Identification of Potential Enhancements for Work Zone Safety in Alabama

For the

Alabama Department of Transportation

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The objective of this report is to evaluate the effectiveness of police presence and double fine signs to reduce speed in work zones in Alabama and to measure the actual speed and time headway of vehicles in work zones and upstream of work zones. This report monitored a total of 254,841 vehicles for speed and time headway at five Interstate work zone locations where four different types of road work was proceeding. Research methods included a literature search, live field data collection with cameras equipped with Machine Vision Processing (MVP), and data analysis.

The report finds that level of service is reduced when vehicles enter the work zone. Police presence is the most effective method of reducing speed in work zones. The standard deviation of the speed of vehicles also increases as they enter the work zone. Time headway decreases from the non-work zone case to work zone cases, which helps explain why misjudging stopping sight distance/following too close is the most frequent cause of crashes in work zones in Alabama.

The researchers recommend that ALDOT review its method of setting work zone speed limits in light of new recommendations in the 2000 MUTCD. They also affirm that reducing speed using police presence is the most effective method in use in Alabama.</td></tr>
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Executive Summary

Previously, faculty and staff at the University of Alabama (UA) performed a comprehensive review of computerized work zone crash data for Alabama for the years 1994-1998 (UTCA project 00107). The study found that misjudging stopping sight distance and following too closely are the most frequent causes for work zone crashes, that the ratio of drivers speeding in work zones to drivers speeding in non-work zone crashes is 1.2 to 1, and that work zone crashes are significantly over represented on Interstate and U.S. highways. Based on that study, the Alabama Department of Transportation (ALDOT) funded a second project, where UA personnel performed fieldwork at five work zones on Interstate highways to evaluate the following operational conditions:

- The speed of vehicles traveling through work zones compared to the speed in free-flow condition just upstream of the work zones.
- The time headways of vehicles in work zones and just upstream.
- The effectiveness of the presence of state troopers in reducing speed through work zones.
- The difference in speeds in work zones before and after "construction fines double in work zones" legislation was enforced in Alabama.

A total of 254,841 vehicles were monitored at five Interstate work zone locations (Rock Mountain Lakes, Prattville, Fosters, Brookwood, and Hoover) where four different types of road work (Road Widening, Resurfacing, Resurfacing at Night, and Interchange Modification) were proceeding. Data was collected for five conditions: Non Work Zone (NWZ), Base WZ, WZ Double Fine, WZ Police, and WZ Police & Double Fine. Following the data analysis, the following conclusions were obtained:

- All work zone types showed Level of Service (LOS) A or B in the NWZ area. LOS for each type was generally reduced by one level when vehicles entered the work zone.
- The hierarchy of measures to control (reduce) mean speed in work zones is police & double fine sign, police presence, double fine sign and base WZ traffic control.
- The standard deviations of speeds for the five locations increased as vehicles entered the work zone. As the level of speed enforcement increased from Base WZ to WZ Police, standard deviation of speeds also increased. This finding may introduce a contradiction: as speeds are reduced to improve safety, speed variability increases, which may reduce safety.
- Time headway decreased from NWZ to Base WZ (27%), then from Base WZ to WZ Double Fine (14%), and from Base WZ to WZ Police (10%). The decrease in time headway helps explain why the most frequent cause of crashes in work zones is misjudging stopping distance/following too close.

Finally, the researchers identify police presence as the most effective method of reducing speed. They also suggest Section 6C.01 of the 2000 *Manual on Uniform Traffic Control Devices* if ALDOT wishes to modify its policy for setting work zone speed limits.

Section 1
Introduction

Previously, faculty and staff at the University of Alabama (UA) preformed a comprehensive review of computerized work zone crash data for Alabama for the years 1994-1998. The objective was to discover characteristics and trends in work zone crash data. The final report published in March 2001 (Lindly, *et al.* 2001) listed several conclusions, including the following:

- Misjudging stopping sight distance and following too closely are the most frequent contributing circumstances of work zone crashes.
- The ratio of drivers speeding in work zone crashes to drivers speeding in non-work zone crashes is 1.2 to 1.
- Work zone crashes are significantly over-represented on Interstate and U.S. highways.

Those conclusions resulted in several recommendations, including the following:

- Safety efforts focused on Interstate and U.S. highways will provide the greatest safety gains.
- Because misjudging stopping distance and following too closely are the most frequently cited causes of work zone crashes, emphasizing the following work zone safety practices will show the greatest safety improvements: limiting vehicle speeds, increasing time headway between vehicles, and warning vehicles of queues ahead.

As a result of the review, the Alabama Department of Transportation (ALDOT) funded a second project to build on the results of the first. In this project, UA personnel performed fieldwork at five work zones on Interstate highways to evaluate the following operational conditions in work zones:

- The speeds of vehicles traveling through work zones compared to the speeds in free-flow conditions just upstream of the work zones.
- The time headway of vehicles in work zones and just upstream.
- The effectiveness of the presence of state troopers in reducing speeds through work zones.
- The difference in speed in work zones before and after "construction fines double in work zones" legislation was enforced in Alabama.

Data was acquired with two Econolite Autoscope Solo cameras, usually mounted on overpasses above the highways. This camera system is equipped with a machine vision processor to automatically collect and tabulate such information as volume, speed, headway, and vehicle type for several lanes of moving traffic.

The project resulted in basic research data that describes driver behavior in Interstate work zones in Alabama. However, there are also specific findings in the areas of police enforcement and work zone speed limits that offer promise of increased safety in work zones.

Section 2
Literature Review

The safe and efficient flow of traffic through construction and maintenance work zones is a major concern to transportation officials, the highway industry, and the traveling public throughout the U.S. The safety of motorists and workers in work zones has been the subject of many research studies.

2.1 What Is A Work Zone?

"A work zone is an area of traffic way with highway construction, maintenance, or utility work activities" (Turner 1999). Signs, channeling devices, barriers, pavement markings, and/or work vehicles typically mark a work zone. It extends from the first warning sign or flashing lights on a vehicle to the "End of Road Work" sign or the last traffic control device. A work zone may be of short or long duration, and it may include stationary or moving activities (Turner 1999).

2.2 Work Zone Crashes

"A work zone accident is a traffic accident in which the first harmful event occurs within the boundaries of a work zone or on an approach to or exit from a work zone, resulting from an activity, behavior, or control related to the movement of the traffic units through the work zones" (Turner 1999). In Alabama, a work zone crash is significantly (27%) more likely to involve a fatality than a non-work zone crash (Lindly *et al.* 2001).

2.3 Why Work Zones? Why Work Zone Crashes?

Today, a high percentage of highway funds are being used to preserve (resurface, restore, rehabilitate, and reconstruct) the existing highway system. At the same time, the traveling public is demanding a high degree of mobility, and vehicle miles of travel are rapidly increasing. Thus, the necessity of work zones is increasing. Highway construction creates congestion; as a result, crash rates increase, causing even more congestion (FHWA 1998).

2.4 Severity of Work Zone Crashes

Work zone crashes are a continuing problem. Several studies have concluded that work zones have a tendency to increase crashes. Noel, *et al.* (1987) conducted research on controlling speed at work zones that was published by the Federal Highway Administration (FHWA). That report describes a study of 10 randomly selected construction projects in California in 1965, which showed a 21.4% increase in the crash rate and a 132% increase in the fatality rate compared to non-work zones. The FHWA report also describes a study of 207 highway resurfacing projects on two lane highways where Graham et al. reported a 61% increase in total accidents, a 67% increase in injuries, and a 68% increase in fatalities during construction. Additionally, according to Graham, the Virginia Highway Research Council reported a 119% increase in accident frequency in construction zones on I-495 in Northern Virginia. These studies demonstrate that work zones increase the potential for traffic accidents.

The National Highway Traffic Safety Administration (NHTSA) determined that over 700 fatalities, 24,000 injury crashes, and 52,000 property-damage-only crashes occur every year in work zones in the U.S., which according to the FHWA, account for nearly $4.4 billion in costs to motorists and others every year (National Work Zone Safety Information Clearinghouse 2001). An overall summary of work zone fatal crashes for the U.S. and Alabama is shown in Table 2-1.

Table 2-1. Work Zone Fatalities, Motorists Plus Workers (1986-1999)

Year	WZ Fatalities for US	WZ Fatalities for AL
1986	691	14
1987	702	5
1988	780	17
1989	782	18
1990	786	12
1991	680	16
1992	647	14
1993	762	10
1994	833	9
1995	771	6
1996	719	15
1997	658	6
1998	772	13
1999	868	18

Source: Reference (FHWA 2001) and (Ullman et al., 1997)

The fatality rate for highway construction workers is twice the rate for other types of construction. According to the Bureau of Labor Statistics, heavy and highway construction in 1992 and 1993 experienced a rate of 39 deaths for every 100,000 workers, compared with 19 deaths per 100,000 workers for all construction and 6 per 100,000 for all industries. In 1996, 133 highway workers were killed in work zones in the US (125 in 1995). Approximately 35% of these highway workers fatalities were directly related to traffic moving through the work zones (FHWA 1998). Over 20,000 workers are injured yearly in roadway work zones (Fosbroke, *et al*. 2001).

In total in the past decade, more than 8,000 people lost their lives in work zone crashes (FHWA 2000). Despite these alarming statistics, inconsistencies in defining and reporting work zone crashes may make the problem worse than indicated above.

2.5 Causes of Work Zone Crashes

Crashes in highway work zones are due to a combination of factors, including driver error, inadequate visibility, poor road surface condition, roadway obstructions, inadequate traffic control, and improper management of material, equipment, and personnel in work zones. "Unsafe operating speeds for existing condition is a frequent driver's error and 85% of work zone accidents are the result of an unsafe behavior, not the failure of the system" (Lucker 2001). Fors reported in 2000 that according to the National Highway Transportation Safety Administration, speeding is a contributing factor in 30% of all accidents and fatalities (Fors 2000). According to E. Norris Tolson, Secretary of the North Carolina Department of Transportation, "the biggest problems in work zones are attentiveness and speed" (Kedjidjian 1999). To increase awareness of the need to be especially attentive and safety-conscious when operating in a work zone, FHWA held the "National Work Zone Safety Awareness Week" from April 3-7, 2000. The FHWA's stated mission for this week was "Speeding traffic is the number one cause of injury and death in our nation's work zones. If a driver would slow to posted speed limits in work zones, disengage from distracting activities such as cellular telephone usage, and be aware of the workers, countless lives would be saved."(FHWA 2000).

In 2000, Lindly (*et al.* 2001) investigated work zone crashes in Alabama. That research used the Critical Analysis Reporting Environment (CARE) (UA 1998) accident report database to identify over-represented characteristics of work zone crashes in Alabama. The study found that most work zone crashes were rear-end crashes, and the most frequent cause for crashes was "misjudging stopping distance/following too closely".

Unfortunately, there are still many inadequacies in crash databases. They rely primarily on accident reports for the data and are limited by many factors, including the scope of the report form, the reporting officer's thoroughness, and the accuracy with which the paper information is transferred to the computer database. These databases do not often provide a complete picture of the circumstances surrounding a work zone crash. Additionally, as there is no nationally recognized definition of work zone or work zone related accidents (Turner 1999), it is likely that work zone crashes have been substantially under-reported (Raub and Sawaya, 2000). According to the FHWA, many states disagree with the Fatal Accident Reporting System (FARS) database, claiming that the actual numbers of work zone fatalities are greater than those reported in FARS (FHWA 1998).

2.6 Speed Control Techniques

A number of speed control techniques are currently used by state transportation agencies throughout the country. These techniques range from posting regulatory and advisory speed limit signs to using the latest technologies to attempt to reduce speeds in work zones. The standard practice of using signs to control speeding in work zones is not working: drivers are generally not responsive to purely advisory and regulatory speed signing in work zones (Noel *et al.* 1987) For this reason, innovative traffic control measures are being implemented, as described below.

2.6.1 Police Enforcement

One of the most effective work zone speed management techniques found in the course of this literature review is police enforcement. There is widespread agreement that the most effective way of controlling speed in the work zone is to have a stationary, staffed police car with flashing lights at the beginning of the work zone (FHWA 1998). Circulating police enforcement, where a police car moves around the work zone, is another type of enforcement, but it is not as effective as stationary police presence.

A study entitled "Field Evaluation of Work Zone Speed Control Techniques" published in 1985 evaluated the short-term effectiveness of four speed control methods: flagging, law enforcement, changeable message signs, and effective lane width reduction (Richard *et al.* 1985). The studies were conducted at six work zone sites on four types of highways: undivided multilane arterial (one site), rural freeway (two sites), urban freeway (one site), and rural two-lane highway (two sites).

To perform the studies, one of the four treatments was installed, the necessary data were collected, and the treatment was removed. When the treatment had been completely removed and traffic had returned to normal, another treatment was installed and the procedure was repeated. Treatments were installed in one travel direction only. Allowing time for data collection, each treatment was in place for one to two hours. In general, two or three treatments, plus a base condition, were evaluated per day at a site. Thus, the studies took three to four days to complete at each site. Studies were conducted only during daylight, off-peak periods when traffic was free flowing.

Treatment effects on speeds were determined by evaluating speeds at three speed stations within the work zone study sites. The first speed station at each site was located upstream and out of sight of any work zone signing or activity. The second station was immediately downstream of where the speed control treatments were implemented. The third and final station was positioned farther downstream of the treatment location to determine if the treatments suppressed speeds beyond the point of treatment. For each treatment, 125-vehicle speed samples were collected simultaneously at the three speed stations. Speeds were determined by measuring vehicle travel times through a marked distance of 200-feet on the roadway. Travel times were manually measured and recorded using digital, electronic stopwatches.

Treatments were evaluated on the basis of their effectiveness in reducing speeds at Station Two. Flagging that complied with the Manual on Uniform Traffic Control Devices (MUTCD) reduced mean speed only 5 to 12 percent at freeways; stationary police cars reduced mean speed 8 to 15 percent at freeways; changeable message signs reduced speed 3 to 9 percent at freeways; and effective lane reduction treatment reduced mean speed only 3 percent at freeways. From this study it was found that a stationary patrol car was the most effective in reducing speed on freeways.

Noel et al. studied a six-lane freeway in Delaware under one-and two-lane-closure conditions during short-term (about three days) and long-term (more than 10 days) data collection periods for four speed control measures: MUTCD flagging, innovative flagging, stationary police cruiser with lights and radar on, and uniformed police traffic controller (Noel *et al.* 1987). Eight study sites were selected on Interstate 495. Researchers measured speed at three locations: where the first warning sign for the work zone was placed (Station A), the starting point of lane closure (Station B), and in the work area (Station C). For each treatment and speed station, at least 100 speed observations per lane were made. Two portable electromagnetic loop detectors mounted on rubber mats were used in each through lane to collect speed, volume, and vehicle classification.

The effect of the treatment was evaluated based on the speed change between Station C and the upstream base station, Station A. A stationary police car was found to be significantly more effective in reducing speeds than any other treatment. The long-term study showed that speeds were reduced by 8.4 mph and 6.4 mph for one- and two-lane-closures case studies, respectively. Speeds were increased by 0.8 mph and 1.4 mph and decreased by 3.8 mph and 3.0 mph for one- and two-lane-closures respectively for MUTCD Flagging and Innovative Flagging for long term studies. For the uniformed police controller in the long-term study, speed was reduced by 3.3 mph for both one- and two-lane-closures. For the short-term study, speeds were reduced by 3.7 mph and 4.0 mph for one- and two-lane-closures case studies when the stationary police car was present. MUTCD flagging increased speed by 2.6 mph and reduced speed by 4.7 mph for one- and two-lane-closures, respectively. The uniformed police controller reduced speed 3.5 mph and 5.3 mph for one- and two-lane-closures, respectively. Innovative Flagging reduced speed 1.7 mph and 3.6 mph for one- and two-lane-closures, respectively. In net, this study clearly found the stationary police vehicle to be the most effective speed control method.

The Iowa State Department of Transportation conducted a survey of 63 state transportation agencies with a response rate of 62 percent during the summer of 1999. Every state and a number of non-DOT transportation agencies (e.g., state turnpike commissions) were surveyed. This survey summarized the work zone speed reduction policies or procedures reported by more than 30 state transportation agencies throughout the country (Maze *et al.* 2000). During construction activities, most participating state agencies reported reducing speed limits to 10 mph less than the posted speed. A few agencies often reduce speed limits by 20 mph. Furthermore, among 12 identified speed reduction strategies (i.e., regulatory signs, advisory signs, changeable message signs, police enforcement, ghost police car, flaggers, speed display, drone radar, rumble strips, lane narrowing, pavement marking, and highway advisory radio) the use of regulatory speed limit signs and police enforcement are the most common practices reported by the agencies. Only 7% of the participating agencies consider the use of regulatory signs to be an effective speed reduction strategy. Most of the agencies (70%) consider police enforcement to be very effective in imposing speed limit compliance at work zones.

The State of North Carolina performed a research study to examine motorist perceptions, opinions, expectations, and other psychological factors which influence their driving activity in work zones (Kane *et al.* 1999). Most drivers report that while they usually feel calm in work zones, there are situations when they feel uncertain or confused. Many drivers also reported that they sometimes feel nervous, uncomfortable, or irritated. These undesirable feelings often result from speeding and discourteous driving by others. Drivers agreed that an increased presence of law enforcement would have the greatest effect on driver behavior in work zones.

2.6.2 Enhanced Fines Legislation

Enhanced fines legislation for violations occurring in work zone areas has become extremely popular and has been implemented in most states. In 1990, only three states had enacted legislation of this type. By 1997, 42 of the 50 states had adopted similar legislation. The majority (28 of 42) of enhanced fine laws passed by the states are limited to speeding violations within a work zone. Nine of 42 states (21%) increase fines for all traffic violations that occur within a work zone. Thirteen (31%) of the states with enhanced fines legislation specified actual fine amounts (generally higher than normal) to be levied for violations cited within the work zone. Other states specify that the fine will be either a fixed increase above normal, or doubled, depending on the amount of the original fine (Ullman, *et al.* 1997).

Another common stipulation found in many of the states' laws requires that construction or maintenance workers must be present in the work zone at the time of violation for the increased fine structure to be valid. Arkansas limits increased fines to work zones located on access-controlled facilities (Ullman, *et al.* 1997).

"Analysis of fatal accidents occurring in work zones between 1984 and 1995 indicated that the implementation of an increased fine law had no consistently measurable effect upon fatal work zone accident frequency. A few states showed a significant change in accident frequencies (some increased, others decreased). Fatal work zone accidents in most states with legislation, however, did not differ significantly from what would have been expected had no legislation been enacted" (Ullman, *et al.* 1997).

Limited data were also available on total work zone accidents in states where legislation has been enacted. From those data it appears that the implementation of the law itself has not had a measurable effect on total work zone accident frequencies. Researchers observed a measurable decrease in accidents in Pennsylvania, which began placing stationary law enforcement personnel in the approach area to each work zone (Ullman, *et al.* 1997).

G. L. Ullman reported that between 1985 and 1995, 50% of the states having a double fine law in place experienced no change in work zone speeds. 28% of the states experienced speed decreases, and 22% of the states experienced speed increases. In Texas, after the implementation of a double fine law, 36% of drivers surveyed said they practiced defensive driving, whereas before the law only 20% of drivers said so (Ullman, 2001).

Texas Transportation Institute (TTI) researchers conducted speed studies at ten work zone sites before and after the implementation of work zone double fine laws. The law was implemented in Texas in January 1998 (Ullman, *et al.* 2000). Test sites ranged from two-lane highways to multilane freeways. Studies were conducted at each site before the initiation of the law (in November and December 1997) and then at the same sites again several months after the law had been implemented (April and May 1998). Researchers measured speeds of at least 125 free-flowing vehicles at each site during daylight, off-peak traffic periods. At seven of the sites, traffic was measured in both directions of travel.

Overall, it appears that the implementation of the law did not have an appreciable effect on speeds at the sites examined. At four of the ten sites, average speeds were unchanged between the before and after conditions. Changes at the remaining sites included both increases and decreases in average speeds. At some sites, average speeds increased in one direction but decreased in the other. Changes in average speed after law implementation (relative to the before-law condition) ranged from a 4 mph decrease at two sites to a 6 mph increase at another. Differences in average speeds were statistically insignificant at six of the ten sites. Similar trends were evident when considering the 85^{th} percentile speed of traffic at these sites.

Significant reductions in motorist non-compliance with the speed limit were noted at only two of the ten sites, while at another site, noncompliance increased significantly. Noncompliance with the posted speed limit was unchanged between the before and after periods at seven of the ten sites. More than two-thirds of the motorists were exceeding the posted speed limit at seven of the ten sites examined.

Alabama implemented double fines legislation on August 1, 2001. The new law states, "Upon conviction of a construction speed zone violation, the operator of the motor vehicle shall be assessed a fine double the amount prescribed by law outside a construction zone. The fine shall only be doubled for construction zone violations if construction personnel are present. The Department of Transportation, or its agents, shall indicate the presence of construction personnel or department employees with appropriate signs. The signs, placed at the entrance of the construction zone, shall also warn of the doubled fines for speeding within a construction zone" (HB 444 1975). The text of the Alabama legislation is included in Appendix A.

2.7 Effect of Speed Variance

Stuster *et al.* (1998) reviewed a study conducted in 1964 involving 10,000 drivers on 600 miles of rural highways. This study obtained a relationship between vehicle speed and crash incidence. According to that relationship, crash rates were lowest for travel speeds near the mean speed of traffic and increased with greater deviations above and below the mean speed. The 1964 study also reported that low speed drivers are more likely to be involved in accidents than relatively high-speed drivers (Solomon 1964). Later, a similar analysis involving 2,000 vehicles involved in daytime crashes on Interstate freeways confirmed Solomon's results (Cirillo 1968).

Australian researchers found a trend of increasing crash involvement for speeds above the mean speed in both rural and urban conditions (Flides, *et al.* 1991). Harkey, *et al.* 1990, replicated the same relationship between crash rates and mean speed on urban roads. Those researchers compared police-estimated travel speed of 532 vehicles involved in crashes over a 3-year period to 24-hr speed data collected on the same section of non-55 mph roads in Colorado and North Carolina.

Hauer (1971) in his theoretical analysis of overtaking stated that "the indiscriminate public crusade against speeding should be replaced by a balanced approach emphasizing the dangers of both fast and slow driving." Lave (1985) mentioned speed variance as a contributor to crashes. He also suggested that raising the speed limit would result in fewer crashes in situations where variance was reduced once the higher speed limit was in place. Lave concluded, "speed limits designed to reduce the fatality rate should concentrate on reducing variance. This means taking action against slow drivers as well as fast ones."

Garber and Gadiraju (1988) reported that minimal variance can be obtained when posted speed limit is less than 10 mph below the design speed. They also concluded that crash rates increased with increasing variance on all types of roadways.

The relationship between crash rate and deviation from the mean speed implies that speed variance is an important parameter of roadway safety.

2.8 Work Zone Speed Limit Procedure

Migletz *et al*. (1999), developed a procedure for setting work zone speed limits. The procedure classifies work zones by the potential hazard present, as represented by the location of work activities or traffic control in relation to the traveled way. They also concluded that a minimal increase in accident rate and speed variance occurred in work zones with a 10 mph reduction in work zone speed limit. They suggested that this procedure could be implementable and could maximize traffic safety in work zones.

2.8.1 First Study

The researchers performed two studies. The first study was to develop a uniform procedure for determining work zone speed limits that was not based on a single existing procedure but rather on the procedures of seven participating states. The second study was to assess the implementability of the procedures for setting work zone speed limits (Migletz, *et al*. 1999).

For the first study, a survey was conducted with a response rate of 87% (45 out of 52 highway agencies). The survey found three general policies for establishing work zone speed limits: (1) avoiding the need for speed limit reductions whenever possible, (2) using blanket speed limit reductions at all work zone sites, and (3) establishing the need for a work zone speed limit reduction based on specific factors.

Migletz conducted another survey with a response rate of 83% (43 out of 52 agencies). It showed that 29% of states avoid reducing work zone speed limits whenever possible, 8% have "blanket" reduced work zone speed limits, and 63% reduce work zone speed limits based on an identified procedure or set of factors.

For the first study, accident data from before and during work activities were collected for work zones. Speed data were collected upstream of and within work zones. Analysis of speed data was structured to determine the effects of specific levels of speed limit restrictions from 0 to 30 mph. The change in mean speed, 85th percentile speed, speed limit compliance, and speed variance from upstream of the work zone to within the work zone were analyzed. An analysis was conducted to determine the work zone speed limit policies that minimized the typical increase in speed variance from upstream of to within the work zone, and that minimized the increase in crash rates from the period before construction to the period during construction.

An average decrease in mean speeds of 5.1 mph was observed in work zones when the speed limit was not reduced at all. In work zones where the speed limit was reduced, the mean speed decreased as the speed limit decreased. The 85th percentile speed reduced similarly, except that the reduction was 2 to 3 mph less than the reduction found for mean speed.

Migletz also found that compliance with work zone speed limits was generally greatest where the speed limit was not reduced, and decreased when the speed limit was reduced by more than 10 mph. In work zones without a speed limit reduction, the percentage of vehicles exceeding the speed limit was 21.7% lower than upstream of the work zone.

Migletz found that for work zones where speed limits were not reduced, the speed variance was 61% higher than the upstream speed variance. For work zones with a speed limit reduction of 10 mph, the increase in speed variance in the work zones was only 34%. For work zones with speed limit reductions of 15 mph or more, the increase in work zone speed variance was 81 to 93%. This finding strongly imputes that a 10-mph speed limit reduction in work zones might offer significant crash reductions.

The research team also performed a crash study. Crash data from before and during work activities were collected for 66 work zone sites. The study showed that the minimum percentage increases in the fatal-plus-injury crash rates occur for a 10-mph speed limit reduction at work zones. Work zones without speed limit reductions had the next smallest increase in the fatal-plus-injury crash rate. The reduction in speed variance (discussed in the previous paragraph) is the most probable reason of the lower crash rate for 10 mph speed limit reductions.

2.8.2 Second Study

The work zone speed limit procedure was validated in the second study through its implementation on a trial basis at 30 work zones in seven states. Work zones where speed limits were not reduced and those where speed limits were reduced by 10 mph were included.

As in the first study, mean speed decreased in work zones even when there was no speed limit reduction. The weighted average reduction of mean speed in work zones with no speed reductions was 4.3 mph for all vehicle types. Reduction in mean speed in work zones with speed limit reductions of 10 mph was 9.4 mph for all vehicle types. Similar changes were observed for 85th percentile speed.

In the second study, speed variances increased by 16% and 10% for speed limit reductions of zero and 10 mph respectively, whereas in first study, speed variance increased by 61 and 34% for speed limit reductions of zero and 10 mph respectively.

2.8.3 Setting Speed Limits

Migletz's recommended work zone speed limit procedure provides a rational method for considering engineering factors in selecting an appropriate work zone speed limit. The approach of classifying work zones by the potential hazard (as represented by location of work activities or traffic controls in relation to the traveled way) is intended to establish speed limits based on actual conditions in the work zone, instead of using the prevailing speed on the work zones.

The recommended procedure has four steps: (a) determine the existing speed limit, (b) determine the work zone condition that applies, (c) determine which factors for appropriate conditions apply to the specific site, and (d) select the work zone speed limit reduction.

Overall, the report suggests that application of the work zone speed limit procedure leads to more uniform speeds and, therefore, should produce safer and more efficient traffic operations than the less-formalized procedures used in setting work zone speed limits in the first study.

Some of Migtetz's results have been adopted in the Millenium Edition MUTCD as shown below:

> Reduced speed limits should be used only in the specific portion of the temporary traffic control zone where conditions or restrictive features are present. However, frequent changes in the speed limits should be avoided. A temporary traffic control plan should be designed so that vehicles can travel through the temporary traffic control zone with a speed limit reduction of no more than 16 km/h (10 mph).
>
> A reduction of more than 16 km/h (10 mph) in the speed limit should be used only when required by restrictive features in the temporary traffic control zone. Where restrictive features justify a speed reduction of more than 16 km/h (10 mph), additional driver notification should be provided. The speed limit should be stepped down in advance of the location requiring the lowest speed, and an additional temporary traffic control warning devices should be used.
>
> Reduced speed zoning (lowering the regulatory speed limit) should be avoided as much as practical because drivers will reduce their speeds only if they clearly perceive a need to do so.
>
> Support:
>
> Research has demonstrated that large reductions in the speed limit, such as a 50 km/h (30 mph) reduction, increase speed variance and the potential for crashes. Smaller reductions in the speed limit of up to 16 km/h (10 mph) cause smaller changes in speed variance and lessen the potential for increased crashes. A reduction in the regulatory speed limit of only up to 16 km/h (10 mph) from the normal speed limit has been shown to be more effective."

2.8 ADAPTIR: An Effective Speed Control System

The ADAPTIR (Automated Data Acquisition and Processing of Traffic Information in Real Time) system uses variable message signs (VMS) equipped with radar units, along with a software program to interpret the data, to display appropriate warning and advisory messages to motorists based on real-time measurements of traffic conditions. The system measures traffic speeds using doppler radar at several points within and upstream of a work zone. The data are then sent to a central control system, which analyzes the data to pinpoint patches of traffic congestion and selects the appropriate prerecorded message to post on the VMS just upstream of the site. The messages prepare the motorists for traffic conditions ahead. According to the developer, the economic benefit of reducing delays and improving safety at work zones can outweigh the cost of the Adaptir system by a factor of six or more. (Scranton Gillette Communications, Incorporated, 1999)

The system was successfully used in Kentucky on I-64. Kentucky concluded that the ADAPTIR system is an effective method to provide real time information to motorists approaching a work zone (Agent 1999).

2.9 Time Headway in Work Zones

A review of relevant literature found no evidence of research that measured time headway within work zones. As previously noted, Lindly, *et al.* 2001 found that “misjudging stopping distance/following too closely” was the most frequent cause of crashes in work zones. Thus, time headway in work zones is an area that should be explored.

Section 3
Design of Experiment

Ensuring the validity of the data collected during the course of research is of great importance, and can be obtained through the design and execution of a statistically sound experimental plan. This section of the report details the construction of the experimental plan.

3.1 Background

The experimental design process requires that a number of parameters and levels be investigated. Parameters are the general variables to be investigated (Example: time of day). Levels are the more specific subsets of parameters (Example: morning or afternoon). Cases are defined (for the purposes of this research) as a parameter-level pair. In order to determine the number of cases to be investigated, the following formula is used:

$$C = L_1^{P_1} + L_2^{P_2} + \ldots + L_n^{P_n} \qquad \text{.........................(1)}$$

Where C = number of cases to be investigated and L = number of levels associated with parameter P.

Because the flow of traffic is fundamentally variable (it is reasonable to assume that traffic parameters such as volume, speed, etc. will vary from one day to the next), one collection of data for each case is not sufficient. A determination must be made as to how many times data must be gathered for each particular case.

This determination is made by assuming that traffic volume is the controlling traffic parameter. The assumption follows that when traffic volume varies significantly, traffic speeds and other traffic parameters will vary accordingly. If traffic volume for a particular case does not vary significantly, then the number of times data must be gathered for that case is minimal. This statistical variance-based data collection determination method is quantified by the equation:

$$n = \left[\frac{z_{\alpha/2}\sigma}{E} \right]^2 \qquad \text{..(2)}$$

Where:

$z_{\alpha/2}$ = the positive z value that is at the vertical boundary for the area of $\alpha/2$ in the right tail of the standard normal distribution. This value is a function of the desired level of confidence of the experiment undertaken.
σ = the population standard deviation
n = sample size
E = Margin of error

This equation is based upon the assumption that traffic volumes are normally distributed (i.e., were traffic volumes over a specified period to be repeatedly collected, the resulting distribution would be normal).

Prior to the execution of the experimental plan, none of the variables contained within the above sample size equation are known. Because volume is assumed to be the controlling variable, it is used as the primary parameter for sample size determination. Volume data must be collected and analyzed in order to calculate a standard deviation and determine an appropriate margin of error.

3.2 Experimental Plan Development

The following section details the development of the experimental plan for this research.

3.2.1 Parameters

As discussed in section 3.1, parameters are the most general variables being investigated in an experiment. In order to reduce the data collection workload, the number of parameters must be carefully selected. For the purposes of this research, the following parameters were chosen:

- Work Zone – Individual work zones were selected in Tuscaloosa, Jefferson, and Montgomery counties. The work zones were selected based upon the type of work being done within them.
- Time – Because traffic flow and the level of work ongoing in construction zones varies widely throughout the day, time has been selected as a parameter for this experiment.
- Law Enforcement – The effect of the presence of law enforcement is of great interest to work zone personnel and transportation officials and is thus included as a parameter. Evidence also suggests that law enforcement presence provides a significant positive influence on vehicular speeds and behaviors.

3.2.2 Levels

Levels are the more specific elements associated with each individual parameter. As evidenced in equation (1), the number of levels used in the construction of the experiment must be carefully limited. Large numbers of levels exponentially increase the number of cases for which data must be collected. For this research project, efforts were made to minimize the number of levels. The selected parameters and their associated levels are summarized in Table 3-1.

Table 3-1. Experimental Parameters and Levels

Parameters	Levels	Short-Form	WZ Type
Work Zone	I-20/59 from Brookwood to I-459 Interchange (Rock Mountain Lakes)	Rock Mountain Lakes	1
	I-65 at Prattville	Prattville	1
	I-20/59 from Fosters to Tuscaloosa	Fosters	2
	I-20/59 from McFarland Blvd. To Brookwood	Brookwood	3
	I-459 (Hoover)	Hoover	4
Time	PM Peak	PM Peak	NA
	Night	Night	NA
Law Enforcement	Law Enforcement Present/Double Fines Signs NOT Present	WZ Police	NA
	Law Enforcement NOT Present/Double Fines Signs NOT Present	Base WZ	NA
	Law Enforcement NOT Present/Double Fines Signs Present	WZ Double Fine	NA
	Law Enforcement Present/Double Fines Present	WZ Police & Double Fine	NA

WZ Type codes: 1= Roadway Widening, 2 = Resurfacing, 3 = Resurfacing at Nighttime, 4 = Interchange Work

It is important to note that only the Brookwood site was subject to nighttime construction work. Also, studies of work zones with "Double Fines Present" signs were restricted to the Fosters, Hoover, and Brookwood work zones. In calculating of the number of cases to be studied, this was taken into account. The required number of cases follows:

> Number Cases = (4 Work Zones/Law Enforcement Present/Double Fines Signs Not Present) + (4 Work Zones/Law Enforcement Not Present/Double Fines Signs Not Present) + (3 Work Zones/Law Enforcement Not Present/Double Fines Signs Present) + (1 Work Zones/Law Enforcements Present/Double Fines Present) = 12 Cases

3.2.3 Level of Confidence

In order to calculate how many times data must be collected for each case, a determination must be made as to what "level of confidence" is acceptable. Level of confidence is defined as:

> The probability value (1-α) associated with a confidence interval, which attempts to provide an estimated range of values for an unknown parameter. In this case, the unknown parameter is the mean of the population μ, and the range of values is ± the margin of error *E.*

The selected level of confidence has a direct effect on the number of samples that must be collected for each particular data case. For most exploratory scientific research (as was conducted during this project), a 90% confidence level is acceptable. Using a 90% confidence interval, the sample size calculation becomes:

$$n = \left[\frac{1.64\sigma}{E}\right]^2 \qquad \text{……………………………………..(3)}$$

3.2.4 Initial Volume Data

Because the population standard deviation (*σ*) for traffic volumes at the work zone locations under investigation was not known, the value was estimated. In order to make this estimate, three data collections were conducted at each work zone prior to primary data collection. During these collections, volume data was collected, and an estimate of the population standard deviation was made.

3.2.5 Margin of Error

Margin of error is an additional statistical measure of the accuracy of the parameter being estimated, in this case the traffic volume. Margin of error has been defined as:

> The acceptable level of variation of the estimated parameter within the specified level of confidence.

For example, "There is a 95% confidence interval that the data collected falls within ± the margin of error of the average".

The determination of margin of error is largely subjective and at the discretion of the experimenter. In order to be consistent throughout the course of this experiment, the acceptable margin of error was set at 7.5% of the mean volume of the data collected during the initial volume data collection for each site. Thus, margin of error might vary from work zone to work zone but will remain a consistent percentage from location to location.

3.2.6 Sample Size Calculations

In order to determine the appropriate sample size needed to ensure a statistically significant sampling of each case, equation (1) was modified to account for a 90% level of confidence, resulting in equation (3). Equation (3), along with preliminary volume counts, was used to determine appropriate sample sizes for each work zone. This calculation translated to performing 3-6 days of counting at each site for each case.

Section 4
Field Methodology

This chapter describes the process of data collection. In short, it answers "Where?" "How?" "When?" and "By whom?" for the data collection process.

4.1 Description of Work Zone Locations

This section states how the specific sites were selected, what type of roadwork was under way, and what traffic control plans (TCP) were used at the sites.

4.1.1 Site Selection Technique

The sites were selected based on the following criteria:

- Functional class of facilities.
- Uninterrupted flow of traffic.
- Variation of the type of work zone.

As discussed in the review of literature, Interstate highways accounted for 23% of work zone accidents in Alabama (Lindly *et al.*, 2001). Given the limited-access nature of this type of facility, uninterrupted flow typically exists. A list of potential construction projects was obtained from ALDOT personnel that were within 100 miles of the University of Alabama. From that list, five Interstate work zone locations were selected in consultation with ALDOT personnel. These five locations were divided into four groups based on the types of roadwork they contained.

4.1.2 Locations of Work Zones

Table 4-1 briefly describes the work zone locations, and Figure 4-1 displays the site locations.

Table 4-1. Description of Work Zone Locations

No.	Work Zone Type	Location	Length of Roadwork (miles)	Time of Road Work	Type of Activity		
					Road Work	Changes in Lanes	Changes in Speed Limit
1	1	Rock Mountain Lakes	9.12	Day	Grade, drain, base, and pave in median with permanent median barrier rail	2 lanes to 2 lanes	70 mph to 55 mph
2	1	Prattville	0.5	Day	Grade, drain, base, and pave in median with permanent median barrier rail	2 lanes to 2 lanes	70 mph to 55 mph
3	2	Fosters	9.66	Day	Planing, resurfacing, guardrail, and traffic stripe	2 lanes to 1 lane	70 mph to 50 mph
4	3	Brookwood	13.62	Night	Planing, resurfacing, guardrail, and traffic stripe	2 lanes to 1 lane	70 mph to 50 mph
5	4	Hoover	1.66	Day	Interchange modification	3 lanes to 3 lanes	70 mph to 55 mph

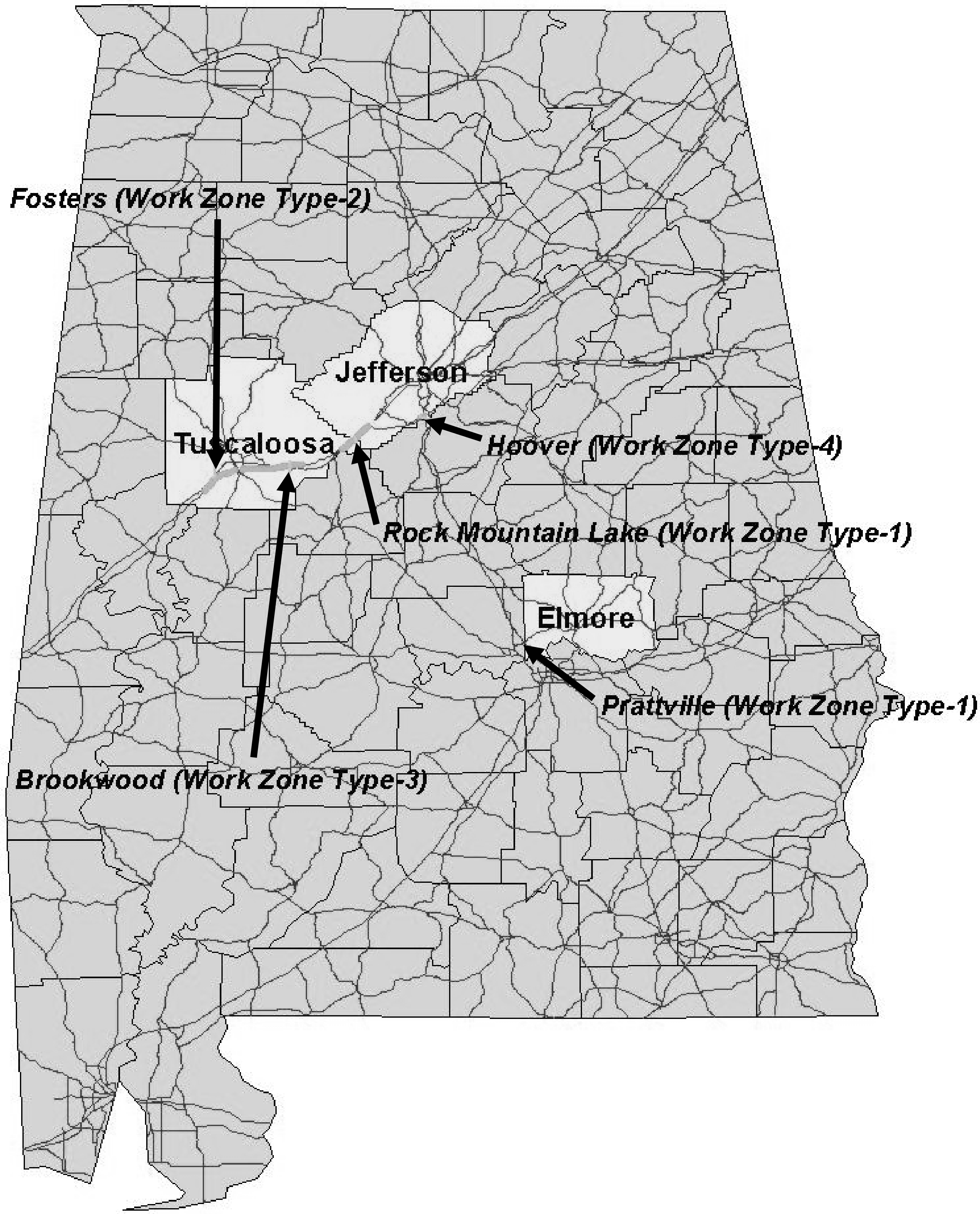

Figure 4-1. Locations of Work Zones.

4.1.3 Description of Work Zones

The following section describes the work zone locations in brief.

Work Zone (WZ) Type 1 WZ Type 1 consists of two locations: Rock Mountain Lakes and Prattville. Road widening was conducted in the median, adjacent to the left lane of the two lanes of the roadway for 9.12 miles and 0.50 miles respectively. As construction did not infringe on the traveled way, no lane closures were necessary. The roadway had two lanes prior to the work zone and two lanes inside the work zone. Work was conducted during the daytime, and the research team collected data from 2:30 to 6:00 pm. At these locations, data was collected for NWZ, Base WZ and WZ Police conditions. NWZ speed limit was 70 mph, and WZ speed limit was 55 mph for these work zones.

Work Zone (WZ) Type 2 WZ Type 2 consists of one location, Fosters, where resurfacing was conducted on one closed lane, and all traffic was diverted to the other lane. At this location, data was collected for the following conditions: NWZ, Base WZ, WZ Double Fine, and WZ Police conditions. NWZ speed limit was 70 mph, and WZ speed limit was 50 mph for this WZ type. Work was conducted during the day, and the research team collected data from 2:30 to 6:00 pm.

Work Zone (WZ) Type 3 WZ Type 3 consists of only the Brookwood location, where resurfacing was conducted on one closed lane, and traffic was diverted to the other lane. At this location, data was collected for only three conditions: NWZ, WZ Double Fine, and WZ Police & Double Fine. As data collection was started at Brookwood after August 1, when the double fines legislation had already been enacted statewide and double fine signs had already been placed, no data could be available for base WZ and WZ Police conditions. Hence, it created another WZ condition, which was WZ Police & Double Fine, with police and double fine signs both present. NWZ speed limit was 70 mph, and WZ speed limit was 50 mph for this WZ type. Work was conducted during the night, and the research team collected data from 8:00 pm to 12:00 pm.

Work Zone (WZ) Type 4 WZ Type 4 consists of the Hoover location. Here, interchange modification work was underway at a ramp near the rightmost lane of the three lanes of the roadway. As construction did not infringe on the traveled way, no lane closures were necessary. Data collection was conducted during the day from 2:30 to 6:00 pm. At this location, data was collected for the following conditions: NWZ, Base WZ, WZ Double Fine, and WZ Police. NWZ speed limit was 70 mph, and WZ speed limit was 55 mph for this WZ type.

4.1.4 Traffic Control Plans (TCPs) in Work Zone Locations

Traffic Control Plans (TCPs) used for the work zone locations were provided by ALDOT and matched with the appropriate TCP from the MUTCD. Table 4-2 shows the TCP's for the different work zone types.

Table 4-2. Description of TCP for the Various Work Zone Types

Work Zone Type	TCP According to MUTCD	
	Typical Application Number	Figure Number & Name
1	5	* 6H-5: Shoulder Closure on Freeway
2	33	6H-33: Stationary Lane Closure on Divided Highway (Short Term)
3	33	6H-33: Stationary Lane Closure on Divided Highway (Short Term)
4	43	6H-43: Partial Exit Ramp Closure

** Indicates that for work zone type 1, all work was in the median instead of the shoulder.*

4. 2 Description of Data Collection Technique

The method by which data was collected during the project is described in this section.

4.2.1 Data Collection Team

Four team members in two groups collected data for each location. One group collected data upstream of the work zone at a location referred to in this report as the "Non Work Zone" location. The other group collected data inside the work zone at a location referred to in this report as the "Work Zone" location.

4. 2. 2 Data Collection Cases

Two speed control measures typically used in work zones are police presence and increased fines. "Police presence" indicates that during roadwork a police car is placed within the work zone. Increased fines legislation was implemented for the first time in Alabama on August 1, 2001. This legislation states that fines are doubled for speeding violations inside work zones. Four basic WZ cases were considered for data collection along with NWZ data:

- NWZ: This is the free flow condition just upstream of the selected work zone sites, where no roadwork is going on. This situation is referred to as the "NWZ" case in this report.
- WZ (No Police, No Double Fine): For this case, inside the work zones, police and double fine signs were absent and only work zone traffic control devices were present. This situation is referred to as the "Base WZ" case in this report.
- WZ (No Police, Double Fine): Here, inside the work zones there were only double fine signs along with base WZ conditions. This situation is referred to as "WZ Double Fine" in this report.
- WZ (Police, No Double Fine): In this situation, only police was present along with base WZ conditions. It is referred to as "WZ Police" in this report. Figure 4-2 shows the typical presence of police in work zones.
- WZ (Police, Double Fine): Here, inside the work zones both police and double fine signs were present along with base WZ conditions. This situation is referred to as " WZ Police & Double Fine" in this report.

The following data was collected for each of the five cases:

- Time headway between vehicles.
- Speed of individual vehicles.
- Total volume of vehicles.
- Length of vehicles.

Figure 4-2. Police Presence in Work Zones.

4.2.3 Number of Data Collection Days

The number of days data would be collected for each case was determined using the formula:

$$n = \left[\frac{z_{\alpha/2}\sigma}{E} \right]^2 \quad \text{..4-1}$$

The details of the equation are discussed in Section 3 'Design of Experiment'. Its use resulted in setting three to six days of data collection per case, depending on the site and the traffic volume at the site (see Table 4-3).

4.2.4 Duration of Data Collection

Data was collected during the typical road construction time, i.e., the months of June to October. As previous research indicated that 4 pm-6 pm is the critical time period for WZ crashes (Lindly *et al.* 2001), data was collected from 2:30 pm – 6 pm for daytime work zones. For the work zone where roadwork was performed at nighttime, data was collected from 8 pm -12 pm.

Table 4-3. Summary of Data Collection Days

Work Zone Type	Location	Number of Days					Data Collection Period
		NWZ	Base WZ	WZ Double Fine	WZ Police	WZ Police & Double Fine	
1	Rock Mountain Lakes	6	6	-	6	-	(2:30-6) pm
1	Prattville	3	3	-	3	-	(2:30-6) pm
2	Fosters	2	2	2	2	-	(2:30-6) pm
3	Brookwood	5	-	5	-	5	(8-12) pm
4	Hoover	3	3	3	3	-	(2:30-6) pm

One assumption was made in determining data collection days: a set of NWZ days is assumed to serve as a valid comparison to all WZ cases. So, for purposes of comparing NWZ data with different WZ cases, NWZ data was collected only once, not four times (one time for each of the four other WZ cases).

Table 4.3 displays some gaps in data collection days. For example, a gap in data collection days for WZ Police & Double Fine is observed for all locations except Brookwood. As data collection was started at Brookwood after August 1, after "fines doubled signs" had been placed at all work zones around the state, it was not possible to collect data without the doubled fine signs present. For this reason, a special case termed "WZ Police & Double Fine" arose at Brookwood. For this same reason, no Base WZ data or WZ Police data could be obtained there.

A gap in data collection is also observed for WZ Double Fine for Rock Mountain Lakes and Prattville. The reason for this gap is that research work was completed at these sites before August 1.

4.2.5 List of Equipment

The research team used the following equipment:

- Two Vans: These vans were used for transportation of team members and storage of project equipment. Two vans were required in order to collect data from two sections of roadway simultaneously.
- Two Econolite Autoscope Solo Pro Machine Vision Processor (MVP) units with the software "Autoscope Network Browser Version 4.2": One camera could collect data across all lanes of one direction of a roadway. These cameras were placed on overpasses to collect data from the roadway below.
- Two Laptop Computers, each having 20 GB of hard drive capacity. Autoscope cameras were connected to the laptops for data collecting and data storing.

- Four Marine Batteries, each having 75 AH of power: The laptops and camera system were powered by marine batteries. Estimated life of the each re-chargeable marine batteries was 8 hours. In practice, 4-6 hours of battery life was routinely observed.
- Two Inverters: Inverters were used to convert the DC current provided by the battery to AC current.
- Two six foot high step ladders: The cameras were mounted on the ladders for data collection as shown in Figure 4-3.
- Traffic Control Devices: Signs, Cones, and Barrels.
- Safety Vests.
- Miscellaneous: Hammer, Rope, Measuring Tape, etc.

4.2.6 TCP Used During Data Collection Period

The equipment was set up on overpasses above the highway being observed. To protect the equipment and personnel, TCP Typical Application 6 (shown in Figure 6H-6: Shoulder Work with Minor Encroachment (TA-6) of the Millennium Edition MUTCD) was used by the research team. The photograph in Figure 4-4 shows the TCP used on an overpass for data collection.

The researchers were concerned that the equipment set up shown in Figure 4-4 was too visible to traffic, potentially affecting traffic behavior. However, to measure all lanes of traffic, the camera must be placed both high over the pavement and not far from the edge of the pavement. The placement on overpasses was adopted as a compromise between visibility by motorists and data collection height requirements.

4.2.7 Amount of Data

Each of the 3.5 to 4-hour periods of data gathering recorded data for 2,000 to 7,000 vehicles. During the 62 periods of data collection, a total of 254,841 vehicles were observed.

Figure 4-3. Placement of Machine Vision Processor Camera on An Overpass.

Figure 4-4. Photograph of TCP Used During Data Collection.

4.2.8 Details of Data Collection Process

Data was acquired with two Econolite Autoscope Solo cameras, mounted on overpasses above the roadway. This camera system is equipped with a machine vision processor (MVP) to automatically collect and tabulate such information as volume, speed, and time headway for several lanes of moving traffic. One camera was used for data collection for all lanes in one direction of a roadway.

Problems Before Data Collection The only problem faced before data collection was finding overpasses within the work zone where the equipment could be placed. For the NWZ case, the research team sometimes had to proceed further than the desired 1 or 2 miles upstream of the WZ location.

The Autoscope needs a height of approximately 30 feet to adequately view enough road for multi-lane data collection. So, an overpass was almost a necessity to set up the Autoscope.

Preparation for Data Collection The Autoscope must be calibrated for each roadway section for which data will be collected. To set the geometry of the location into the camera, the team members measured the height of overpass on which they would set up their equipment, measured the lane width, measured precisely the distance between three points on the roadway that act as reference points, etc. Another preparation step before data collection was to charge fully the marine batteries before field work began.

The Parameters Collected with Autoscope The following data was collected:

- Vehicle Time headway: A Count Detector was placed in each lane of the image of the calibrated roadway section. Whenever a vehicle passed, that count detector turned "on" and increased the counter value by one. When the vehicle leaves, the detector turned "off". This time interval was recorded in milliseconds. From consecutive "off" to "on" readings, time headway could be measured for each vehicle.
- Speed: A Speed Detector was placed in each lane of the calibrated image of the roadway section. Whenever a vehicle passed that detector, speed was recorded in miles per hour to two significant digits.
- Total volume of vehicles: A Station Detector for each lane as well as for the roadway was placed on the calibrated image of the roadway section. This detector was set to record a summary of volume, mean speed, and mean time headway after every 15 minutes of data collection time.

Problems During Data Collection Several problems occurred during the data collection period. Early in this project, 3 to 5 minutes of data were lost when a battery lost power during data collection. Additionally, adverse weather conditions such as heavy rainfall or strong wind sometimes prevented the research team from collecting data.

Data Downloading The data collected through the Autoscope was automatically saved in text format. It was transferred into Microsoft Excel files for further data cleaning and analysis.

Data Reduction From the data stored in Excel files, data from specific detectors were selected and kept in separate worksheets. Then for each specific time period, data was cleaned to isolate desired parameters such as average speed, 85^{th} percentile speed, standard deviation of speed, percent of vehicles above speed limit, average time headway, percent of vehicles below specified time headways, etc.

Section 5
Data Analysis

Table 4-3 showed that data was collected during a total of 62 time periods for the five work zones. For each case (e.g., for the 6 collection periods for Rock Mountain Lakes for the NWZ condition) the data was aggregated into sets. Each set was analyzed to yield the following information:

- Level of service.
- Frequency plots for speed distribution.
- Average speed and 85th percentile speed.
- Hourly and 15-minute distribution of speed.
- Standard Deviation of speed.
- Percent of vehicles above speed limit.
- Effectiveness of speed-control, determined by the percent change in speed from the Base WZ case to police presence and double fine signs case.
- Vehicle time-headways.
- Frequency plots for time headway distribution.
- Standard deviation of time headway.
- Percent of vehicles operating with potentially unsafe time headway (evaluated for both 1.0 seconds and 2.5 seconds).
- Peak hour factor (PHF).

The analyses described above are summarized in Tables 5-1 through 5-15. Tables 5-1 through 5-10 present result of analyses principally performed on raw speed data. The odd numbered tables (Tables 5-1, Table 5-3, etc.) present analyses illustrating mean speed results for the five test sites. The even-numbered tables present analyses illustrating 85th percentile speed for the five test sites.

Tables 5-1 through 5-10 were constructed in three sections. The top section presents mean speed data in mph for each day that data was taken, with standard deviation of speed in parentheses. The middle section illustrates how speed changed from case to case within the site. The lower section presents the site speed limit, percent of vehicles traveling above the speed limit, maximum density, level of service, and average number of vehicles counted daily, for several cases at that site.

Tables 5-11 through 5-15 present time headway analyses for the five sites. The top section presents mean time headway data in seconds for each day data was taken. Values in parenthesis indicate standard deviation of mean time headway. The middle section presents the percent of vehicles traveling below 1.0 second and 2.5 second headways. The lowest section presents speed limit, percent of vehicles traveling above the speed limit, maximum density, and level of service for several cases at a test site. The 1.0 second value of time headway is described in the AASHTO *Green Book* as a potentially suitable value for minimum brake reaction time "for the unexpected event". In a 60 mph work zone, 1.0 second brake reaction time translates to staying at least 88 feet behind the vehicle in front for safety. The *Green Book* goes on to recommend 2.5 seconds for design-criterion brake reaction time because "it exceeds the 90th percentile reaction time for all drivers." Thus, the proportions of vehicles traveling at time headways below those values provide an indirect indication of how many vehicles are using unsafe driving practices (AASHTO 2001).

Much of the remainder of Section 5 will explore the values presented in Tables 5-1 through 5-15.

5.1 Statistical Methods

The data described above was analyzed with three statistical tests.

5.1.1 Normality Test of Speed Data

The following conditions were applied to work zone data collection results:

- Data is collected over the same time period each day (2:30 pm to 6:00 pm data collection for 4 locations and 8:00 pm to 12:00 pm at one location).
- Days assumed to be unique (Alabama football gamedays, holidays, weekends) were excluded from the speed data collection.

Speed data for all five cases (NWZ, Base WZ, WZ Double Fine, WZ Police and WZ Police & Double Fine) for all five locations were tested for normality. According to the Kolmogorov-Smirnov Normality test, at the 95% level of confidence, 60% of the speed data were proven to be normally distributed. As most of the speed data showed normal distribution, it was assumed that overall speed distribution was normal, and data was analyzed based on that assumption.

5.1.2 Hypothesis Testing of Speed Data: One sided Z-test

After aggregating data for the conditions described in Table 4.3, the following questions were investigated:

- Are the double fines signs effective in reducing speeds?
- Is police presence effective in reducing speeds?
- Is the reduction in speed statistically significant?

To answer these questions, one-sided z-tests were performed. Reductions in speed from the NWZ case to each of other four cases were calculated. In the same way, reductions in speed from the Base WZ condition to each of following conditions were calculated: WZ Double Fine, WZ Police, and WZ Police & Double Fine conditions. As shown in Tables 5.1-5.10, speed changes in all these conditions were statistically significant at the 95% level of significance.

5.1.3 Proportion Testing of Time Headway data and Speed Data

Several proportion tests were performed. The first checked whether the percent of vehicles traveling above the speed limit was statistically different from NWZ to Base WZ conditions, then it checked whether the percent of vehicles traveling above the speed limit changed from WZ Base condition to other WZ conditions. A second proportion test checked whether the percent of vehicles below unsafe time headway was statistically different at the various conditions mentioned above. For all cases, the percent of vehicles above the speed limit and the percent of vehicles below unsafe time headways was found to be statistically different.

5.2 Summary of Results

This section summarizes the results of data analysis for all five-work zone locations in four work zones types. It starts with tables 5-1 through 5-15, and then proceeds with a discussion of the observations that may be drawn from the tables and the data from which they were prepared.

Table 5-1. Summary of Mean Speed: Rock Mountain Lakes

WZ Type 1: Grade, Drain, Base, and Pave in Median: Narrowed Left Lane: 2 lanes to 2 lanes

Day Number	NWZ		Base WZ		WZ Police	
	Right Lane	Left Lane	Right Lane	Left Lane	Right Lane	Left Lane
1	67.85 (5.82)	76.20 (5.41)	58.15 (5.30)	58.90 (5.26)	49.00 (4.00)	49.00 (4.00)
2	66.46 (5.62)	68.30 (4.47)	54.51 (4.70)	58.77 (5.63)	49.25 (6.00)	56.60 (5.62)
3	66.56 (5.75)	68.42 (4.60)	57.20 (5.20)	56.80 (4.45)	43.00 (12.00)	49.00 (14.0)
4	67.98 (5.91)	71.10 (4.63)	55.34 (5.10)	59.30 (5.71)	50.20 (6.90)	52.60 (6.32)
5	71.61 (4.60)	74.10 (5.10)	55.10 (4.82)	56.40 (4.80)	45.50 (5.26)	52.20 (5.42)
6	65.46 (5.41)	71.50 (4.76)	56.20 (5.50)	57.10 (5.97)	50.70 (7.40)	56.80 (8.11)
Mean Speed (mph)	67.65	71.60	56.08	57.88	47.94	52.70
Std. Dev. (mph)	5.87	5.60	5.25	5.66	7.83	8.00
Speed hange from NWZ (mph)			-11.57*	-13.72*	-19.71*	-18.90*
% Speed Change from NWZ			-17.10%	-19.20%	-29.14%	-26.40%
Speed Change from WZ [(a)] (mph)					-8.14*	-5.18
% Speed Change from WZ [(a)]					-14.51%	-8.95%
Total Vehicles	14,489	13,806	19,482	14,835	19,232	12,945
Speed Limit	70 mph		55 mph		55 mph	
% Vehicles Over Speed Limit	# 43.50%		# 54.25%		# 14.04%	
Maximum Density	14.13 pc/mi/ln		22.33 pc/mi/ln		23.92 pc/mi/ln	
Level of Service	B		C		C	

Values in parenthesis indicate standard deviation of speed

(a) Indicates WZ without Police and Double Fine

(-) Indicates Reduction in Speed

** Indicates P values from Hypothesis Testing are equal to zero, i.e., speed changes are statistically significant*

(#) Proportion Testing shows that % of vehicles above speed limit is statistically different for the three cases.

Table 5-2. Summary of 85th Percentile Speed: Rock Mountain Lakes

WZ Type 1: Grade, Drain, Base, and Pave in Median: Narrowed Left Lane: 2 lanes to 2 lanes

Day	NWZ		Base WZ		WZ Police	
Number	Right Lane	Left Lane	Right Lane	Left Lane	Right Lane	Left Lane
1	74.00 (5.82)	82.00 (5.41)	63.00 (5.30)	64.00 (5.26)	52.70 (4.00)	52.80 (4.00)
2	72.00 (5.62)	73.00 (4.47)	65.00 (4.70)	65.00 (5.63)	55.00 (6.00)	63.00 (5.62)
3	72.00 (5.75)	73.00 (4.60)	62.00 (5.20)	62.00 (4.45)	51.50 (12.00)	56.40 (14.00)
4	74.00 (5.91)	76.00 (4.63)	60.00 (5.10)	66.00 (5.71)	58.00 (6.90)	59.00 (6.32)
5	77.00 (4.60)	79.00 (5.10)	60.00 (4.82)	62.00 (4.80)	51.00 (5.26)	58.00 (5.42)
6	71 (5.41)	76.00 (4.76)	60.00 (5.50)	62.00 (5.97)	58.00 (7.40)	63.00 (8.11)
Mean 85^{th} % Speed (mph)	73.33	76.50	61.67	63.50	54.37	58.70
Std. Dev. (mph)	5.87	5.60	5.25	5.66	7.83	8.00
Speed Change from NWZ (mph)			-11.66*	-13.00*	-18.96*	-17.80*
% Speed Change from NWZ			-15.90%	-17.00%	-25.86%	-23.27%
Speed Change from WZ [(a)] (mph)					-7.30*	-4.80*
% Speed Change from WZ [(a)]					-11.84%	-7.56%
Total Vehicles	14,489	13,806	19,482	14,835	19,232	12,945
Speed Limit	70 mph		55 mph		55 mph	
% of Vehicles Above speed limit	# 43.50%		# 54.25%		# 14.04%	
Maximum Density	14.13 pc/mi/ln		22.33 pc/mi/ln		23.92 pc/mi/ln	
Level of Service	B		C		C	

Values in parenthesis indicate standard deviation of speed

(a) Indicates WZ without Police and Double Fine

(-) Indicates Reduction in Speed

** Indicates P values from Hypothesis Testing are equal to zero, i.e., speed changes are statistically significant*

(#) Proportion Testing shows that % of vehicles above speed limit is statistically different for the three cases.

Table 5-3. Summary of Mean Speed: Prattville

Work Zone Type 1: Grade, Drain, Base, and Pave in Median: Narrowed Left Lane: 2 lanes to 2 lanes

Day Number	NWZ		Base WZ		WZ Police	
	Right Lane	Left Lane	Right Lane	Left Lane	Right Lane	Left Lane
1	65.50 (5.42)	71.50 (4.75)	61.44 (5.60)	65.55 (4.97)	58.60 (5.47)	61.30 (5.53)
2	67.60 (5.64)	73.04 (4.88)	58.84 (5.94)	62.76 (5.54)	58.91 (5.89)	61.00 (5.80)
3	65.31 (5.57)	69.44 (4.85)	58.35 (5.80)	65.34 (4.60)	54.72 (5.27)	56.22 (5.43)
Mean Speed (mph)	66.14	71.33	59.54	64.55	57.41	59.51
Std. Dev. (mph)	5.62	4.95	5.94	5.32	5.85	6.04
Speed Change from NWZ (mph)			-6.60*	-6.78*	-8.73*	-11.82*
% Speed Change from NWZ			-10.00%	-9.51%	-13.20%	-16.60%
Speed Change from WZ[(a)] (mph)					-2.13*	-5.04*
% Speed Change from NWZ					-3.58%	-7.81%
Total Vehicles	6,969	5,344	6,026	7,376	8,283	9,127
Speed Limit	70 mph		55 mph		55 mph	
% Vehicles Over Speed Limit	# 24.40%		# 86.99%		# 70.03%	
Maximum Density	13.43 pc/mi/ln		18.40 pc/mi/ln		23.35 pc/mi/ln	
Level of Service	B		C		C	

Values in brackets indicate standard deviation of speed

(a) Indicates WZ without Police and Double Fine

(-) Indicates Reduction in Speed

** Indicates P values from Hypothesis Testing are equal to zero, i.e., speed changes are statistically significant*

(#) Proportion Testing shows that % of vehicles above speed limit is statistically different for the three cases.

Table 5-4. Summary of 85th Percentile Speed: Prattville

Work Zone Type 1: Grade, Drain, Base, and Pave in Median: Narrowed Left Lane: 2 lanes to 2 lanes

Day Number	NWZ		Base WZ		WZ Police	
	Right Lane	Left Lane	Right Lane	Left Lane	Right Lane	Left Lane
1	71.00 (5.42)	76.00 (4.75)	67.00 (5.60)	71.00 (4.97)	64.00 (5.47)	67.00 (5.53)
2	73.00 (5.64)	78.00 (4.88)	65.00 (5.94)	68.00 (5.54)	65.00 (5.89)	67.00 (5.80)
3	71.00 (5.57)	74.00 (4.85)	65.00 (5.80)	70.00 (4.60)	60.00 (5.27)	62.00 (5.43)
Mean 85th % speed (mph)	71.67	76.00	65.67	69.67	63.00	65.33
Std. Dev. (mph)	5.62	4.95	5.94	5.32	5.85	6.04
Speed Change from NWZ (mph)			-6.00*	-6.33*	-8.67*	-10.67*
% Speed Change from NWZ			-8.37%	-8.33%	-12.10%	-14.04%
Speed Change from WZ[(a)] (mph)					-2.67*	-4.34*
% Speed Change from WZ					-4.10%	-6.23%
Total Vehicles	6,969	5,344	6,026	7,376	8,283	9,127
Speed Limit	70 mph		55 mph		55 mph	
% Vehicles Over Speed Limit	# 24.40%		# 86.99%		# 70.03%	
Maximum Density	13.43 pc/mi/ln		18.40 pc/mi/ln		23.35 pc/mi/ln	
Level of Service	B		C		C	

Values in brackets indicate standard deviation of speed

(a) Indicates WZ without Police and Double Fine

(-) Indicates Reduction in Speed

** Indicates P values from Hypothesis Testing are equal to zero, i.e., speed changes are statistically significant*

(#) Proportion Testing shows that % of vehicles above speed limit is statistically different for the three cases.

Table 5-5. Summary of Mean Speed: Fosters

WZ Type 2: Planing, Resurfacing, Guardrail, and Traffic Stripe: Periodic Lane Closure: 2 lanes to 1 lane

Day Number	NWZ	Base WZ	WZ Double Fine	WZ Police
1	65.22 (5.78)	52.40 (9.83)	53.92 (5.76)	48.84 (4.48)
2	64.04 (6.40)	48.48 (6.20)	50.92 (5.76)	23.87 (10.12)
Mean Speed (mph)	64.63	50.43	52.42	36.36
Std. Dev. (mph)	6.11	7.45	5.95	14.72
Speed Change from NWZ (mph)		-14.20*	-12.21*	-28.27*
% Speed Change from NWZ		-21.97%	-18.90%	-43.74%
Speed Change from WZ [a] (mph)			+1.99*	-14.07*
% Speed Change from WZ [a]			+3.95%	-27.90%
Total Vehicles	5,089	4,567	4,427	4,168
Speed Limit	70 mph	50 mph	50 mph	50 mph
% of Vehicles Over Speed Limit	# 13.33	# 43.10	# 58.10	# 16.76
Maximum Density	8.04 pc/mi/ln	20.00 pc/mi/ln	19.34 pc/mi/ln	23.40 pc/mi/ln
Level of Service	A	C	C	C

Values in parenthesis indicates Standard Deviation

(a) Indicates WZ without Police and Double Fine.

(-) Indicates Reduction in Speed.

(+) Indicates Increase in Speed.

** Indicates P values from Hypothesis Testing are equal to zero, i.e., speed changes are statistically significant*

(#) Proportion Testing shows that % of vehicles above speed limit is statistically different for the three cases.

Table 5-6. Summary of 85th Percentile Speed: Fosters

WZ Type 2: Planing, Resurfacing, Guardrail, and Traffic Stripe: Periodic Lane Closure: 2 lanes to 1 lane

Day Number	NWZ	Base WZ	WZ Double Fine	WZ Police
1	70.50 (5.78)	61.00 (9.83)	60.00 (5.76)	34.00 (10.12)
2	70.00 (6.40)	54.00 (6.20)	57.00 (5.76)	53.00 (4.48)
Mean 85^{th}% Speed (mph)	70.25	57.50	58.50	43.50
Std. Dev. (mph)	6.11	7.45	5.95	14.72
Speed Change from NWZ (mph)		-12.75*	-11.75*	-26.75*
% Speed Change from NWZ		-18.15%	-16.73%	-38.10%
Speed Change from WZ [(a)] (mph)			+1.00*	-14.00*
% Speed Change from WZ [(a)]			+1.74%	-24.35%
Total Vehicles	5,089	4,567	4,427	4,168
Speed Limit	70 mph	50 mph	50 mph	50 mph
% of Vehicles above speed limit	# 13.33	# 43.10	# 58.10	# 16.76
Maximum Density	8.04 pc/mi/ln	20.00 pc/mi/ln	19.34 pc/mi/ln	23.40 pc/mi/ln
Level of Service	A	C	C	C

Values in parenthesis indicates Standard Deviation

(a) Indicates WZ without Police and Double Fine.

(-) Indicates Reduction in Speed.

(+) Indicates Increase in Speed.

** Indicates P values from Hypothesis Testing are equal to zero, i.e., speed changes are statistically significant*

(#) Proportion Testing shows that % of vehicles above speed limit is statistically different for the three cases.

Table 5-7. Summary of Mean Speed: Brookwood

WZ Type 3: Planing, Resurfacing, Guardrail, and Traffic Stripe: Periodic Lane Closure: 2 lanes to 1 lane: Night work: No Base WZ

Day Number	NWZ	Base WZ	WZ Police
1	78.04 (9.44)	39.77 (7.90)	32.45 (6.10)
2	69.00 (8.76)	43.29 (18.90)	16.32 (5.90)
3	77.44 (7.25)	48.50 (15.40)	17.01 (4.88)
4	73.23 (8.60)	61.77 (11.11)	23.51 (6.59)
5	70.91(7.78)	61.96 (8.11)	17.73 (5.26)
Mean Speed (mph)	73.72	51.06	21.40
Std. Dev. (mph)	8.99	15.80	7.25
Speed Change from NWZ (mph)		-21.66*	-52.32*
% Speed Change from NWZ		-29.40%	-70.97%
Total Vehicles	7,745	9,362	7,352
Speed Limit	70 mph	50 mph	50 mph
% Vehicles Over Speed Limit	# 61.98	# 54.20	# 0.12
Maximum Density	4.22 pc/mi/ln	17.00 pc/mi/ln	56.99 pc/mi/ln
Level of Service	A	B	E

Values in brackets indicate standard deviation of speed

(-) Indicates Reduction in Speed

** Indicates P values from Hypothesis Testing are equal to zero, i.e., speed changes are statistically significant*

(#) Proportion Testing shows that % of vehicles above speed limit is statistically different for the three cases.

Table 5-8. Summary of 85th Percentile Speed: Brookwood

WZ Type 3: Planing, Resurfacing, Guardrail, and Traffic Stripe: Periodic Lane Closure: 2 lanes to 1 lane: Night work: No Base WZ

Day Number	NWZ	Base WZ	WZ Police
1	88.00 (9.44)	48.00 (7.90)	38.00 (6.10)
2	78.50 (8.76)	64.00 (18.90)	22.00 (5.90)
3	84.50 (7.25)	64.00 (15.40)	22.00 (4.88)
4	80.50 (8.60)	72.00 (11.11)	30.00 (6.59)
5	78.00 (7.78)	70.00 (8.11)	22.00 (5.26)
Mean 85^{th}% Speed (mph)	81.90	63.60	26.80
Std. Dev. (mph)	8.99	7.25	15.80
Speed Change from NWZ (mph)		-18.30*	-55.10*
% Speed Change from NWZ		-22.34%	-67.30%
Total Vehicles	7,745	9,362	7,352
Speed Limit	70 mph	50 mph	50 mph
% of Vehicles Above speed limit	# 61.98	# 54.20	# 0.12
Maximum Density	4.22 pc/mi/ln	17.00 pc/mi/ln	56.99 pc/mi/ln
Level of Service	A	B	E

Values in brackets indicate standard deviation of speed

(-) Indicates Reduction in Speed

** Indicates P values from Hypothesis Testing are equal to zero, i.e., speed changes are statistically significant*

(#) Proportion Testing shows that % of vehicles above speed limit is statistically different for the three cases.

Table 5-9. Summary of Mean Speed: Hoover

WZ Type 4: Interchange Modification: Road Work on Ramp along the Right Lane: 3 lanes to 3 lanes

Day	NWZ			Base WZ			WZ Double Fine			WZ Police		
Number	Right	Middle	Left	Right	Middle	Left	Right	Middle	Left	Right	Middle	Left
1	64.74	69.6	77.12	57.06	61.62	67.76	56.95	59.50	65.34	48.55	49.65	52.82
	(5.58)	(4.93)	(5.00)	(5.88)	(5.67)	(10.20)	(5.36)	(5.52)	(7.64)	(8.20)	(5.84)	(12.61)
2	71.7	68.91	69.68	60.77	64.97	67.6	52.2	56.56	58.34	38.14	47.13	51.09
	(5.71)	(4.61)	(4.55)	(5.42)	(6.14)	(12.66)	(5.68)	(5.14)	(9.63)	(17.43)	(7.30)	(10.46)
3	65.06	68.93	75.9	61.47	65.31	72.03	53.13	54.35	57.65	52.79	51.17	54.39
	(5.61)	(5.05)	(5.53)	(7.45)	(9.20)	(7.83)	(5.14)	(4.57)	(6.57)	(5.28)	(3.84)	(9.70)
Mean Speed (mph)	67.17	69.15	74.23	59.77	63.97	69.13	54.09	56.80	60.44	46.49	49.32	52.77
Std. Dev. (mph)	6.50	4.87	6.00	6.60	7.30	10.66	5.77	5.02	8.82	14.10	6.35	11.10
Speed Change from NWZ (mph)				* -7.40	* -5.18	* -5.10	* -13.08	* -12.35	*-13.79	*-20.68	*-19.83	*-21.46
% Speed Change From NWZ				-11.01%	-7.51%	-6.87%	-19.50%	-17.90%	-18.60%	-30.77%	-28.68%	-28.91%
Speed Change from WZ [(a)](mph)							* -5.68	* -7.17	* -8.69	* -13.28	* -14.65	* -16.36
% Speed Change From WZ							-9.50%	-11.21%	-12.57%	-22.22%	-22.90%	-23.67%
Total Vehicles	4,596	6,883	3,686	6,729	8,539	4,838	7,156	8,807	4,355	6,336	7,560	4,732
Speed Limit	70			55			55			55		
% Vehicles Over Speed Limit	# 42.95			# 87.30			# 48.30			# 16.25		
Maximum Density	9.75 pc/mi/ln			12.20 pc/mi/ln			14.07pc/mi/ln			15.30 pc/mi/ln		
Level of Service	A			B			B			B		

Values in parenthesis indicate standard deviation of speed

(a) Indicates WZ without Police and Double Fine

(-) Indicates Reduction in Speed

** Indicates P values from Hypothesis Testing are equal to zero, i.e., speed changes are statistically significant*

(#) Proportion Testing shows that % of vehicles above speed limit is statistically different for the three cases.

Table 5-10. Summary of 85th Percentile Speed: Hoover

WZ Type 4: Interchange Modification: Road Work on Ramp along the Right Lane: 3 lanes to 3 lanes

Day Number	NWZ			Base WZ			WZ Double Fine			WZ Police		
	Right	Middle	Left	Right	Middle	Left	Right	Middle	Left	Right	Middle	Left
1	70.00	74.35	82.00	63.00	67.00	76.00	62.00	65.00	72.00	56.00	55.00	61.00
	(5.58)	(4.93)	(5.00)	(5.88)	(5.67)	(10.20)	(5.36)	(5.52)	(7.64)	(8.20)	(5.84)	(12.61)
2	78.00	73.00	74.00	66.00	71.00	77.00	58.00	62.00	65.00	54.00	54.00	59.00
	(5.71)	(4.61)	(4.55)	(5.42)	(6.14)	(12.66)	(5.68)	(5.14)	(9.63)	(17.43)	(7.30)	(10.46)
3	70.00	74.00	82.00	68.00	73.00	79.00	58.00	59.00	63.00	58.00	55.00	59.00
	(5.61)	(5.05)	(5.53)	(7.45)	(9.20)	(7.83)	(5.14)	(4.57)	(6.57)	(5.28)	(3.84)	(9.70)
Mean 85th% Speed (mph)	72.67	73.78	79.33	65.67	70.33	77.33	59.33	62.00	66.67	56.00	54.67	59.67
Std. Dev.(mph)	6.50	4.87	6.00	6.60	7.30	10.66	5.77	5.02	8.82	14.10	6.35	11.10
Speed Change From NWZ (mph)				* -7.00	* -3.45	* -2.00	* -13.34	* -11.78	*-12.66	*-16.67	*-19.11	*-19.66
% Speed Change from NWZ				-9.63%	-4.68%	-2.52%	-18.36%	-15.96%	-15.96%	-22.94%	-25.90%	-24.78%
Speed Change from WZ [(a)](mph)%							* -6.34	* -8.33	* -10.66	* -9.67	* -15.66	* -17.66
Speed Change from WZ							-9.65%	-11.84%	-13.85%	-14.73%	-22.27%	-22.84%
Total Vehicles	4,596	6,883	3,686	6,729	8,539	4,838	7,156	8,807	4,355	6,336	7,560	4,732
Speed Limit	70			55			55			55		
% Vehicles over Speed Limit	# 42.95			# 87.30			# 48.30			# 16.25		
Maximum Density	9.75 pc/mi/ln			12.20 pc/mi/ln			14.07pc/mi/ln			15.30 pc/mi/ln		
Level of Service	A			B			B			B		

Values in parenthesis indicate standard deviation of speed

(a) Indicates WZ without Police and Double Fine

(-) Indicates Reduction in Speed

** Indicates P values from Hypothesis Testing are equal to zero, i.e., speed changes are statistically significant*

(#) Proportion Testing shows that % of vehicles above speed limit is statistically different for the three cases.

Table 5-11. Summary of Mean Time Headway (TH): Rock Mountain Lakes

WZ Type 1: Grade, Drain, Base, and Pave in Median: Narrowed Left Lane: 2 lanes to 2 lanes

Day Number	NWZ		Base WZ		WZ Police	
	Right Lane	Left Lane	Right Lane	Left Lane	Right Lane	Left Lane
1	4.48 (3.53)	4.11 (5.40)	3.20 (4.54)	4.10 (6.36)	3.28 (3.28)	5.27 (7.24)
2	4.56 (3.74)	4.86 (6.79)	3.20 (4.35)	3.87 (6.16)	3.76 (3.66)	6.41 (8.51)
3	4.40 (3.50)	4.60 (6.33)	3.84 (5.30)	4.60 (7.22)	3.57 (3.62)	6.17 (9.20)
4	5.07 (4.23)	6.64 (8.53)	4.03 (5.35)	4.57 (7.24)	3.40 (3.42)	5.66 (7.40)
5	5.00 (3.95)	5.85 (8.02)	3.41 (4.81)	4.31 (6.70)	3.28 (3.28)	5.27 (7.25)
6	4.52 (3.75)	5.20 (7.42)	3.13 (4.70)	4.40 (6.84)	2.86 (2.81)	3.97 (5.82)
Mean TH (sec)	4.53	5.07	3.41	4.28	3.36	5.33
Std. Dev. (sec)	3.80	7.03	4.84	6.74	3.37	7.55
%TH lower than 1.0 s	# 18.50%		# 35.20%		# 25.70%	
%TH lower than 2.5 s	# 43.66%		# 63.76%		# 54.05%	
Total Vehicles	14,489	13,806	19,482	14,835	19,232	12,945
Speed Limit	70 mph		55 mph		55 mph	
% Vehicles Over Speed Limit	# 43.50%		# 54.25%		# 14.04%	
Maximum Density	14.13 pc/mi/ln		22.33 pc/mi/ln		23.92 pc/mi/ln	
Level of Service	B		C		C	

Values in parenthesis indicates standard deviation

(#) Proportion testing shows % of TH lower than both 1.0 seconds and 2.5 seconds are statistically different for the three cases.

Table 5-12 Summary of Mean Time Headway (TH): Prattville

WZ Type I: Grade, Drain, Base, and Pave in Median; Narrowed Left Lane: Two Lanes to Two Lanes

	NWZ		Base WZ		WZ Police	
Day Number	Right Lane	Left Lane	Right Lane	Left Lane	Right Lane	Left Lane
1	4.48 (3.53)	4.12 (5.42)	5.50 (4.76)	9.67 (12.33)	3.52 (4.25)	3.81 (5.68)
2	4.70 (4.38)	9.50 (12.67)	5.10 (4.64)	2.97 (4.20)	3.76 (4.14)	3.42 (5.05)
3	5.50 (4.84)	9.95 (12.86)	5.05 (4.83)	3.58 (5.34)	5.11 (4.87)	4.00 (5.62)
Mean TH (sec.)	4.90	7.86	5.20	4.12	4.13	3.74
Std. Dev. (sec.)	4.25	9.73	4.74	6.73	4.43	5.44
% TH below 1.0 s	# 16.56%		# 24.41%		# 30.10%	
% TH below 2.5 s	# 40.86%		# 50.23%		# 56.86%	
Total Vehicles	6,969	5,344	6,026	7,376	8,283	9,127
Speed Limit	70 mph		55 mph		55 mph	
% of Vehicles Over Speed Limit	# 24.40%		# 86.99%		# 70.03%	
Maximum Density	13.43 pc/mi/ln		18.40 pc/mi/ln		23.35 pc/mi/ln	
Level of Service	B		C		C	

Values in parentheses indicate standard deviations.

 # Proportional testing shows that percentages of TimeHeadways lower than both 1.0 seconds and 2.5 seconds are statistically different for the three cases.

Table 5-13. Summary of Mean Time Headway (TH): Fosters

WZ Type 2: Planing, Resurfacing, Guardrail, and Traffic Stripe: Periodic Lane Closure: 2 lanes to 1 lane

Day Number	NWZ	Base WZ	WZ Double Fine	WZ Police
1	8.86 (11.00)	10.30 (17.32)	4.69 (5.83)	3.91 (5.00)
2	9.97 (12.90)	4.72 (8.13)	4.69 (5.83)	5.15 (8.31)
Mean TH (sec)	9.40	6.20	4.69	4.50
Std. Dev. (sec)	11.94	11.58	5.83	6.82
% TH below 1.0 s	(#) 10.33	(#) 17.55%	(#) 20.20%	(#) 21.43%
% TH below 2.5 s	(#) 29.30%	(#) 54.92%	(#) 50.80%	(#) 56.82%
Total Vehicles	5,089	4,567	4,427	4,168
Speed Limit	70 mph	50 mph	50 mph	50 mph
% of Vehicles above speed limit	# 13.33		# 43.10	
Maximum Density	8.04 pc/mi/ln	20.00 pc/mi/ln	19.34 pc/mi/ln	23.40 pc/mi/ln
Level of Service	A	C	C	C

Values in parenthesis indicates standard deviation

(#) Proportion testing shows that % of TH lower than both 1.0 seconds and 2.5 seconds are statistically different for the three cases

Table 5-14. Summary of Mean Time Headway (TH): Brookwood

WZ Type 3: Planing, Resurfacing, Guardrail, and Traffic Stripe: Periodic Lane Closure: 2 lanes to 1 lane: Night work: No Base WZ

Day Number	NWZ	WZ Double Fine	WZ Police & Double Fine
1	19.69 (26.82)	10.16 (17.83)	8.80 (11.61)
2	15.10 (23.23)	5.70 (9.14)	3.05 (5.47)
3	11.72 (15.40)	8.48 (12.91)	3.90 (6.15)
4	18.55 (27.36)	5.31 (8.48)	5.20 (8.33)
5	14.36 (18.92)	7.11 (11.95)	4.78 (8.65)
Mean TH (sec)	15.88	6.96	4.67
Std. Dev. (sec)	22.15	11.86	7.97
% TH below 1.0 s	(#) 7.01%	(#) 38.61%	(#) 25.55%
% TH below 2.5 s	(#) 19.50%	(#) 58.1%	(#) 48.34%
Total Vehicles	7,745	9,362	7,352
Speed Limit	70 mph	50 mph	50 mph
% Vehicles Over Speed Limit	# 61.98	# 54.20	# 0.12
Maximum Density	4.22 pc/mi/ln	17.00 pc/mi/ln	56.99 pc/mi/ln
Level of Service	A	B	E

Values in parenthesis indicates standard deviation

(#) Proportion testing shows that % of TH lower than both 1.0 seconds and 2.5 seconds are statistically different for the three cases.

Table 5-15. Summary of Mean Time Headway (TH): Hoover

WZ Type 3: Interchange Modification: Road Work on Ramp along the Right Lane: 3 lanes to 3 lanes

Day	NWZ			Base WZ			WZ Double Fine			WZ Police		
Number	Right	Middle	Left	Right	Middle	Left	Right	Middle	Left	Right	Middle	Left
1	7.65	4.98	10.06	5.08	3.83	6.68	5.31	4.01	8.97	5.23	4.11	7.66
	(6.98)	(4.54)	(12.21)	(4.93)	(3.77)	(8.42)	(5.46)	(4.22)	(11.06)	(5.00)	(4.00)	(9.33)
2	7.72	5.00	9.65	5.24	3.85	6.91	4.26	3.49	6.44	3.62	3.32	4.92
	(6.89)	(4.57)	(11.84)	(5.32)	(3.91)	(8.26)	(4.37)	(3.62)	(7.71)	(4.48)	(3.47)	(6.53)
3	8.15	5.37	9.29	5.24	3.99	7.37	4.69	3.55	8.53	4.23	3.52	6.40
	(6.76)	(4.89)	(11.45)	(5.27)	(4.17)	(9.47)	(4.85)	(3.80)	(10.94)	(4.06)	(3.57)	(7.96)
Mean TH (s)	7.84	5.12	9.67	5.19	3.89	6.99	4.75	3.68	7.98	4.36	3.65	6.33
Std. Dev. (s)	6.88	4.67	11.83	5.17	3.95	8.71	4.90	3.88	9.91	4.62	3.70	7.88
% TH below 1.0 s	# 10.83%			# 17.85%			# 19.63%			# 20.40%		
% TH below 2.5 s	#30.50%			# 42.71%			# 45.04%			# 47.88%		
Total Vehicles	4,596	6,883	3,686	6,729	8,539	4,838	7,156	8,807	4,355	6,336	7,560	4,732
Speed Limit	70 mph			55 mph			55 mph			55 mph		
% Vehicles Over Speed Limit	# 42.95			# 87.30			# 48.30			# 16.25		
Maximum Density	9.75 pc/mi/ln			12.20 pc/mi/ln			14.07pc/mi/ln			15.30 pc/mi/ln		
Level of Service	A			B			B			B		

Values in parenthesis indicates standard deviation

(#) Proportion testing shows that % of TH lower than both 1.0 seconds and 2.5 seconds are statistically different for the three cases

5. 2. 1 Summary of Volume/Density/PHF Data

Using guidelines established in the *Highway Capacity Manual* (HCM), levels of service (LOS) for the NWZ condition and approximated LOS for the WZ conditions were determined. They are listed in Tables 5-1 through 5-15. Exhibit 23-2, "LOS Criteria for Basic Freeway Segments" of Chapter 23, "Basic Freeway Segments of Highway Capacity Manual" was used for determining LOS for both NWZ and WZ conditions. To obtain LOS values using Exhibit 23-2, Free Flow Speeds (FFS) should be within 75 mph to 55 mph. For the NWZ condition, free flow speed was 70 mph, so it was possible to identify the LOS from maximum density (pc/mi/ln) and maximum service flow rate (pc/hr/ln) values provided in that exhibit. For WZ conditions, free flow speeds were often less than 55 mph. To get a LOS for these speeds, maximum service flow rate (pc/hr/ln) values in exhibit 23-2 were extrapolated. For this reason, LOS's obtained for WZ are considered as approximate.

<u>Level of Service (LOS)</u> LOS shows the performance of the roadway. A summary of LOS values for the four types of work zones is illustrated in Table 5-16.

LOS decreases from the NWZ case to all other cases for each work zone type. This situation is expected, as work zones are more crowded than upstream locations. For three work zone types, LOS remains constant for each case other than NWZ. However, for Type 3 (Brookwood), LOS decreases from "C" at WZ Double Fine to "E" at WZ Police & Double Fine.

Table 5-16. Summary of Level of Service (LOS)

Cases	WZ Types			
	1	2	3	4
	Level of Service (LOS)			
NWZ	B	A	A	A
Base WZ	C	B	-	B
WZ Double Fine	-	B	C	B
WZ Police	C	B	-	B
WZ Police & Double Fine	-	-	E	-

<u>PHF</u> Peak hour factor (PHF) values were calculated based on 15-minute volumes of vehicles. For all work zone types, for all the locations, for the NWZ condition and all WZ conditions, and for each day's data, PHF fell within a normal range of 0.85 to 0.99. Consequently, these values are not listed in Table 5-1 through 5-15.

5. 2. 2 Summary of Speed Data

Mean speed, 85^{th} percentile of speed, standard deviation of speeds, percent of vehicles above the speed limit, frequency distribution of speed, and hourly and 15-minute distributions of speed were computed from the speed data.

<u>Mean Speed</u> Mean speed was used to measure the changes in speed due to police presence and double fine signs. Mean speed for any condition (NWZ, Base WZ, WZ Double Fine, WZ Police, or WZ Police & Double Fine) is the average speed of all vehicles during the data collection periods for that condition. Table 5-17 briefly illustrates the summary of mean speed data. The data is very similar to data from Tables 5-1 through 5-10, but small differences arise because the data has been averaged.

In the four work zones for which Base WZ data was available, mean speed decreased from NWZ to Base WZ. That result is expected, because speed limits decrease when vehicles enter work zones. The average decrease in mean speed is roughly 15%.

For the two work zones where the mean speed decreased from NWZ to WZ Double Fine can be evaluated, speeds do decrease, but only about the same amount as the decrease from NWZ to Base WZ (21.97% and 8.46% compared to 18.90% and 18.66%). This finding indicates that Double Fine Signs by themselves may not appreciably affect speeds in work zones.

Mean speed from NWZ to WZ Police was evaluated in four of the work zones. This evaluation shows the highest reduction in mean speed, averaging roughly 29%. Brookwood is a special case. It is the only site where speed changes for both NWZ to WZ Double Fine and from NWZ to WZ Police & Double Fine were measured. Brookwood exhibits a 29.4% drop for the first case and a 71% drop for the second case. These values indicate that Double Fine Signs performed well, and that the addition of police presence slowed traffic significantly more. A glance back at Table 5-7 indicates that the significant extra drop in mean speed occurred in each of the five test days and was not an isolated occurrence.

The last rows of Table 5-17 reinforce the finding that police presence serves as the best means of slowing traffic in work zones. For the two sites measuring change in mean speed from Base WZ to WZ Double Fine, the reductions in speed are a 3.95% increase and an 11.10% decrease. For the four sites that measure the change from Base WZ to WZ Police, the reduction averaged roughly 17%.

It must be mentioned that WZ Types 1 and 4 had no lane closures, only lane constriction. Types 2 and 3 involved lane closures. Thus, the decreases in mean speed are generally greater in those work zones that have fewer lanes inside the work zone compared to free flowing traffic upstream.

Table 5-17. Summary of Mean Speed

Cases	WZ Types				
	1		2	3	4
	Rock Mountain Lakes	Prattville	Fosters	Brookwood	Hoover
Speed Changes from NWZ to Base WZ (mph)	-12.65	-6.73	-14.20	-	-5.90
% of Speed Changes from NWZ to Base WZ	-18.15%	-9.76%	-21.97%		-8.46%
Speed Changes from NWZ to WZ Double Fine (mph)	-	-	-12.21	-21.66	-13.07
% of Speed Changes from NWZ to WZ Double Fine	-	-	-18.90%	-29.40%	-18.66%
Speed Changes from NWZ to WZ Police (mph)	-19.31	-10.30	-28.27	-	-20.66
% of Speed Changes from NWZ to WZ Police	-27.77%	-15.00%	-43.74%	-	-29.45%
Speed Changes from NWZ to WZ Police & Double Fine (mph)	-	-	-	-52.32	-
% of Speed Changes from NWZ to WZ Police & Double Fine	-	-	-	-71.00%	-
Speed Changes from Base WZ to WZ Double Fine (mph)	-	-	+ 1.99	-	-7.18
% Speed Changes from Base WZ to WZ Double Fine	-	-	+ 3.95%	-	-11.10%
Speed Changes from Base WZ to WZ Police (mph)	-6.66	-3.60	-14.07	-	-14.76
% Speed Changes from Base WZ to WZ Police	-11.73%	-5.70%	-27.90%	-	-22.93%

- Indicates reduction in speed
+ Indicates increase in speed

<u>85th Percentile Speed</u> The 85th percentile speed is often associated with the maximum safe speed, so changes in 85th percentile speed were considered to be very important. The 85th percentile speed is the speed value below which 85 percent of all vehicles are traveling during the data collection period.

Table 5-18 shows the summary of 85th percentile speed values for all work zone types. The results are similar to the results for mean speed.

- 85th percentile speed in Base WZ was approximately 12% lower than in NWZ on average.
- 85th percentile speeds in WZ Double Fine were approximately 19% lower than NWZ on average.
- 85th percentile speeds in WZ Police were approximately 25% lower than NWZ on average.
- 85th percentile speeds in Brookwood dropped 22.34% in WZ Double Fine and 67.30% in WZ Police & Double Fine compared to NWZ.
- 85th percentile speeds reduced approximately 5% on average for the two sites that measured Base WZ to WZ Double Fine condition.
- 85th percentile speeds reduced approximately 15% on average for the four sites that measured Base WZ to WZ Police.

In general, the results show that police presence is the most effective method of reducing speeds in work zones. WZ Types 2 and 3 again showed generally larger reductions in speed because they involved lane closures.

Table 5-18. Summary of 85th Percentile Speed

Cases	WZ Types				
	1		2	3	4
	Rock Mountain Lakes	Prattville	Fosters	Brookwood	Hoover
Speed Changes from NWZ to Base WZ (mph)	-12.33	-6.20	-12.75	-	-4.15
% of Speed Changes from NWZ to Base WZ	-16.45%	-8.35%	-18.15%	-	-5.61%
Speed Changes from NWZ to WZ Double Fine (mph)	-	-	-11.75	-18.30	-12.60
% of Speed Changes from NWZ to WZ Double Fine	-	-	-16.73%	-22.34%	-16.76%
Speed Changes from NWZ to WZ Police (mph)	-18.40	-9.67	-26.75	-	-18.48
% of Speed Changes from NWZ to WZ Police	-24.57%	-13.10%	-38.10%	-	-24.54%
Speed Changes from NWZ to WZ Police & Double Fine (mph)	-	-	-	-55.10	-
% of Speed Changes from NWZ to WZ Police & Double Fine	-	-	-	-67.30%	-
Speed Changes from Base WZ to WZ Double Fine (mph)	-	-	+ 1.00	-	-8.44
% Speed Changes from Base WZ to WZ Double Fine	-	-	+ 1.74%	-	-11.80%
Speed Changes from Base WZ to WZ Police (mph)	-6.05	-3.51	-14.00	-	-14.33
% Speed Changes from Base WZ to WZ Police	-9.70%	-5.20%	-24.35%	-	-19.95%

- Indicates reduction in speed
+ Indicates increase in speed

Reduction in Mean Speed vs. 85th Percentile Speed A comparison of Tables 5-17 and 5-18 shows that, in general, the percentages that mean speeds are reduced by the various cases are somewhat higher (by roughly 5% to 20%) than the percentage 85th percentile speeds are reduced by the same cases. This trend indicates that fast drivers do not slow in work zones as much as typical drivers do.

Standard Deviation The standard deviation of speed is a measure of its variation. As cited in Section 2, several researchers have found that higher speed variability correlates with higher crash rates. Standard deviation values of speed for each case (NWZ, Base WZ, WZ Double Fine, WZ Police and WZ Police & Double Fine) for all sites were calculated and placed in Tables 5-1 through 5-10. A summary of standard deviation values is illustrated in Table 5-19. The data is very similar to data from Tables 5-1 through 5-10, but small differences arise because the data has been averaged.

In general, speed variability values are higher in the various work zone cases than in the NWZ case. However, when Base WZ speed variability is compared to other work zone cases, no consistent trend up or down is observed.

Table 5-19. Summary of Standard Deviation of Speed (mph)

Cases	WZ Types				
	1		2	3	4
	Rock Mountain Lakes	Prattville	Fosters	Brookwood	Hoover
	Standard Deviation (mph)				
NWZ	6.07	5.95	6.11	8.99	6.27
Base WZ	5.52	6.04	7.45	-	8.76
WZ Double Fine	-	-	5.95	15.80	6.90
WZ Police	8.47	6.03	14.72	-	11.10
WZ Police & Double Fine	-		-	7.25	-

Migletz *et al.* (1999), states that crash rates increase with deviation in mean speed, and that a minimum increase in crash rate and speed variance occurred in work zones with a 10 mph reduction in work zone speed limit. They write that setting work zone speed limits in this way is implementable and can be used to maximize traffic safety in work zones. Garber and Gadiraju (1988) reported that minimal variance can be obtained when the posted speed limit is less than 10 mph below design speed.

Percent of Vehicles Above Speed Limit This parameter indicates the percentage of vehicles that are speeding for any condition (NWZ, Base WZ, WZ Double Fine, WZ Police and WZ Police & Double Fine). Table 5-20 summarizes the percent of vehicles above the speed limit for all WZ types.

In Table 5-20, the most useful statistics for ALDOT are the decreases in speeds that various enforcement cases generate. For example, for Rock Mountain Lakes, police enforcement reduces the percentage of speeders from 54.25% to 14.04%. In general, the table shows that police presence is most effective in this regard, with WZ Double Fine being effective in one case but not in a second.

Table 5-20. Summary of Percent of Vehicles Above Speed Limit

Cases	WZ Types				
	1		2	3	4
	Rock Mountain Lakes	Prattville	Fosters	Brookwood	Hoover
	Percent of Vehicles Above Speed Limit				
NWZ	43.50%	24.40%	13.33%	61.98%	42.95%
Base WZ	54.25%	86.99%	43.10%	-	87.30%
WZ Double Fine	-	-	58.10%	54.20%	48.30%
WZ Police	14.04%	70.03%	16.76%	-	16.25%
WZ Police & Double Fine	-		-	0.12%	-

Frequency Plots for Speed Distribution Frequency plots of speed were prepared for NWZ, Base WZ, WZ Double fine, WZ Police, and WZ Police & Double Fine conditions for all five locations. These plots were used to learn the shapes of the distribution curves, which determines the type of analysis to be performed. The data appeared to be normal, but, as is typical with very large data sets, normal distribution was not verified. For that reason, frequency plots were drawn taking every 100^{th} speed value among the initial data. 60% of the resulting distributions came out normal. In general, it was assumed that all speed distributions were normal. Due to space limitation and similarity of distribution among all other sites, only the speed distribution for one representative site (Prattville) is shown in Appendix B.

Hourly and 15-minute Distribution of Speed Hourly and 15-minute speed distributions were prepared for all sites. Results were typically consistent, which means that within the data collection period, no particular hour or particular 15-minute period was vastly different. Figures describing these distributions for all other sites are not included in this report for reasons of space.

5. 2. 2 Summary of Time Headway Data The research team calculated mean time headway, standard deviation, and percent of vehicles lower than unsafe time headway for each work zone site. A frequency distribution of time headway was also plotted.

Mean Time Headway Researchers calculated the mean value of time headways for all the vehicles for each case (NWZ, Base WZ, WZ Double Fine, WZ Police and WZ Police & Double Fine) for each of the WZ locations. Table 5-21 shows the summary of mean time headway data for all work zones. The values are very similar to those in Tables 5-11 through 5-15, but small differences arise because the data has been averaged.

Table 5-21 shows that headways were reduced from the NWZ case to the Base WZ case for all four cases for which the comparison can be made. The percentage drop in headway ranged from 22% to 34% and indicates that vehicles are more closely spaced in time at a typical work zone than they are upstream.

The drop in headway from Base WZ to WZ Double Fine can be examined for two sites: Fosters and Hoover. Headway was further reduced at both locations (24% and 3%, respectively).

Headway change from Base WZ to WZ Police can be measured in four locations. Headway increases 10% at Rock Mountain Lakes but decreases 9%, 27%, and 12% at the other sites.

The general drop in time headway as vehicles enter a work zone negatively impacts safety. Presumably, it is one of the reasons that rear end crashes are so prevalent in work zones.

Table 5-21. Summary of Mean Time Headway

Cases	WZ Types				
	1	1	2	3	4
	Rock Mountain Lakes	Prattville	Fosters	Brookwood	Hoover
	Mean Time Headway (Seconds)				
NWZ	4.83	5.60	9.40	15.88	7.06
Base WZ	3.79	4.23	6.20	-	5.10
WZ Double Fine	-	-	4.69	6.96	4.95
WZ Police	4.17	3.87	4.50	-	4.50
WZ Police & Double Fine	-		-	4.67	-

Percent of Vehicles Below Unsafe Time Headway The AASHTO *Green Book* suggests that 1.0 second may be a suitable minimum brake reaction time for unexpected events. It also recommends 2.5 seconds as the design criterion for brake reaction time because it covers more than 90% of all drivers. The researchers calculated the percentage of vehicles having time headway below those brake reaction times and termed those vehicles as "vehicles exhibiting unsafe time headway." Table 5-22 illustrates the summary of vehicles below 1.0 second and 2.5 second time headways for all work zones. The data is very similar to data from Tables 5-11 through 5-15, but small differences arise because the data has been averaged.

For all work zone locations, the percentages of vehicles below "unsafe" headways increased from the NWZ case to the Base WZ case. For example, in Hoover, the increase was from 10.83% to 17.85% for the 1.0 second headway and was from 30.50% to 42.71% for the 2.5 second headway. Usually, there was an additional, but smaller, increase in unsafe headway times for the other cases. However, in a small number of cases, there was a decrease from the Base WZ to other cases.

In general, Table 5-22 demonstrates that time headways decrease inside work zones. In this analysis, the locations where the number of lanes decreased in the work zone (Types 2 and 3) did not show a markedly greater percentage of unsafe drivers compared to work zone types 1 and 4 where lanes were only constricted.

Table 5-22. Summary of Percent of Vehicles Below Unsafe Time Headway

Cases	WZ Types				
	1		2	3	4
	Rock Mountain Lakes	Prattville	Fosters	Brookwood	Hoover
	Percent of Vehicles Below Unsafe Time Headway (1.0 Seconds)				
NWZ	18.50%	16.56%	10.33%	7.01%	10.83%
Base WZ	35.20%	24.41%	17.55%	-	17.85%
WZ Double Fine	-	-	20.20%	38.61%	19.63%
WZ Police	25.70%	30.10%	21.43%	-	20.40%
WZ Police & Double Fine	-		-	25.55%	-
	Percent of Vehicles Below Unsafe Time Headway (2.5 Seconds)				
NWZ	43.66%	40.86%	29.30%	19.5%	30.50%
Base WZ	63.76%	50.23%	54.92%	-	42.71%
WZ Double Fine	-	-	50.80%	58.1%	45.04%
WZ Police	54.05%	56.86%	56.82%	-	47.88%
WZ Police & Double Fine	-	-	-	48.34%	-

<u>Standard Deviation of Time Headway</u> Previous studies relate high standard deviation of speeds to increased crashes. However, there is no such study relating time headway to crashes. In general, for all work zone types and all work zone locations, standard deviation of time headway decreased from NWZ to Base WZ condition, from Base WZ condition to WZ Double Fine condition, and then from WZ Double Fine condition to WZ Police condition. (Table 5-23 summarizes the standard deviation of time headways values for all work zones, the data is very similar to data from Tables 5-11 through 5-15, but small differences may arise because the data has been averaged). Thus, it appears that there is no direct relationship between increased standard deviation of time headway and increased crashes. The presumed relationship may be better explained by the findings of Table 5-22.

Table 5-23. Summary of Standard Deviation of Time Headway

Cases	WZ Types				
	1		2	3	4
	Rock Mountain Lakes	Prattville	Fosters	Brookwood	Hoover
	Standard Deviation of Time Headway (Seconds)				
NWZ	5.60	7.21	11.94	22.15	7.90
Base WZ	5.77	5.95	11.58	11.86	5.80
WZ Double Fine	-	-	5.83	-	6.40
WZ Police	5.60	5.00	6.82	-	5.45
WZ Police & Double Fine	-		-	7.97	-

Frequency Distribution Frequency distribution for time headway for all conditions (NWZ, base WZ, WZ Double Fine, WZ Police, and WZ Police & Double Fine) for all locations were plotted. The data follow a gamma distribution for all the cases. Due to space limitation and similarity of distribution, only the time headway distribution for one representative site (Prattville) is shown in Appendix C.

Section 6.0
Summary, Conclusions & Recommendations

The report is based on data collected at five Interstate work zone locations (Rock Mountain Lakes, Prattville, Fosters, Brookwood, and Hoover) in Alabama, where four different types of roadwork (road widening, resurfacing, resurfacing at night, and interchange modification) were occurring. At four of the five locations, roadwork was conducted in the daytime; at one location, road work was conducted at night. Data were collected by the research team from 2:30 to 6:00 pm where roadwork occurred in the daytime and from 8:00 to 12:00 pm where roadwork was conducted at night.

Data was collected for five conditions (NWZ, Base WZ, WZ Double Fine, WZ Police, and WZ Police & Double Fine). NWZ data was collected once upstream of a work zone, and then it was compared to work zone data under different conditions.

Summary of Volume Data

For the five locations, a total of 254,841 vehicles were monitored for speed and time headway. All work zone types showed LOS A or B in the NWZ area. LOS for each type generally reduced by one level when vehicles entered the work zone. The exception was Type 3, where LOS decreased from A to C at WZ Double Fine and then to E in WZ Police & Double fine. Type 3 (Brookwood location) was one of two locations where two lanes were reduced to one lane.

Summary of Speed Data

Mean speed, 85th percentile speed, standard deviation of speed, percent of vehicles above the speed limit, frequency distributions of speed, and hourly and 15-minute distributions of speed were computed from speed data.

Conclusions on Speed Data

Speed data provided the following conclusions:

- The hierarchy of measures to control (reduce) mean speed in work zones is police presence, double fine sign, and base WZ traffic control. Change in mean speed from Base WZ to other cases gave the following results: WZ Double Fine reduced mean speed an average of approximately 4%; WZ Police reduced mean speed by approximately 17%.
- 85th percentile speeds followed the same trends as mean speeds: the hierarchy of speed reductions from least to most was WZ Double Fine followed by WZ Police. The 85th percentile speed reductions from Base WZ to those cases were 7% and 15%, respectively.
- Police presence was also the most effective method of reducing the percentage of speeding vehicles in a work zone. The average rate of speeders in the Base WZ case in the four locations was approximately 70%. WZ Police reduced the percentage of speeders

to approximately 29%. For the two locations where the percent speeders for the WZ Double Fine case could also be measured, the percent speeders were approximately 53%.

- Other researchers have found that increased variability of speed increases the chances for crashes. As expected, standard deviation of speed for the five locations increased as vehicles entered the work zone (and reduced their speed) and continued to increase as enforcement increased. The question may arise, "What is the appropriate speed limit inside work zones to minimize speed variability." The Millenium Edition MUTCD provides guidance in this matter, "A reduction of more than 16 km/h (10 mph) in the speed limit should only be used when required by restrictive features in the temporary control zone." It continues by saying, "Reduced speed zoning (lowering the regulatory speed limit) should be avoided as much as practical because drivers will reduce their speeds only if they clearly perceive a need to do so."

Summary of Time Headway Data

Mean time headway, standard deviation of time headway, and percent of vehicles traveling with less than safe time headway were computed with the time headway data.

Conclusions on Time Headway Data

Time headway data resulted in the following conclusions:

- Time headway decreased approximately 27% from NWZ to Base WZ for the four locations where this difference could be measured.
- Time headway decreased approximately 14% from Base WZ to WZ Double Fine for the two locations where this difference could be measured.
- Time headway decreased approximately 10% from Base WZ to WZ Police for the four locations where this difference could be measured. (One of the sites actually showed an increase.)
- The decrease in time headway helps explain why the most frequent cause of crashes in work zones is misjudging stopping distance/following too close.
- The authors selected 1.0 seconds and 2.5 seconds as two points below which time headways might be termed unsafe. The percentage of vehicles demonstrating these unsafe headways increased from NWZ to Base WZ (an increase from 14% to 24% for the 1.0 second headway and an increase from 36% to 53% for the 2.5 second headway). Additional but smaller increases in the percentage of unsafe headways were usually observed when extra enforcement such as Double Fine signs or Police Presence was added. The last finding seems to introduce a contradiction: when extra enforcement is added, safety (as measured by "unsafe" time headways) may decrease.
- Standard deviations of time headway were calculated for all cases. In general, standard deviation decreased from NWZ to Base WZ. Standard deviation generally decreased further when additional enforcement was added.

Recommendations

The five Interstate work zones tested during the research exhibited the following characteristics:

- Work zones involving no lane reduction set speed limits at 55 mph (reduced from 70 mph upstream of the work zone). Work zones involving lane reductions set speed limits at 50 mph.
- Police presence is the favored method of speed limit enforcement.

Considering current ALDOT practice as listed immediately above, the following recommendations are suggested as a means of providing safer and more efficient traffic operation in Interstate work zones in Alabama:

- Recent research (Migletz *et al*.,1999) suggests that speed variation (and thus danger of crashes) is minimized when speed limits in work zones with minimal geometry change are set 10 mph below the speed limit just upstream. The researchers recommend that ALDOT investigate using the speed limit guidance stated in Section 6C.01 of the Millenium Edition MUTCD.
- Research performed for this report indicates that police presence (or police presence coupled with Double Fines signs) reduces speeds significantly more than Base WZ or WZ Double Fines cases. Thus, researchers recommend that ALDOT continue the use of police presence when speed reduction is desired.

Section 7
References

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APPENDIX A

Text of Alabama Double Fine Legislation

HB444

Enrolled, An Act,

To amend Section 32-5a-176.1 of the Code of Alabama 1975, relating to speed limits in construction zones, to provide for doubled fines for persons speeding within a construction zone when construction personnel are present.

BE IT ENACTED BY THE LEGISLATURE OF ALABAMA:

Section 1. Section 32-5a-176.1 of the Code of Alabama 1975, is amended to read as follows:

“$32-5A-176.1.

“(a) The state Department of Transportation is hereby authorized and empowered to set the speed limits in urban and rural construction zones along state and interstate highways. Such construction zone speed limits shall be posted on the department’s standard size speed limit signs at least one hundred feet in advance of the entrance to a construction zone. Law enforcement authorities shall enforce ~~such~~ construction zone speed limits. in ~~the same manner that they enforce normal speed limits along state and interstate highways and violations of construction zone speed limits shall be penalized as prescribed by law or ordinance for a normal speed limit offense~~. Upon conviction of a construction speed zone violation, the operator of the motor vehicle shall be assessed a fine of double the amount prescribed by the law outside a construction zone. The fine shall only be doubled for construction zone violations if construction personnel are present ~~or operating equipment is on the road or immediately adjacent to the road under construction~~. The Department of

Transportation, or its agents, shall indicate the presence of construction personnel or department employees with appropriate signs. The signs, placed at the entrance of the construction zone, shall also warn of the doubled fines for speeding within a construction zone.

"(b) The state Department of Transportation is hereby further authorized and empowered to promulgate and implement such administrative rules and procedures as it deems necessary to both carry out the provisions of subsections (a) of this section and to ensure the safety of private and public construction and maintenance personnel working in designated construction zones on state and interstate highways."

Section 2. A person subject to a penalty pursuant to $32-5A-176.1 shall not assessed additional court costs on conviction.

Section 3. This act shall become effective on the first day of the third month following its passage and approval by the Governor, or its otherwise becoming law.

APPENDIX B

Speed Profiles

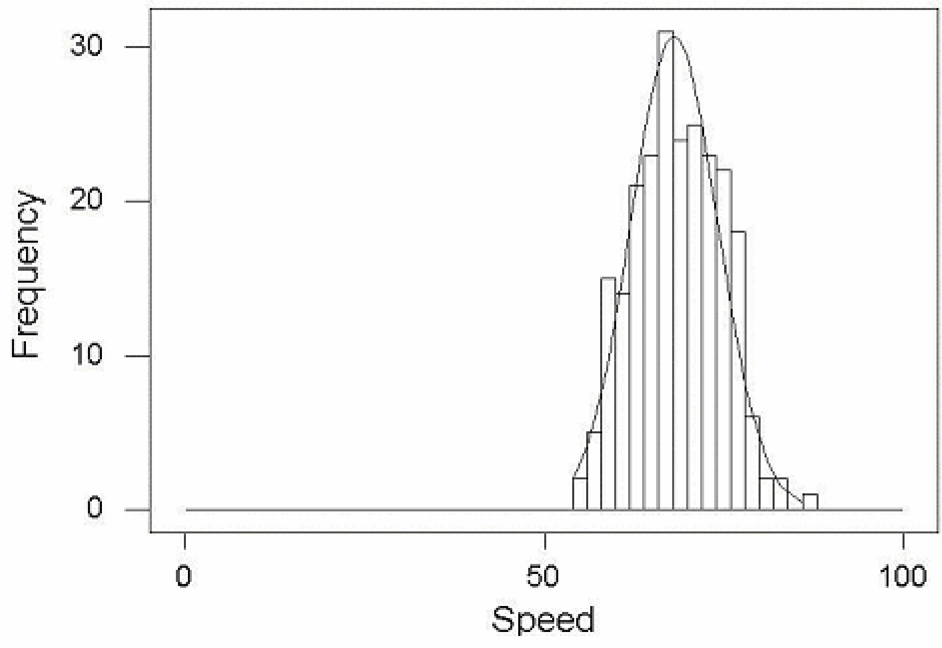

Figure B-1. Speed Distribution: Prattville: NWZ

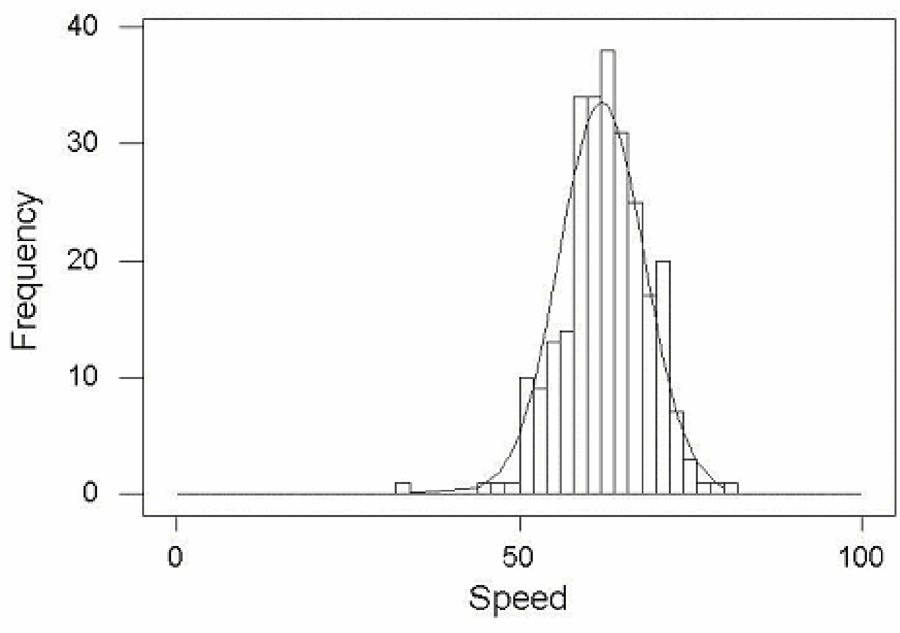

Figure B-2. Speed Distribution: Prattville: Base WZ

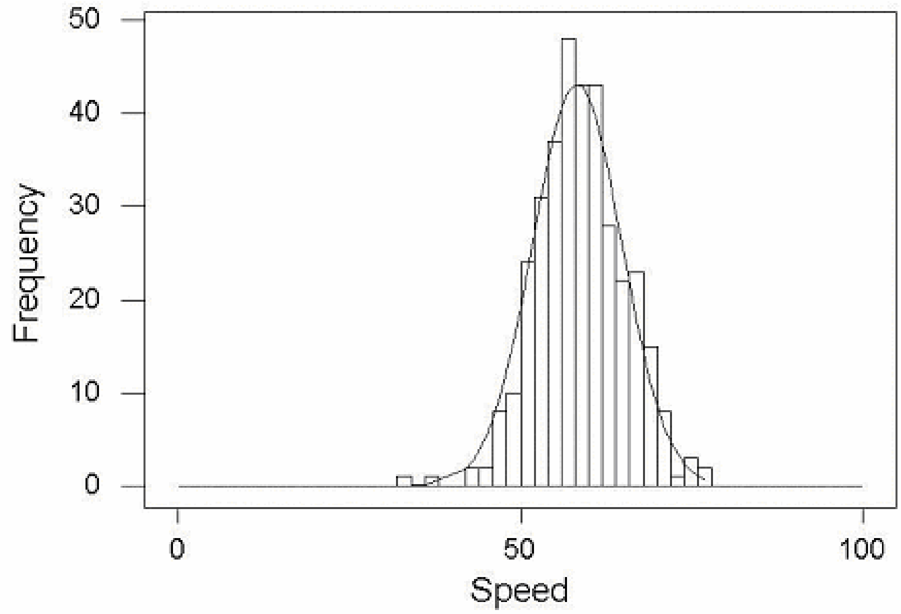

Figure B-3. Speed Distribution: Prattville: WZ Police

APPENDIX C

Time Headway Distribution

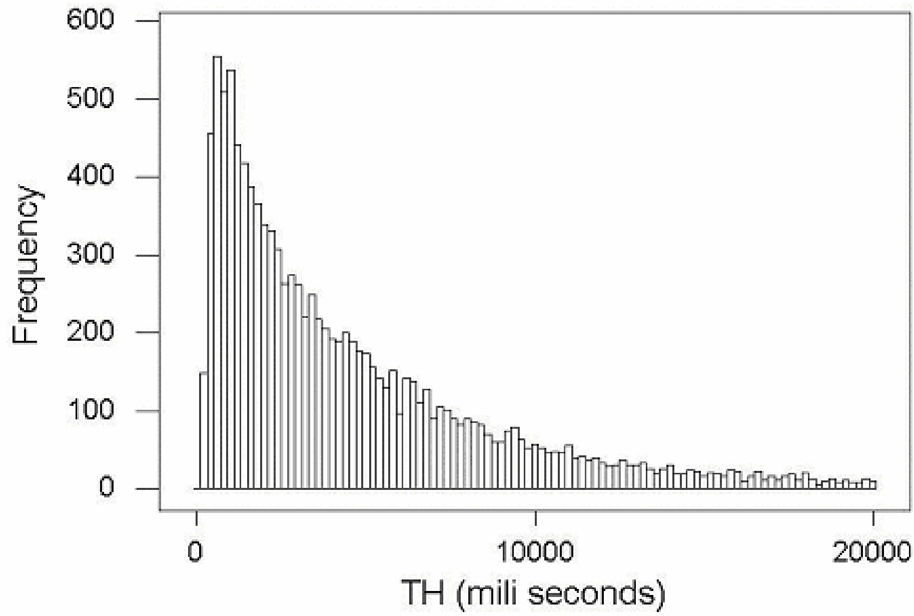

Figure C-1. Time Headway Distribution: Prattville: NWZ

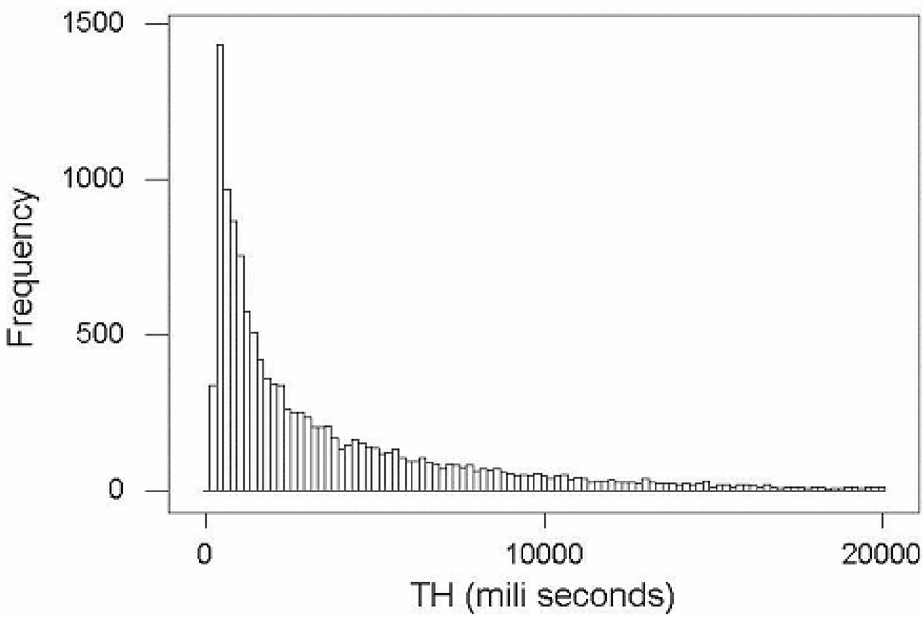

Figure C-2. Time Headway Distribution: Prattville: Base WZ

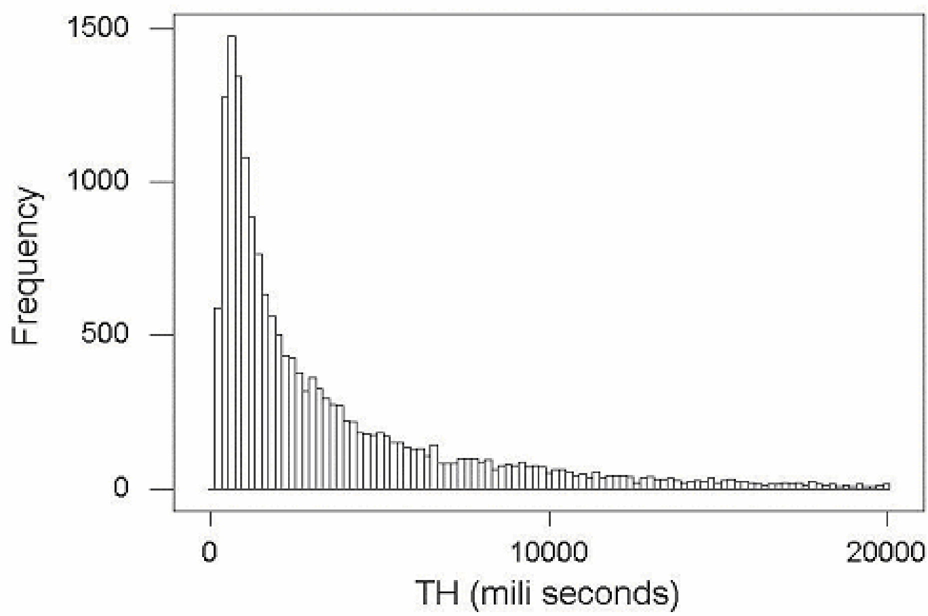

Figure C-3. Time Headway Distribution: Prattville: WZ Police