virginia (25)	1973-1975	+ 119%
Several states (10)	1976-1978	+ 7%
Illinois (26)	1980-1985	+ 88%
New Mexico (27)	1983-1985	+ 33%
Several states (28)	1986-1988	+ 47%
Indiana (29)	1993	+ 33%

As stated previously, the number of accidents annually in work zones on Interstate 81 has been steadily increasing. At sites 1A, 1B, and 3 of this study (each were work zones of one day duration), no accidents were observed. Site 2 is a long-term project lasting approximately two years. Some accidents have occurred during this period; however, none took place during the data collection effort. Therefore, calculations of accident rates at the work zones studied are not feasible. An accident rate change must be estimated for the calculation of user costs due to accidents in work zones on Interstate 81, as such data specific to I-81 does not exist. Of the studies listed in Table 5.1, the last two are most applicable to the scenario considered here. The accident rate changes listed with Burns' study (28), and Pal's study (29) are based solely on work zones that took place on four-lane freeways and in which single lane closures were the traffic control employed. Based on this information, the rates from these two studies will be averaged, and an accident rate increase of 40% will be used in the subsequent user cost calculation pertaining to work zones on Interstate 81 in Virginia.

Determination of accident rates in work zones involves many assumptions. Accident rates are typically expressed as number of accidents per 100 million of vehicle-miles traveled (VMT). For a work zone of a specific duration of time, a time unit must be incorporated (i.e. accidents per vehicle mile-hour). Collection of this work zone exposure data could only be performed directly if the exact traffic volumes through a particular work zone, as well as the work zone's length and duration, were known. The typical method of estimating exposure so that a work zone accident rate can be developed is by using accident records and hourly traffic counts. In addition, the number of hours in which work zones were in place in a year and the average length of these work zones must be determined. Some assumptions are usually employed to estimate total work zone existence (length times duration). The assumptions used in terms of work zone exposure may account for some of the variability among work zone accident rate increases.

The change in accident rate for a particular highway segment upon installation of a work zone and the associated temporary traffic control may be a function of many variables, including:

- Length of work zone (distance)
- Type of work being performed
- Duration of work zone (period of time)
- Type of traffic control devices used
- Alignment / sight distance approaching the work zone

Calculation of accident rates using accident reports, and comparison of rates from different states is complicated by inconsistencies in accident reporting procedures from state to state and in how work zone accidents are designated on the reports. Studies on accident rates have noted that these difficulties compromise the accuracy of the rates so calculated (24).

5.2.2 Accident Costs

Costs associated with accidents constitute a portion of total highway user costs. Highway user costs are discussed in detail in the next section of this thesis. The accident cost component for a particular highway segment can be calculated by multiplying the accident rate on that section by the average monetary value of the property damage from accidents, and, if available, the medical costs associated with treatment of injuries in those accidents.

Other accident costs not borne by the highway user include those associated with temporary traffic control and emergency response efforts. These costs, borne mainly by public entities, typically comprise a small portion of the total accident cost.

By employing the assumed accident rate and using other data, some estimation of accident costs in work zones on Interstate 81 in Virginia can be made. A search of accident data maintained by the Virginia Department of Transportation yielded some useful data. 1451 accidents occurred on I-81 in Virginia in 1993. Among these accidents, the average amount of property damage was $10,576. In comparison with other major Interstates in Virginia (Routes 64, 66, 77, 85, 95), I-81 accidents had the highest average amount of property damage. However, its average accident rate for the period 1991-1994 of 0.405 accidents per million vehicle-miles traveled was the second lowest among the same routes (13). Unfortunately, in the records of property damage due to accidents, no distinction was made between work zone accidents and non-work zone accidents. Therefore, in the calculation of highway user costs due to work zone accidents, an assumption is made that the value of $10,576 can be used for property damage per accident that occurred in a work zone. In the estimation of accident costs in the next section, this figure will be used.

5.3 User Impacts

The presence of work zones affects the motoring public in many ways. Increases in costs related to slower travel and safety risks, and deterioration in level of service on a particular highway segment, can be quantified to measure the impact of work zones on highway users. While a work zone represents an increased cost to the traveler, a tradeoff takes place since the slower speeds typical of work zones provide a user benefit by enhancing safety. Slower speeds reduce the potential probability and severity of accidents by increasing the available amount of perception-reaction time and reducing the momentum and energy dissipated in an impact.

Costs of highway travel can be divided into two general groups: those related to the vehicle and those which are a function of the transportation system. Expenses associated with operating a motor vehicle include loan repayments, maintenance costs, fuel, etc. Transportation system costs are those which are related to travel, such as the cost of travel time and costs related to accidents. In the case of system costs related to work zones, increases in travel time due to speed reductions, congestion (delays), or detours, and increases in accident rates represent additional costs incurred by highway users when traveling through work zones. The greater the speed reduction (from normal conditions) is, the higher the user cost will be. The user costs associated with the work zones studied for this thesis, and for work zones on Interstate 81 in Virginia are covered below.

The level of service on a transportation facility can also be affected by the presence of work zones and their impact on the traffic stream. The reduced speeds typical of a work zone, without an increase in traffic volume, translate into a lower level of service. This relationship can be modeled by applying queuing theory using a demand-supply analogy represented by the ratio of volume to capacity (30).

5.3.1 User Costs at Sites Studied

The relationship described above can be applied to the sites studied in this project to compute the actual value of the costs associated with those work zones. For each site studied, the determination of travel costs due to the work zone requires measurement of the mean speed of traffic in work zone and normal conditions. Additionally, the free-flow travel times and capacities at each site must be also be known. At site 2, the work zone had been in place for approximately fourteen months when data was collected to measure the effects of the unmanned radar unit on speeds, and was expected to remain in place for about ten more months. Due to the ongoing construction at this location, site 2 was not included in this analysis. The above parameters could be determined for sites 1A and 1B (site 1), and site 3, as these were short-term work zones and return visits were made to these locations to obtain speed data under normal conditions. At site 1, the speed limit was reduced to 55 mph, while at site 3 it was allowed to remain at 65 mph. These scenarios will allow for the determination of additional user costs due to speed limit reductions at work zones. However, it must be remembered that the user benefit of improved safety comes with reduced speeds. The additional speed measurements were taken at sites 1 and 3 when traffic volumes were similar to those observed in the previous data collection efforts. The methodology outlined in Section 3.4 was used again; however, only one condition was studied (unmanned radar was not tested), and only one observation station was needed at each site (speed changes were not being measured). Although only mean speed data are utilized in the user cost analysis, all of the measures of effectiveness developed in the unmanned radar studies were calculated. These data, as well as comparisons between conditions, are contained in Appendix E.

The model used to determine costs due to increased travel time and reduction in level of service states is based on queuing theory and considers the change in the ratio of observed travel time per unit distance to free flow travel time per unit distance. A dimensionless parameter descriptive of the highway segment, *j*, represents level of service and is defined as a function of the free flow travel time and the capacity of the subject highway segment using Davidson's link performance function. This relation, shown in Figure 5.1, taken from reference 34, can be written as:

$$T / T_f = [1 - (1 - j) (v / c)] / [1 - (v / c)] \quad \text{where} \qquad (6)$$

T = *observed travel time (per unit distance)*

T_f = *free flow travel time (per unit distance)*

j = *level of service parameter* ($0 < j < 1$)

v / c = *volume-to-capacity ratio*

This relationship can be applied to data collected at sites 1 and 3 to determine changes in level of service and travel times at those sites. It will be assumed that the value for *j* changes due to the presence of the work zone. As j increases, the level of service decreases. To apply the formula to the collected data, a form for each condition will be used. T becomes T_W (observed travel time in minutes per mile through the work zone). j becomes j_W (level of service in work zone conditions). Similarly, T_N is the travel time in minutes per mile in normal conditions, and j_N is the level of service under normal conditions with traffic flows similar to those observed in the work zone.

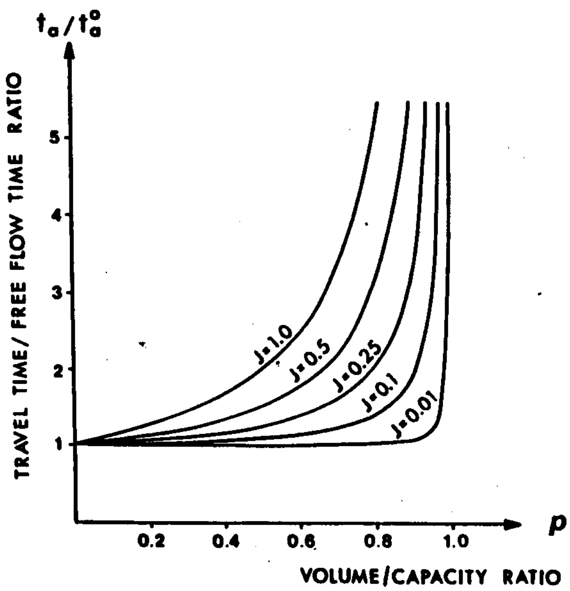

Figure 5.1 Traffic Volume - Travel Time Relationship

Upon consideration of the data contained in Appendix E and recommendations from the Highway Capacity Manual (31), a free flow speed of 70 mph will be assumed for both sites. Therefore, T_f = 60 / 70 = 0.857. Values for v / c , the volume-to-capacity ratio, must also be determined for each site. At site 1, the mean speed in the work zone was 57.0 mph, thus T_W = 60 / 57.0 = 1.053. At site 3, the mean speed in the work zone was 62.8 mph, thus T_W = 60 / 62.8 = 0.956. From Appendix B, it can be seen that the volume at site 1 was 1327 passenger cars per hour (pcph), and at site 3 the volume was 1275 pcph. Assuming a capacity of 2200 pcph per lane (31), the values of v / c are 0.302 at site 1 and 0.290 at site 3. When inserted into equation 6, the values of j_W are 0.53 and 0.28 for sites 1 and 3 respectively.

To compare these levels of service with normal operating conditions, speed data were collected at these sites when work zones were not present and when traffic volumes were at similar levels. At site 1, the mean speed was 68.7 mph, thus T_N = 60 / 68.7 = 0.873. At site 3, the mean speed was 67.6 mph, thus T_N = 60 / 67.6 = 0.888. At site 1, under normal conditions, j_N = 0.05, and at site 3, j_N = 0.09. These calculations are summarized in Table 5.2. The level of service provided to highway users on these sections of Interstate 81 clearly decreased in the presence of single lane closures needed for maintenance. At milepost 158 northbound (site 1) in the presence of a single lane closure with the speed limit reduced from 65 mph to 55 mph, the level of service parameter *j* increased from 0.05 to 0.53. At milepost 164 southbound (site 3) in the presence of a single lane closure with a speed limit of 65 mph, *j* increased from 0.09 to 0.28. When comparing the two sites, it can be seen that when the speed limit is reduced in a lane closure, the increase in travel time and deterioration in level of service are considerably greater. However, this further decline in level of service observed from a travel time standpoint also improves safety as lower speeds allow drivers more time to react and reduce forces dissipated in an accident.

Table 5.2 Levels of Service at Sites Studied

Parameter	**Site 1**	**Site 3**
v / c (volume-to-capacity ratio)	0.302	0.290
T_f (free flow travel time, min/mile)	0.857	0.857
T_N (normal condition travel time, min/mile)	0.873	0.888
T_W (work zone condition travel time, min/mile)	1.053	0.956
T_D (travel time delay, min/mile)	0.180	0.068
j_N (normal condition level of service)	0.045	0.089
j_W (work zone condition level of service)	0.529	0.283

To compute the total delay encountered by motorists at these work zones, the length of the work zones and the traffic volumes which flowed through them must be known. The key assumption made in these calculations is that queues did not occur at these sites; obviously, user costs increase dramatically upon formation of a queue as travel speeds become very low. At each site, work zone length *(WZL)* was approximately 1.5 miles. The traffic volume through the work zone *(TV)* can be estimated as a function of average daily traffic (ADT). From Table 3.1, it can be seen that the ADT at each site is 30,000 vehicles per day. Each work zone was in place approximately 12 hours (7:00 am to 7:00 pm). Examination of data from nearby permanent counting stations reveals that almost 75% of the ADT occurs during this period; therefore, about 22,500 vehicles were affected. The following formula can be used to determine total delay *(D)* at a particular work zone:

$$D = TV \times WZL \times T_D \qquad (7)$$

By applying the appropriate values of T_D from Table 5.2, equation 7 yields a total delay of 6075 vehicle-minutes at site 1 and 2295 vehicle-minutes at site 3. The impact of reduced speed limits on total delay is evident as the total delay at site 1 was 2.65 times that at site 3. These delays may be viewed as not significant in a practical sense, as the average delay encountered by a vehicle was 0.27 minutes at site 1 and 0.10 minutes at site 3.

The user costs associated with these work zones can now be determined, as no accidents occurred at these sites. As time spent in queue would otherwise be productive time at the end of a motorist's trip, a time value (V_T) of $15 / hour, or 25 cents per minute, will be assumed. The user cost due to delay (UC_D) can be found as:

$$UC_D = D \times V_T \qquad (8)$$

Applying equation 8 to each site, the total user cost incurred at site 1 was $1518.75; and at site 3 it was $573.75. User costs due to delays at these sites would have become much more significant if volume had reached capacity and queues formed.

5.3.2 General Application of User Costs

Work zones are almost a daily occurrence along an Interstate highway during spring, summer, and fall for the performance of ordinary maintenance and maintenance replacement activities. Widening and reconstruction activities can occur all year. These work zones require changes in traffic control which result in higher costs incurred by highway users.

The user costs due to delay calculated above, along with costs due to an increased rate of accidents, can be extended to estimate user costs associated with work zones on an annual basis for Virginia's 325-mile section of Interstate 81.

Nearly all work zones on I-81 require either lane closures or shoulder closures. Lane closures are typically scheduled in off-peak periods to reduce or eliminate congestion, so queuing will not be considered in the following analysis. Shoulder closures are typically short-term work zones without speed limit reductions. These work zones have little effect on driver behavior in terms of speed changes and increased accident risks. Since user costs associated with shoulder closures are not of the same magnitude as in lane closures, they are not considered in the following analysis.

The single lane closure is the predominant form of temporary traffic control used in highway maintenance operations. In some instances, the Virginia Department of Transportation (VDOT) reduces the speed limit (usually to 55 mph). Examples include lane closures which are in place for extended periods or encroach greatly on traffic. However, in most cases the speed limit is left at 65 mph. To determine annual user costs in I-81 work zones, an estimate of exposure of traffic to work zones must be developed. A system of comprehensive logging of work zones typically does not exist, as many parties (various VDOT work units and contractors' crews) set up work zones on highways. One approach is to estimate the annual existence of lane closures in terms of length and duration and multiply by ADT to determine vehicle-miles of work zone exposure on an annual basis.

On the 87 mile section of I-81 in VDOT's Salem District, a typical day saw about ten miles of lane closure with a typical duration of twelve hours. This five mile-days of lane closures generally occur daily from April through November. After discounting bad weather days, this results in about 180 days of lane closures, and 900 mile-days per year of annual lane closure existence *(ALCE)*. Assuming that the rate of lane closures needed for maintenance in Salem District is equal to the rates in the Staunton and Bristol Districts, the existence figure can be extrapolated to Virginia's entire portion of I-81 as approximately 3400 mile-days. The final piece of data needed is the average annual daily traffic *(AADT)* on I-81 in Virginia. This figure can be determined by taking AADT link by link, multiplying each AADT value by link length, and dividing into total length, thus computing a weighted average AADT. Using 1995 AADT data in this format, provided by VDOT, the weighted average AADT is 31,700 vehicles per day. Annual exposure *(AE)* can then be found as:

$$AE = ALCE \text{ x } AADT \qquad (9)$$

Equation 9 yields an annual exposure of 107,780,000 vehicle-miles through lane closures in work zones on I-81 in Virginia.

User costs due to travel time delays will be developed using travel time delay values presented in Table 5.2. The work zone exposure level can then be multiplied by travel time delay for the appropriate speed limit conditions, and then by a cost of time value to develop the travel time cost increase. Thus, the total annual delay *(AD)* can be computed as:

$$AD = AE \text{ x } T_D \qquad (10)$$

It will be assumed that speed limits are reduced to 55 mph in 50% of lane closures. Thus, by applying equation 10 and the appropriate value of T_D to 55 mph work zones, *AD* is 161,670 vehicle-hours, and for 65 mph work zones *AD* is 61,075 vehicle-hours. Summing the previous two values yields 222,745 vehicle-hours of total annual delay. Annual user cost due to delay (AUC_D) can be found as:

$$AUC_D = AD \text{ x } V_T \qquad (11)$$

Applying equation 11, the total user cost due to delay in work zones on I-81 in Virginia in 1995 is approximately $3,341,000.

Increased accidents constitute a component of highway user costs in work zones. The assumed accident rate increase of 40% and average accident cost of $10,576 developed in Section 5.2 form the basis of these calculations. Extrapolating the 1993 accident cost figure of \$10,576 in 1993 dollars by 5% annually, \$11,660 will be used for accident cost *(AC)* in 1995, in conjunction with the use of 1995 traffic data. The average accident rate *(AR)* on Interstate 81 is 0.405 accidents per million vehicle-miles; this rate will be assumed true for 1995. A 40% accident rate increase in work zones *(ARI)* is assumed as stated in the previous section. The annual user cost due to increased accident rate (AUC_A) can be found as:

$$AUC_A = AR \times ARI \times AE \times AC \quad (12)$$

Applying equation 12, the user cost due to the accident rate increase in work zones on the subject section in 1995 is approximately \$204,000.

Costs due to delays (increased travel time) and increased probabilities of accidents have been considered in this analysis; the subsequent determination of annual user cost *(AUC)* can be performed as:

$$AUC = AUC_A + AUC_D \quad (13)$$

Applying equation 13 for 1995, the estimated total user cost associated with traveling through work zones on Interstate 81 in Virginia is approximately \$3,545,000. Based on the data collected at study sites 1 and 3, and assumptions employed in estimating accident rates in work zones, exposure to work zones by traffic, and the value of time, the user costs associated with work zones have been so estimated.

5.4 Owner Impacts

Highway system owners, such as VDOT, are impacted by work zones and the temporary traffic control associated with them in terms of costs and benefits as well. In addition to the cost of the highway work itself, the responsible agency faces costs associated with temporary traffic control, public relations, and inspection of the work. The key benefit to the agency is the deferral of major maintenance (replacement or rehabilitation) by conducting minor, short-term maintenance operations.

The costs associated with the actual highway maintenance activity constitute the key component of owner costs incurred while a work zone is in place. This cost component, which includes labor, equipment, and materials expenses for the operation, is regularly budgeted for on annual basis. While this work, undertaken to maintain and improve the highway system, usually necessitates the installation of a work zone, these costs are not generally considered with owner costs associated with the work zone itself. The main component of work zone owner costs lies in the installation and maintenance of the temporary traffic control devices needed to maintain an orderly flow of traffic while providing safety benefits for highway workers and motorists. The current trend with work zone traffic control is that its share of the total cost attributed to maintenance or reconstruction operations is increasing. For example, traffic control costs comprised about 30% of the contract for a recent bridge deck replacement project on a four-lane primary highway. Standards for traffic control in work zones are becoming more stringent and require more protection for both workers and motorists, providing a safety benefit but increasing cost.

Other costs incurred by highway agencies include those associated with other resources involved with work zones, such as inspection of the work and public relations. As highway initiatives shift further toward rehabilitation and replacement projects, these efforts typically require full-time inspectors for quality assurance purposes. Public information efforts are increasing as well. Costs attributed to the traffic control scheme, such as with the use of variable message signs and highway advisory radio stations, are part of an effort to better inform drivers about work zones. Use of newspapers, radio, television, and other forms of media to inform drivers, are becoming increasingly common as well. While rising traffic control costs are the primary components of owner costs associated with work zones, these costs take other forms as well.

The key owner benefit of work zones is the deferral of major maintenance projects, such as replacement or rehabilitation, through the performance of short-term, ordinary maintenance. VDOT classifies maintenance activities into two subcategories: ordinary maintenance (OM) and maintenance replacement (MR). Ordinary maintenance consists of routine short-term operations which keep the roadway from further deteriorating. Examples of OM activities include patching of potholes in asphalt or concrete pavement, ditching, and mowing. MR activities are typically broader in scope and attempt to restore the roadway to a higher service condition. Such efforts include resurfacing (repaving) sections of asphalt roadway, replacement of a concrete bridge deck, and replacement of deteriorated or substandard traffic control devices. MR activities occur less frequently in the life-cycle of roadway than OM activities, but generally cost more and require more in terms of traffic control. The benefits of work zones, particularly those for OM activities whose duration is measured in terms of hours instead of days or months, is deferral of MR or long-term activities. Frequent OM activities with lesser costs for both highway users and owners translate into the deferral and possible savings of future MR activities and their associated costs.

Economic impacts of highway work zones can be examined in terms of costs and benefits for both highway users and transportation providers. A motorist (user) faces quantifiable changes in the cost of the using the highway system upon encountering a work zone. The primary cost changes are due to speed reductions and delays, thus increasing travel time, and increased accident rates, thus increasing the risks associated with driving. These costs have been determined for the work zones studied on Interstate 81, and by making some assumptions, the user costs have been generalized to the entire section of I-81 in Virginia on an annual basis. Potential user benefits are more difficult to define and quantify. From the standpoint of the highway management agency (owner), the primary cost directly related to the presence of a work zone is that associated with the necessary traffic control. Savings due to deferral of major maintenance activities through good highway maintenance management techniques constitute the primary owner benefit of highway work zones.

Chapter 6 Conclusions and Recommendations

6.1 Conclusions on Unmanned Radar and Police Presence

This research effort was undertaken in order to assess the effectiveness of unmanned radar as a speed control technique in freeway work zones. The motivation for this research was provided by the Virginia Department of Transportation's recent acquisition of unmanned radar units for the purpose of improving safety in work zones. After conducting a literature review on many common speed control techniques, including law enforcement and unmanned radar, data was collected in work zones on Interstate 81 in Virginia. Three work zone types and various unmanned radar and police presence schemes were studied, and the collected data were statistically analyzed. Based on the results of this recent effort and on past research on unmanned radar, conclusions on its effectiveness and recommendations for its use were developed.

The research conducted for this report indicates that unmanned radar is an effective speed control device in freeway work zones in Virginia. Proper use of unmanned radar provided significant reductions in mean speeds and in percent of traffic exceeding the speed limit, minor reductions in speed variance, and reductions in eighty-fifth percentile speeds at all sites studied. Based on this research effort, changes in measures of effectiveness as a result of unmanned radar use, as traffic approaches a work zone on a freeway in Virginia, include:

- Reductions in mean speed of 0.8 mph to 2.3 mph
- Reductions in standard deviation of speed of 0.1 mph to 0.5 mph
- 6% to 20% reductions in percent of traffic exceeding the speed limit
- Reductions in eighty-fifth percentile speed of 1.1 mph to 3.9 mph

The above reductions reflect changes in the measures of effectiveness between control and treatment conditions.

The studies of the effectiveness of unmanned radar were conducted in work zones on Interstate 81 in Virginia, where radar detectors are illegal. However, law enforcement authorities estimate that 15% to 25% of the traffic on I-81 uses radar detectors. Past research on radar detector use indicates that vehicles exceeding the speed limit and trucks are more likely to use radar detectors than the traffic stream as a whole. Speeders always constitute an important target group of speed control efforts, and trucks comprise a relatively large portion of the traffic stream on I-81. The above effects of unmanned radar use improve safety and reduce the probabilities of and severity of accidents in work zones.

At all sites studied, statistically significant reductions in mean speed were observed as traffic entered the work zone. These reductions ranged from 1.4 mph to 3.1 mph with the unmanned radar in operation at sites where regular police patrol was not existent. At the same sites, mean speed changes without speed control techniques were in the range of +0.1 mph to -0.8 mph. At a site where the expectation of police presence and speed limit enforcement is present, a mean speed reduction of 2.0 mph occurred. With unmanned radar and police presence, the respective changes were -2.8 mph and -2.9 mph.

Standard deviation, the square root of variance, was used as a measure of speed variance. A greater reduction in speed variance as traffic entered the work zone was realized at every site when speed control techniques were applied. The change in standard deviation of speed ranged from +0.1 mph to -0.8 mph with the unmanned radar in operation at sites where regular police patrol was not existent. Without unmanned radar the changes ranged from +0.4 mph to -0.3 mph. At a site where the expectation of police presence and speed limit enforcement is present, the standard deviation of speed decreased by 0.4 mph without speed control techniques. With unmanned radar and with police presence, the decrease was 0.7 mph.

Statistically significant reductions in percent of traffic exceeding the speed limit occurred at most sites when the unmanned radar unit was in operation. Only at the site with regular police patrol did a statistically significant reduction occur without speed control techniques present. At that site, a 15% reduction in percent of traffic speeding occurred without speed control, while reductions of 21% and 17% were observed with unmanned radar and police presence, respectively. At the other sites, reductions ranged from 2% to 11% without unmanned radar, and from 10% to 27% with unmanned radar in operation.

Considerably greater reductions in eighty-fifth percentile speed as traffic entered the work zones were observed at all sites upon the use of speed control techniques. At the sites where police patrol was not common, changes in eighty-fifth percentile speed ranged from +0.2 mph to -0.9 mph without unmanned radar, while the range was -0.9 mph to -4.5 mph with unmanned radar in operation. At the site where police presence was expected, the eighty-fifth percentile speed decreased by 2.0 mph when no speed control techniques were applied. When unmanned radar and police presence were used, the changes were -5.0 mph and -4.7 mph respectively.

By comparing data from the various sites studied, the following inferences can be made:

- Speed patterns in short-term work zones experience greater impacts due to unmanned radar use than do speeds in long-term work zones
- Unmanned radar has greater impact on speed patterns in work zones where police presence is not common than where police patrol is expected by drivers
- Where the expectation of police presence and speed limit enforcement is well-established, unmanned radar can be substituted periodically with no adverse impact on speed patterns
- Where the expectation of police presence and speed limit enforcement are well-established, significant reductions in mean speed and in percent of traffic exceeding the speed limit still occur when speed control techniques are not present

- Placement of the radar unit is more effective when placed immediately before the beginning of the lane or shoulder closure than when placed one half-mile in advance
- Slightly greater benefits are realized in a right lane closure than in a left lane closure in the same location.

The above conclusions are based on data collected at three sites, one with a left lane closure and right lane closure on consecutive days, one with a left shoulder closure, and one with a left lane closure. While data was collected in work zones on Interstate 81, expectations for changes of measures of effectiveness may be applied to all freeways in Virginia. The specific changes noted may have limited application to other types of highways, and to highways in other states where radar detectors are legal and more widespread use can be expected.

6.2 Recommendations on the Use of Unmanned Radar

As a result of this study and past research, the following recommendations are made regarding the use of unmanned radar as a speed control technique:

- Highest consideration should be given to use of unmanned radar in lane closures which are present for less than one day and for which no advance notice of the work zone is given to the public
- Unmanned radar can be used to supplement law enforcement by substitution in a limited manner for police presence in any work zone which is regularly patrolled and driver expectation of police presence is high
- The unmanned radar unit should be placed immediately upstream of the beginning of the lane closure taper
- The unmanned radar unit should not be left in one place for more than one day, and when used in long-term work zones, the location and hours of operation should be varied to maximize effectiveness

6.3 Recommendations for Further Research

Further study is recommended to obtain a more comprehensive assessment of the effectiveness of unmanned radar. The collection of more data can add strength to the conclusions drawn herein. Study of a wider range of work zone configurations and on other highway types may provide more recommendations on unmanned radar use.

Development of a timing device which can be operated in conjunction with the radar unit would provide greater variety in patterns of unmanned radar use. By controlling and varying periods of operation, a greater simulation of "live" law enforcement can be provided without the need for a person to manually turn the unit on and off.

Alternate methods of data collection for future studies on unmanned radar should be considered. While accuracy was not compromised using the manual speed trap method, study of nighttime operations and of mobile lane closures could be made feasible with a different method.

The development of a "work zone notification system" would make the scheduling of any work zone data collection effort simpler and reduce the possibility of missed opportunities. With many people in many different offices responsible for the administration of highway maintenance efforts (both public and private), the provision of a central point for supplying work zone information can potentially provide better information to the motoring public as well.