1. Report No. TPF-5(081) & DOT Contract # 09811	2.Government Accession No. NA	3. Recipient's Catalog No. NA
4. Title and Subtitle Evaluation of Work Zone Speed Limits: An Objective and Subjective Analysis of Work Zones in Missouri		5. Report Date February 2011 6. Performing Organization Code NA
7. Author(s) Ghulam H. Bham, PhD, Mojtaba Ale Mohammadi		8. Performing Organization Report No. 00016560/00016445
9. Performing Organization Name and Address Missouri University of Science and Technology Civil, Architectural and Environmental Engineering 1401 N. Pine Street Rolla, MO 65409		10. Work Unit No. NA 11. Contract or Grant No. NA
12. Sponsoring Agency Name and Address Smart Work Zone Deployment Initiative, Iowa State University Mid-America Transportation Center, University of Nebraska		13. Type of Report and Period Covered Final Report 14. Sponsoring Agency Code TPF-5(081)
15. Supplementary Notes Visit www.intrans.iastate.edu/smartwz for color PDFs of this and other research reports.		

16. Abstract

This study objectively and subjectively examined speed characteristics and driver compliance with the posted speed limit in Missouri work zones. The objective evaluation collected vehicle speeds from four work zones with different configurations on I-44. The effects of lane closure, lane width reduction, and construction activity on speeds of cars and trucks were evaluated. Construction activity was found to have a statistically significant effect in reducing vehicle speeds. During no construction, passenger cars and trucks speeds were 3.5 and 2.2 mph higher than their speeds during periods of construction activity, respectively. The vehicle speeds were found to be statistically higher than the posted speed limit in all cases studied except when the lane width was reduced using tubular markers, which reduced the speed of cars and trucks by 8.5 and 11.1 mph for cars and trucks during construction activity, respectively. This figure was respectively 4.0 and 8.1 mph during no construction. Also, compliance with speed limits was lower for posted speed limits of 50 mph versus 60 mph. Two subjective evaluations were conducted: first, work zone speed limit practiced at state departments of transportations were surveyed, and second, drivers' perceptions of driving through the work zones were investigated. Specific questions that evaluated driver perception were related to compliance with the posted speed limit, safety, and the effects of various factors on their speed. Results of subjective evaluation were consistent with the objective evaluation and showed that drivers suggest a work zone speed limit consistent with the speed that they drove through the work zone. When a work zone was mostly congested, 92% of car drivers and all of the truck drivers suggested a reduction in speed limits. Conversely, 92% of car drivers and 73% of truck drivers suggested a higher posted speed limit when the work zone was not congested. More than 90% of drivers agreed that construction activity prompted them to reduce their speed, a result that confirmed the outcome of the objective analysis.

17. Key Words work zone, speed limit, driver behavior, traffic control devices (TCD), speed compliance, construction activity, lane width	18. Distribution Statement No restrictions		
19. Security Classif. (of this report) Unclassified	20. Security Classif. (of this page) Unclassified	21. No of Pages 100	22. Price NA

Form DOT F 1700.7 (8-69)

EVALUATION OF WORK ZONE SPEED LIMITS: AN OBJECTIVE AND SUBJECTIVE ANALYSIS OF WORK ZONES IN MISSOURI

FINAL REPORT
FEBRUARY 2011

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Sponsored by
the Smart Work Zone Deployment Initiative
FHWA Pooled Fund Study TPF-5(081)

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LIST OF ABBREVIATIONS

Terms	Description/Definition
ASE	Automated Speed Enforcement
CMS	Changeable Message Sign
DSMD	Dynamic Speed Monitoring Display
DOT	Department of Transportation
FFS	Free Flow Speed
HCM	Highway Capacity Manual
LIDAR	Light Detecting and Ranging
LOS	Level Of Service
MoDOT	Missouri Department of Transportation
MOE	Measure Of Effectiveness
MUTCD	Manual on Uniform Traffic Control Devices
NCHRP	National Cooperative Highway Research Program
PCMS	Portable Changeable Message Sign
POST	Portable Overhead Surveillance Trailer
RV	Recreational Vehicle
SUV	Sport Utility Vehicle
VMS	Variable Message Sign
VSL	Variable Speed limit

ACKNOWLEDGMENT

The authors acknowledge research grants from the Smart Work Zone Deployment Initiative administered by the Iowa State University and the Mid-America Transportation Center at the University of Nebraska. They also appreciate Ms. Victoria Woods, Mr. Tim Hellebusch and their staff at Missouri DOT in assisting with data collection. Finally, the authors thank Dr. Praveen Edara from the University of Missouri at Columbia for providing the results of the state DOT survey.

ABSTRACT

Many states have enacted temporary speed reduction regulations for work zones, and a variety of speed limits are in place. The most commonly used speed reductions are 0, 5, 10, and 20 mph. The differences in speed limit have made enforcement difficult as motorists often do not follow or fail to notice changes in speed limits. This study objectively and subjectively examined characteristics of vehicle speeds and drivers' compliance with the posted speed limit.

The objective evaluation extracted free flow speeds of vehicle from four work zones with different configurations located on I-44 near the cities of Waynesville, Rolla, Cuba, and Pacific. The free flowing speeds of cars and trucks were evaluated using statistical tests, studying the effects of lane closure, lane width reduction, and construction activity on vehicle speeds. The objective evaluation found that passenger cars travel at significantly higher speeds than trucks. The speed of cars was on average 1.2 and 1.8 mph higher than trucks, respectively, during no construction and construction periods. The effect of reduced lane width on vehicle speeds was higher when tubular markers were used compared to lane markings. Construction activity had a significant effect, reducing the speed of vehicles. With no construction activity, passenger car and truck speeds were on average 3.5 mph and 2.2 mph higher than speeds with construction activity, respectively.

Vehicle speeds were statistically higher than the speed limit in all cases studied except when the lane width was reduced using tubular markers. When lane width was reduced using tubular markers, the speed of cars and heavy vehicles were lower than the speed limit by 8.5 and 11.1 mph, respectively, with construction activity. This figure was respectively 4.0 and 8.1 mph with no construction activity.

Compliance with speed limits dropped with lower speed limits, 50 mph versus 60 mph. The number of drivers traveling at a speed of at least 5 or 10 mph above the speed limit was considerably higher for sites with 50-mph speed limit compared to sites with 60-mph speed limit during both periods of construction and no-construction activity. Drivers exceeding the speed limit by more than 10 mph were found to be less than 10% with construction, however, this percentage increased to more than 25% and 17% for cars and trucks, respectively, with no construction activity.

The subjective evaluation conducted two surveys. State departments of transportation (DOTs) were surveyed about common practices in work zones and drivers' perceptions of traveling through a work zone were assessed. Twenty-seven states responded to the DOT survey. The dominant factors DOTs use to determine reduced speed limits were the presence of workers, lane width, roadway alignment, and type of activity. Seventy percent of respondents indicated a maximum speed limit reduction of 10 mph in work zones which is consistent with MUTCD guidelines. Most DOTs rely primarily on static speed limit signs but only 25% of the respondents found such signs effective.

Questions on the driver survey addressed safety, drivers' traveling speed in work zones, compliance with the posted speed limit, and the effects of various factors on speed. More than 70% of drivers had few safety concerns about driving among other types of vehicles. An analysis of the responses determined that drivers prefer to be well informed more than a mile before a work zone where workers are present. Fourteen percent of drivers, though, were found to be aggressive in terms of lane changing behavior as they preferred to see the "Lane Closed Ahead" and "Reduced Speed Limit" sign less than 1-mile before the work zone. A similar percentage of drivers exceeding the speed limit by more than 10 mph were found from the objective analysis when no construction was in place. Most drivers indicated that they experienced delay in the work zone, and more than 90% agreed that construction activity reduced their speeds. The results were consistent with the objective evaluation and most drivers suggested a work zone speed limit consistent with their own speed. When a work zone was mostly congested, 92% of car drivers and all of the truck drivers suggested a reduction in speed limit. Conversely, an overwhelming number of participants, 92% of car drivers and 73% of truck drivers, suggested a higher posted speed limit when the work zone was not congested. More than 90% agreed that construction activity reduced their speeds.

CHAPTER ONE

1. INTRODUCTION

As the American highway network ages, federal and state government agencies are allocating a greater portion of funds to reconstruction, maintenance, and rehabilitation of existing highways. As a result, the traveling public encounters a higher number of work zones. The Manual on Uniform Traffic Control Devices (MUTCD) divides work zones into four areas: the advance warning area, the transition area, the activity area, and the termination area. Road users traveling through a work zone are warned of the upcoming hazardous area in the advanced warning area and then directed out of their normal path in the transition area. The transition area frequently forms a bottleneck that can dramatically reduce the traffic throughput, which can slow down the traffic and cause delay. Drivers encounter roadwork in the activity area which again affects their speed and return to their normal path in the termination area.

Hazardous conditions for drivers and construction workers are common in work zones because construction activities disturb normal traffic flow. The disturbances may introduce severe traffic congestion and increase the risk of crashes. Ensuring safety in work zones while maintaining highway capacity has become one of the most overwhelming challenges confronted by traffic engineers and researchers.

Every year crashes in and near highway work zones cause property damage, injuries, and death, not only among workers, but also among drivers. Thus traffic speeds adjacent to a work zone are of great concern. The faster a vehicle is travels, the less time a driver has to react, and the less time workers have to get out of the way if a driver loses control. A faster moving vehicle is also more likely to penetrate a barrier, and to penetrate farther, threatening more workers.

Experience has shown that the effectiveness of signs reducing the speed of traffic through work zones varies. It can depend on the normal posted speed limit and on the geometry and sight distance of the highway. Speed reduction signs posted for long work zones that have no evidence of any activity are not only ineffective, they can make drivers skeptical of the validity of signs posted at other work zones.

In cooperation with MoDOT, a research team from the Missouri University of Science and Technology objectively investigated traffic speeds and driver compliance with posted speed limits in work zones on I-44 to assess systematically the impact of static speed limit signs. This project evaluated the impact of lane closure, lane width reduction, and construction activity on vehicle speeds. This study also conducted subjective evaluations of work zone practices common among departments of transportation and of drivers' perceptions of driving through the work zones. A questionnaire was distributed to randomly selected drivers of trucks and passenger cars. The results of the subjective and objective evaluations were compared to determine whether they are consistent with one another. This effort provides a wider look at the state DOTs, drivers' perspective and evaluates the behavior of drivers in work zones. Another team from the University of Missouri, Columbia as part of this project investigated the speeds of vehicles on I-70 work zones. Another report details the results of that study.

This study investigated traffic speeds and driver compliance with the posted speed limits in work zones and evaluated the impact of static speed limit signs in work zones. The study used free flow speeds (FFS) of vehicles in evaluation of driver behavior. Speed characteristics were also studied and the speeds of trucks and passenger cars were compared. The FFSs within the work zone activity areas were compared with the speed limits. In addition, it compared the 85^{th}

percentile FFS of vehicles to the posted speed limit. The 85th percentile is a useful criterion to evaluate speed limit compliance when a speed limit is enforced in the work zone.

This project surveyed fifty state departments of transportation about their common work zone practices. A subjective evaluation surveyed drivers about the safety of traveling through the work zone, about their actual speeds and about the posted speed limit. It also sought drivers' opinions about the effects of construction activity on their speed and the speed limit compliance of other drivers.

CHAPTER TWO

2. LITERATURE REVIEW

Agencies have adopted approaches such as variable speed limits and speed monitoring and display to increase compliance and safety and thus reduce the likelihood of crashes in work zones, and research has examined the efficiency of these methods. Following is a review of projects, practices, and research on speed limits, particularly in work zones. This review addresses factors affecting speed limits, driver compliance with the speed limits, and enforcement and safety issues.

The safety and efficiency of work zones is of interest to the MoDOT. The department is responsible for construction and maintenance on various types of highways. Their efforts include speed limits determination in work zones, coordination with law enforcement to establish fines in work zones, and implementation of intelligent transportation systems to improve driver compliance with speed limits and other regulations. Proper implementation of strategies should improve the safety of work zones for both workers and the traveling public, and reduce delays and traffic congestion.

2.1 Work Zone Speed Limit

Fundamental to the reduction of speed limits in work zones is the hypothesis that if motorists reduce their speeds crashes will be fewer and less severe. State highway agencies determine work zone speed limits based on one of three policies (MUTCD):

(a) Avoid speed limit reductions whenever possible.

(b) Impose speed limit reductions consistently in work zones.

(c) Establish work zone speed limits on the basis of factors specific to individual projects.

NCHRP Project 3-41 makes the following recommendations regarding work zone speed limit implementation (Migletz et al., 1998):

- Reduced work zone speed limits should be used only during specific periods and only in those portions of the work zone where the engineering factors identified in the speed limit procedure are present.
- Work zone speed limit reductions should be avoided whenever possible, especially where all activities are located on the shoulder or in roadside areas, or when no work activities are in progress.
- A 10-mph reduction below the normal speed limit is desirable in work zones when work takes place on or near the road, particularly on rural freeways, or when personnel are required to work for extended periods in an unprotected position within 10 ft of the edge of the road.
- Avoid blanket policies mandating the reduction of work zone speed limits to a fixed value.
- At locations where work activities are removed from the roadway by 10 ft or more, avoid work zone speed limit reductions.
- Reduced speed limits are generally most appropriate for projects that last at least 24 hours; however, reduced work zone speed limits may be established for projects of shorter duration whenever it is appropriate.
- Where work zone geometrics with reduced design speeds cannot be avoided, the work zone speed limit should not exceed the design speed, even if the work zone speed limit reduction would be greater than 10 mph.

Typically, where a speed limit reduction is called for, the normal posted speed is reduced by 10 mph. Most transportation agencies use regulatory or advisory speed limit signs to convey speed reduction information to the public. Where a reduced speed limit is imposed, the normal limit should be restored during times when there is no work activity or no need for a reduced speed limit.

Experience has shown that the use of signs to reduce the speed of traffic through work zones has varying degrees of effectiveness. The effectiveness of signs may depend on the normal posted speed limit, road geometry, and sight distance. In some cases, it may depend simply on the location of the work zone. Speed reduction signs for long work zones that have no evidence of any activity are not only ineffective, but also can make drivers skeptical of the validity of signs posted at other work zones (Outcalt, 2009).

Long-term work zones with no activity or significant speed reductions and where workers and equipment are far from traffic tend to make drivers doubt the validity of the reduced speed limit. If such cases are frequent, drivers may lose respect for the posted speed limit in other work zones. Speed reductions should be carefully evaluated, and work zone speed limits should be set no lower than necessary and imposed no longer than necessary for the safety of workers and drivers (Outcalt, 2009).

Migletz et al. (2005) developed a procedure to determine the work zone speed limits appropriate during the design and construction phases of a roadway construction project. Accident and speed studies showed that accident rates and speed variance increased only minimally in work zones with a 10-mph reduction in speed limit. This work showed that drivers reduce speeds in work zones, particularly when workers are present, independently of whether or not speed limit reductions are posted. Motorists believe that when work is not adjacent to the traveled way or when no work is being conducted, the speed limit should not be reduced.

Maze et al. (2000) examined speed reduction practices in work zones and reviewed speed control strategies ranging from posting regulatory and advisory speed limit signs to using the latest radar technologies to reduce speeds at work zones. They conducted an extensive survey of 50 states, with a 62% response rate. The survey addressed seven distinctive work zone scenarios and asked whether any speed reduction was implemented for each scenario. Most participating state agencies reported reducing speed limits by 10 mph below the normal posted speed during construction activities. A few agencies even consider reducing speed limits by 20 mph. Such additional speed limit reductions, however, generally require review and recommendation by the appropriate engineering personnel. The majority of agencies reported using regulatory rather than advisory signs to post reduced speed limits in work zones. A few state agencies indicated that speed limit reductions in work zones are considered on a case-by-case basis. The process requires a careful examination of each construction project to determine whether speed reduction is warranted. A few respondents suggested that work zones should be designed so that no speed limit reductions need be imposed. However, if conditions warrant, realistic speed limit reductions should be maintained.

2.2 Factors Affecting Work Zone Speed Limits

State agencies have begun to implement static regulatory and advisory signage in work zones, but research has shown that these do not effectively decrease the number of crashes (Fontaine and Carlson, 2001). Such research has prompted enhancement of the signage system and studies of speed control measures. Further, research has revealed a number of ways to control the speed of vehicles in work zones. These methods include police presence, changeable message signs (CMSs), rumble strips, drone radar, radar-activated speed trailers, temporary traffic control, increased fines, and detours or diversions.

Various factors affect the speed of vehicles passing through a work zone. These include the geometric properties of the roadway, such as number of lanes, lane width, horizontal and vertical curvature, lateral clearance, and traffic control devices and warning signs such as variable speed limit (VSL) signs, speed monitoring and display, flaggers, and law enforcement (Noel et al. 1987).

Richards et al. (1985) conducted studies at four work zone sites, including two on rural freeways, one on an urban freeway, one at an urban arterial site. They evaluated the following work zone speed control strategies: (a) flagging, (b) law enforcement, (c) CMS, (d) effective lane width reduction, (e) rumble strips, and (f) conventional regulatory and advisory speed signage. Their studies suggested that an innovative flagging program, a police traffic controller, and a stationary patrol car were most effective. Agencies used various methods and devices other than law enforcement to motivate drivers to comply with work zone speed limits. The following are a few of the more common speed reduction methods and some of the innovative strategies examined in other recent studies:

1. CMS
2. Speed display trailers or CMS with radar
3. Innovative signs
4. Flagging treatments
5. Lane narrowing
6. Late merge (to avoid road rage due to queue jumping)
7. Transverse striping
8. Rumble strips

Chitturi and Benekohal (2005) investigated the effects of lane width and lateral clearance on the speed of cars and heavy vehicles in work zones. They showed that speed reduction due to the lack of a shoulder on either side was approximately 5.6 mph in a work zone with 12-ft wide lanes. They found that the speed reductions in work zones are significantly greater than those given in the Highway Capacity Manual (HCM) for a basic freeway section of identical lane widths (HCM). The narrower the lanes, the greater the speed reduction. For 11-ft lanes, speeds dropped by 133% more than the value of 1.9 mph recommended by the HCM for basic freeways. For 10.5-ft lanes, the reduction was 69% greater than the HCM value for basic freeways. Narrow lanes reduced the speeds of heavy vehicles more than those of passenger cars. The investigators recommended work zone speed reductions of 10, 7, 4.4, and 2.1 mph for lane widths of 10, 10.5, 11, and 11.5 ft, respectively.

Maze et al. (2000) identified 12 speed reduction strategies, among which regulatory speed limit signs and police enforcement are the most common practices reported by agencies. However, only 7% of the participating agencies consider regulatory signs an effective speed reduction strategy, whereas 70% consider police enforcement engagement to be very effective. Police enforcement, however, is costly and may, therefore, have only a short-term impact on motorists.

A study in Missouri by Graham-Migletz Enterprises (1996) evaluated radar controlled speed matrix signs and concluded that such signs produce modest speed reductions. They found that the presence of law enforcement officers in work zones was more effective than any type of sign available.

Benekohal et al., (1992) studied speed reduction patterns of vehicles in highway work zones. Their studies suggested that drivers change their speeds at various locations within a work zone in response to roadway geometry and traffic control devices. The researchers followed vehicles from the time they entered a 1.5-mile long study section until they exited from it. Automobiles and trucks showed similar speed-reduction patterns. They identified four categories of drivers on the basis of these patterns: About 63% of drivers reduced their speeds considerably after passing the first work zone speed-limit signs (Category 1). Nearly 11% of drivers reduced their speeds when they neared the location of construction activities (Category 2). About 11% of all drivers failed to reduce their high speeds (Category 3). Among the remaining drivers, there was no distinct pattern (Category 4). Drivers in category 1 showed three distinct speed-reduction patterns. The first group decreased their speeds near the first speed-limit signs and had further speed reductions at the work space. The second group drove similarly to the first group, but increased their speed between the two points. The third group reduced their speed near the first speed-limit signs and maintained that speed until they passed the work space. The average speed of the third group decreased as the vehicle approached the work space, but rapidly increased after passing it. Even at the work space, about two thirds of automobile drivers and more than half of truck drivers exceeded the speed limit.

A study conducted by Benekohal et al. (2004) to develop a method to estimate operating speed and capacity in work zones noted that the capacity at which a work zone operates is affected by any reduction in operating speed in that work zone. The reduction in speed may be due to less-than-desirable geometric conditions, work intensity, traffic flow breakdown, weather conditions, local environmental conditions (dust, noise, distraction due work activities, etc.), pavement surface condition, work-zone layout, entering and exiting vehicles, and other factors. Therefore, the relationship between these factors and the reduction in speed must be determined to account for speed reductions. The data for many of these factors were insufficient to develop a relationship between each factor and speed reduction; therefore, the study focused only on those for which sufficient data existed and proposed the following relationship:

$$U_0 = FFS - R_{w1} - R_{LW} - R_{LC} - R_0 \quad (2.1)$$

where:

U_o = operating speed (mph);

FFS = free-flow speed (assumed to be speed limit + 5 mph);

R_{WI} = reduction in speed (in mph) due to work intensity;

R_{LW} = reduction in speed (in mph) due to lane width, based on HCM 2000;

R_{LC} = reduction in speed (in mph) due to lateral clearance, based on HCM 2000; and

R_o = reduction in speed (in mph) due to all other factors (however, if no information on magnitude of speed reduction is available, this reduction should not be applied).

2.3 Evaluation of Speed Limits in Work Zones

This project also reviewed research on evaluation of speed limits in work zones. The following presents, first, some common measures of effectiveness in this regard, then a review of the evaluation of static and variable speed limits.

2.3.1 Measures of Effectiveness

The measures of effectiveness (MOE) used in the evaluation by Richards et al. (1985) of speed control devices included four speed parameters: mean speed, standard deviation of speed, 85th percentile speed, and percentage of vehicles complying with the speed limit.

The parameters used by Migletz et al. (1999) in their study determining appropriate work zone speeds usable during the design or construction phases of a roadway construction project included mean speed, 85th percentile speed, speed limit compliance, and speed variance.

NCHRP Research Results Digest 192 (Graham-Migletz Enterprises, 1996) proposed a uniform procedure for determining work zone speed limits. That project involved interviews of 12 state and local highway officials about the procedure for establishing work zone speed limits and the perceived effectiveness of various speed limit reduction policies. It asked about the attitudes of motorists, construction contractors, and construction liability insurance carriers. The MOEs used in the analysis were:

- mean traffic speed compared to posted speed,
- 85th percentile speed range over posted speed limit,
- number of passenger cars traveling faster than the average truck speed, and
- percentage of drivers exceeding the posted speed limit by more than 5 mph, 10 mph, and 15 mph.

Knodler et al. (2008) developed strategies to manage speed effectively and rational criteria for setting speed limits. Specifically, they recorded the following speed data: 85th and 95th percentile speeds, median speeds, mean speeds, and speed variance. Their analysis focused on free-flow speeds, which were identified by vehicle gaps greater than or equal to 6 seconds. All their speed data, including those for non-free-flow vehicles, were recorded to determine the effect of gaps and free-flow definitions on observed vehicle speeds. Sandberg et al. (2001) used the following as a function of time and location: average speed, 50th percentile speed (median), 85th and 95th percentile speeds, and 10-mph pace.

2.3.2 Static Speed Limits

Regulatory and advisory speed limit signs alone do little to reduce traffic speeds in work zones (Migletz et al., 1999), and drivers do not feel constrained to obey speed limits that they consider unreasonable. If work zone speed limits are too low, drivers will lose respect for the speed control effort, and even active control might not be enough to increase compliance with the posted speed limit.

Agent et al. (2005) examined the criteria and procedures currently used to test speed limits on public roads and recommended appropriate speed limits for various types of roadways based on the data they collected. Those data collected using the moving radar mode showed that travel speeds for most types of highways are substantially above the posted speed limit. In addition, car speeds are slightly above those of trucks. Using the 85th-percentile speed as a standard, the operating speeds for most highway types should be increased for cars and trucks. Data taken before and after speed limit changes indicate that operating speeds change much less than the change in speed limit. The data support the conclusion that motorists will operate their vehicles at a speed they consider appropriate for the roadway geometrics and environment, regardless of the speed limit. Therefore, assuming drivers have an understanding of reasonable speeds, speed limits should reflect driver preferences.

The accident data collected by Lyles et al. (2004) did not show a large difference in the average number of accidents at locations where the speed limit was increased or decreased. Their study recommends that the 85th-percentile speed should be used as the standard method to establish speed limits. This standard reflects actual operating speeds as determined by the overall roadway environment. There are some conditions in which the speed limit should be decreased or increased in work zones, and static speed limits cannot effectively account for these variations. They found the variable speed limit (VSL) displays can change with changing conditions and impose more credible limits on motorists. The same study showed that static speed limit signs have less credibility than the VSL and variable message sign (VMS) systems.

Huebschman et al. (2004) concluded that fixed-panel signs (i.e. not dynamic signs mounted on a trailer) are effective in the heart of a work zone but have little impact prior to the work zone. They expected that the fixed signs would result in lower mean speeds on the approach to the work zone and inside it; however, they found no statistical evidence to support that hypotheses, likely because motorists tend not to reduce their speeds until the work zone is in sight.

The NCHRP Research Results Digest 192 included a comprehensive literature review on use of regulatory and advisory signs (Graham-Migletz Enterprises, 1996). That review suggested that some studies determined that these signs were quite effective, but most showed that they have a negligible effect on vehicle speeds.

2.3.3 Variable Speed Limits

According to a literature review conducted by Kang et al. (2004), most existing VSL systems were designed in response to traffic safety concerns; they were not intended to improve operational efficiency by, for example, maximizing the throughput from a work zone segment or minimizing the average delay for vehicles traveling through the segment. Kang's team proposed a VSL system to maximize work zone throughput. The system computes a sequence of optimal transition speeds based on the dynamic interaction between the work zone and the upstream traffic flow, and adjusts the speed limit displayed based on the detected speed distribution and flow rates, and thus responds effectively to demand variation and noncompliance.

Under normal traffic conditions, the model proposed by Kang et al. (2004) can increase the throughput over the work zone and reduce the average delay over upstream segments of the lane-closure location. Simulation results indicated that although average speeds under VSL control vary little from those without VSL control, the speed variance among those vehicles traveling over the work zone is substantially lower in VSL-controlled scenarios.

A study performed by the Virginia Transportation Research Council in 1994 evaluated CMSs equipped with radar units as a means of reducing speeds in work zones (Garber and Srinivasan, 1994). The radar unit was attached directly to the message sign to measure vehicle speeds, making the signs capable of displaying personalized warning messages. The study concluded that a CMS equipped with a radar unit acts like a dynamic speed control measure and is thus more effective than the static MUTCD signs in altering driver behavior in work zones. Personalized messages to high-speed drivers improved safety by increasing the probability that those drivers would reduce their speeds and by minimizing the overall speed variance in work zones.

Lyles et al. (2004) used a field test to determine the effectiveness of VSLs in work zones; however, their assessment was hampered by a lack of consistent and comprehensive data. Nonetheless, they learned several things about the effectiveness of VSLs. First, in most instances, speeds appeared to increase through the deployment areas when the VSL system was operating. This was the case when other factors, such as ramps, did not add to congestion or require that speed limits be kept low. As a corollary to the increase in average speed, the travel time through the VSL deployment areas decreased. The study concluded that VSL systems are more useful in longer and simpler work zones with short work areas, and they can present far more credible information to the motorist than can static speed limit signs.

Fontaine and Carlson (2001) reported the results of a field study conducted in a rural highway work zone (US 36) to evaluate the effectiveness of portable changeable message signs (PCMSs) as a speed control measure. Their study was conducted in four rural maintenance work zones on low-volume two-lane roads with 70-mph (112.7-km/h) speed limits; work was completed within a single day. Their study determined that the speed display was effective. In the advanced warning area, car speeds were between 2 and 9 mph (3.2 and 14.5 km/h) lower than with normal traffic control. Also, speed displays appeared to produce greater speed reduction in commercial trucks than in passenger cars. Truck speeds were 3 to 10 mph (4.8 to 16.1 km/h) lower with the speed display.

Garber and Srinivasan (1998) conducted research using a CMS equipped with a radar unit on highways in Virginia. The CMS was placed within the work area at the beginning of the lane taper. Four different messages were evaluated during the course of the study, and the message “YOU ARE SPEEDING. SLOW DOWN” was the most effective. They concluded that CMS with radar is effective for short periods (1 week or less) and continues to be an effective speed control technique for up to 7 weeks.

Benekohal and Shu (1992) evaluated the effectiveness of placing a single CMS in advance of work zones. Although the speed reductions were statistically significant, the reduction in truck speeds was not practically significant in most cases. For some automobiles exceeding the speed limit, the CMS did prompt speed reductions of 20%. Lee et al. (2004) investigated the effectiveness of variable speed limits in reducing the potential for freeway crashes. They used a real-time crash prediction model combined with a microscopic traffic simulation model and estimated the changes in crash potential as an effect of speed limit changes. They found that variable speed limits can reduce the average number of crashes by approximately 25% by temporarily reducing speed limits during risky traffic conditions. This study also concluded that the reduction in crash potential is greatest at sites of high traffic turbulence such as downstream of merging locations. Advanced warning to drivers who are approaching these merging locations is likely to reduce the number of crashes.

The study by Lee et al. (2004) also examined the effect of duration of intervention on changes in speed limits. It demonstrated that average total crash potential was significantly lower at 5-minute intervals than at 2-minute intervals. Thus, speed limit reductions that are too brief do not reduce crash potential and may, in fact, increase crash potential due to unnecessarily frequent changes in speed limits. There was no significant difference, however, in average total crash potential between 5-minute and 10-minute intervals, suggesting that these intervals represent a reasonable amount of time for traffic to stabilize after a speed limit change. On the other hand, total travel time was higher for interventions of short duration, perhaps because such interventions cause more turbulence in traffic flow. Also, when an intervention is imposed throughout a simulation, the study is actually examining the effect of fixed speed limits on crash potential. As fixed speed limits decrease, average total crash potential also tends to decrease, but total travel time dramatically increases. Total travel time through work zones with fixed speed limits is significantly higher than that through work zones with variable speed limits. Thus, lower speed limits are desirable from a safety perspective; however, there is an associated penalty in increased travel time. The benefits of speed limit reduction (i.e., reduction in crash potential), therefore, must be balanced with the additional cost of such a reduction (i.e., increase in travel time) to find a cost-effective range of speed limits.

2.4 Enforcement

Ensuring conformance with the posted speed limit poses a challenge to agencies. Many speeding drivers are local residents who are comfortable with the area. These motorists frequently speed through their own neighborhoods. A static speed limit sign alone, although helpful in many areas, is not always effective. Historically, engineers have looked to enforcement tools, either active or passive, as a solution to speeding. Active enforcement entails police vehicles patrolling the roadway and writing tickets to speeding motorists. Passive enforcement relies on the motorists to correct their own driving behavior as a result of seeing a police vehicle or a speed feedback trailer. A portable speed trailer placed along a roadway, for example, can encourage drivers to reduce their speeds. Research has shown, however, that once the police vehicle is out of sight or the speed trailer is removed, vehicle speeds return to their previous levels (Pesti et al., 2001).

Benekohal et al. (1992) evaluated the impact of active enforcement on vehicle speeds in rural interstate work zones in Illinois. The first part of the study measured average traffic speeds while a marked police car circulated through the work zone for four hours. The second part determined whether speeds would increase after the patrol car left the work zone at the end of this period. The study found that the mean speeds of cars and trucks in the work zone were reduced by about 4 and 5 mph, respectively, while a police car was circulating through the area. The number of cars and trucks exceeding the posted speed limit through the work zone was reduced by 14 and 32 percent, respectively. However, one hour after the police car had left the work zone, the mean speed of cars and trucks increased by about 2.5 and 0.5 mph, respectively. This study concluded that, at least for trucks, a lasting speed reduction could be obtained by periodically assigning mobile police cars to work zones.

Police enforcement efforts generally involve the presence of officers, whether stationary or mobile. An officer stationed at a specific location significantly increases speed limit compliance in that immediate area (Benekohal et al., 1992). A circulating police vehicle can cover a larger area but may be less effective at speed reduction. Richards et al. (1985) examined the effectiveness of focused law enforcement using stationary and mobile applications in six work zones on rural and urban highways in Texas. Their study indicated that a stationary patrol car reduced mean speeds by 5-12 mph (6 to 22 percent), whereas a circulating patrol reduced speeds by only 2-3 mph (3 to 5 percent).

In 1999, the Minnesota DOT examined the effectiveness of police enforcement in work zones at three different sites: a rural interstate, an urban freeway, and a metro location (Kamyab et al., 2003). Using a laser gun, speed data were collected with and without an enforcement vehicle present. The patrol car was located approximately 500-600 feet upstream of the work zones, with lights and flashers activated. The posted speed limit on the four-lane divided interstate was 70 mph; this was reduced to 40 mph in the work zone area during construction. The study found that the 85th percentile speed was reduced from 51 to 43 mph when a police vehicle was parked upstream of the work zone. Similarly, on the urban freeway (with a posted speed limit of 55 mph) and the metro location (with a posted speed limit of 50 mph), the 85th percentile speeds were reduced from 66 to 58 mph and from 58 to 47 mph, respectively. These results confirmed that the presence of a law enforcement vehicle considerably improves compliance with posted speed limits.

Police enforcement relies on personal observation supplemented with technology. In 1994-1995, Jones and Lacey (1997) conducted a study in Iowa to compare the effectiveness of laser-based and radar speed enforcement programs. They found that the radar-based speed enforcement program decreased the number of vehicles traveling more than 5 mph over the posted speed limit by about 20 percent. They concluded that laser-based speed measuring devices should supplement rather than replace existing radar measuring technology.

Another technology and strategy used in some work zones is real-time remote speed enforcement. Due to high speeds and traffic volumes in many work zones and limited space to pull speeding drivers over, stopping drivers for traffic violations may be dangerous for both motorists and officers. A remote speed enforcement program uses an automated speed enforcement (ASE) system to detect violators and alert an officer located beyond the work zone of the violation (Fontaine et al., 2002). ASE can use a variety of technologies (e.g., radar, LIDAR, elapsed travel measurements, and in-pavement sensors) to detect vehicle speeds. When a violation is detected, a photograph of the vehicle license plate is taken and transmitted to officers stationed outside of the work area. Once the violating vehicle has passed through the work area, the officer can safely stop the motorist. ASE programs can also mail a ticket to a vehicle. In most states, criminal citations cannot be issued based only on ASE evidence. A Texas Transportation Institute study (Fontaine et al., 2002) examined the technical feasibility of a remote enforcement system, determined whether vehicles could be correctly identified downstream, and surveyed the attitudes of law enforcement agencies toward the system. The study found that a downstream observer could correctly match about 84 to 88 percent of offending vehicles.

A study conducted by Knodler et al. (2008) to developed strategies on rational criteria for setting speed limits recorded the 85th and 95th percentile speeds, median speeds, mean speeds, and speed variance. They found that the baseline 85th and 95th percentile speeds and mean speeds of 40, 38, and 33.5 mph were higher than all equivalent values during the enforcement and public information and education campaigns. During the post-enforcement periods, four of the eleven 24-hour periods had 95th percentile speeds equal to the baseline value, and one period had speeds in excess of the baseline. Nevertheless, the 85th percentile and mean speeds remained lower than the original baseline levels during the post-enforcement period. An analysis of baseline data formed the basis for a rational speed limit for each of the project roadways. This revision resulted in an increase of 5 mph and was reflective of the 85th percentile speed rounded down to the nearest 5-mph increment. In general, the speed parameters tended to drop by 1 to 2 mph during the enforcement period and increase during the post-enforcement period when the 85th percentile speed increased, on average, by 0.3 mph.

Sandberg et al. (2001) conducted a study of locations where a rural highway transitions into an urbanized area. The dynamic speed monitoring display (DSMD) sign, permanently installed in conjunction with a standard static regulatory speed limit sign (MUTCD R2-1), indicated to motorists the speed limit and the speed at which they are driving without causing distraction. Sites with DSMDs experienced reductions in the 50^{th}, 85^{th}, and 95^{th} percentile speeds averaging 6.3, 6.9, and 7.0 mph, respectively. The 10-mph pace speeds also decreased at all the DSMD locations. These results indicate the DSMDs shifted the entire speed distribution at the transition zone. The data showed that the results were fairly consistent across all the DSMD sign locations and all time frames.

Ullman (1991) evaluated the effectiveness of using radar transmissions to reduce speeds without visible enforcement. Results showed that the radar signal, on average, reduced speeds by 3 mph (4.82 km/h) and had a greater effect on commercial trucks than on cars. Jackels and Brannan (1998) conducted a similar study using a radar-controlled speed sign. The study revealed that the 85th percentile speeds were reduced from 68 to 58 mph with the installation of the static signs alone. The installation of the radar-controlled speed sign reduced the 85th percentile further to 53 mph.

Firman et al. (2009) conducted experiments on the speed reduction effects of PCMSs on rural highway work zone in Seneca, Kansas. They measured vehicle speed using two Smart Sensor HD (Model 125) radar sensor systems. The results showed that the PCMS was effective in reducing vehicle speeds in two-lane work zones. The PCMS was significantly more effective when turned on than it was when turned off. When turned on, it reduced vehicle speeds by 4.7 mph over an average distance of 500 feet. When turned off, vehicle speeds decreased by 3.3 mph over 500 feet. Based on the results of data analyses, these researchers concluded that a visible and active PCMS in a work zone significantly reduces the speed of vehicles approaching the work zone. Reduced speed increases driver reaction time, allowing drivers to avoid crashes and thus creating a safer environment for drivers and construction workers.

Outcalt (2009) conducted a study on a divided four-lane highway with good sight distance both in the work zone and upstream where the warning signs began. The normal posted speed limit at the site was 75 mph. Changes in the work zone signs were made to establish speed limits of 70, 65, 60, 55, 50, and 45 mph. Maintenance personnel throughout the state expressed the opinion that the greater the speed limit reduction through the work zone, the more likely drivers were to exceed the speed limit. On the second day, with no law enforcement present, the percentage of speeders increased as the speed limit was lowered until, at 45 mph, nearly one in three drivers was exceeding the posted limit. With speed reductions from the highway normal of 75 mph to 65 mph, 85% of drivers complied with the lower limit (within 2 mph). This compliance rate represents a successful speed limit that drivers respect – fewer than about 1 in 25 exceed the limit by more than 5 mph. However, when the reduction is 15 mph or more, the number of drivers who exceeded the speed limit increased from less than 1/17 with a 15-mph reduction to nearly 1/3 with a 30-mph reduction. Based on the data used in that study, for a speed reduction of 10 mph or less the use of signs can be expected to slow about 85% of traffic to the posted speed. For situations requiring speed reductions of 15 mph or more, additional signs, including radar VMS, and law enforcement vehicles and officers may be necessary. Speed reductions of more than 20 mph will probably require the presence of law enforcement and may necessitate the use of pilot vehicles to force traffic to slow to the posted speed.

The presence of law enforcement at work zone locations is recommended (Outcalt, 2009), especially for work zones requiring more than a 10-mph reduction in traffic speed. The greater the reduction below the normal speed limit, the more important the presence of law enforcement becomes. Speed reductions of more than 20 mph should be used only in extreme cases. Speed limits through the work zone should be raised to the highest safe speed as soon as practical. If possible, speed reduction signs for work zones should be removed when no activity is underway.

Kamyab et al. (2003) investigated the effectiveness of extra enforcement in construction and maintenance work zones based on a literature review and the results of surveys and interviews of state agency representatives. Their investigation indicated general agreement that law enforcement presence and activity in work zones is valuable; very few comments noted negative effects, such as additional congestion.

2.5 Safety

Li and Bai (2008) conducted research on the characteristics of fatal and injury accidents in Kansas highway construction zones between 1992 and 2004, examining them systematically and comparing their major characteristics. The fatal and injury accident distributions over speed limits reveal differences worthy of discussion. Those work zones with speed limits of 51–60 mph had the highest proportion of both fatal and injury accidents. As speed limits decreased, injury accidents became a large proportion of the total; as they increased, the proportion of fatal accidents grew. The greatest number of fatal crashes occurred on highways with speed limits between 61 and 70 mph. This study thus confirmed that high speeds increase the severity of accidents in construction zones.

Kamyab et el. (2000) conducted a study in order to develop better ways of controlling traffic through work zones and thus improving traffic safety and traffic operation through work zones. They compared three different traffic management strategies using three electronic devices: the Wizard CB alert system, a safety warning system and a speed display monitor. The Wizard CB alert system broadcast a message to drivers informing them of an approaching work zone; the safety warning system transmitted a message to vehicles with compatible receivers informing them of an upcoming work zone; and the speed display monitor used radar to detect and display the speeds of passing vehicles. The latter two strategies also served as an actuator for radar-equipped vehicles and created the impression that enforcement officers were present. Of the three devices tested, the Wizard CB alert system provided the most promising results. Neither the safety warning system nor the speed monitor display provided a statistically significant reduction in average speed of vehicles approaching the work zone.

Bai and Li (2006) studied fatal crashes and associated risk factors in work zones to develop effective safety measures for future implementation. The team used crash data from the Kansas DOT’s accident database, along with original accident reports of 157 fatal crashes between 1992 and 2004. These data were evaluated using descriptive and regression analysis. Locations with greatest risk were work zones on rural roads with speed limits from 51 mph to 70 mph or those located on complex geometric alignments.

2.6 Speed limit Compliance

Huebschman et al. (2004) studied reduced speed limits in work zones and evaluated the effectiveness of a combination of fixed and dynamic signs advising motorists of work zone fines and enforcement activity. The study concluded that the dynamic signs had no significant effect. It indicated that the "Construction Zone Traffic Fines" panel sign resulted in a statistically significant reduction of the mean speeds of motorists in the heart of the work zone, where construction activity was underway and workers were present. The study also indicated that the VMSs displaying the number of traffic fines issued to date in the work zone, and updates to this message, produced no meaningful reduction in the mean speeds of motorists. The authors had hypothesized that motorists who traveled through the work zone on a regular basis would notice the number of traffic fines had increased, and would decrease their speeds to avoid paying traffic fines themselves.

Results of a study conducted by Migletz et al. (1999) suggest that average mean speeds decreased by 5.1 mph in work zones where the speed limit was not reduced. In work zones with reduced speed limit, the greater the reduction in speed limit, the greater the reduction in mean speed. Compliance with work zone speed limits was generally greatest where the speed limit was not reduced and decreased where the speed limit was reduced by more than 10 mph. For work zones with speed limits that were not reduced, the speed variance in the work zone 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 zone was only 34%. Finally, for work zones with speed limit reductions of 15 mph or more, the increases in the work zone speed variance above the speed variance upstream of work zones ranged from 81% to 93%.

Speed limit reductions greater than 10 mph below the preconstruction speed limit result in significant speed variance increases. To increase compliance with reduced work zone speed limits, consideration should be given to speed control techniques other than regulatory or advisory speed limits (e.g., police presence, drone radar, etc.) (Migletz et al., 1999). Richards et al. (1985) conducted research to identify effective measures to motivate and encourage drivers to comply with posted speed limits in work zones. Findings from literature and a survey of DOT personnel indicated that a wide variety of methods had been tested to improve compliance. Methods for establishing work zone speed limits differed from state to state. Three devices were tested in this project: a speed display trailer, a CMS with radar, and an orange-border speed limit sign. Results indicated that devices that displayed drivers' speeds significantly improved compliance. A primary factor affecting compliance with work zone speed limits is the risk of collision or injury (Richards et al., 1985). Elements contributing to this risk include:

- traffic volume,
- roadway cross-section (lane and shoulder widths),
- road surface conditions,
- weather conditions,
- awareness of the posted speed limit,
- awareness of workers and equipment present in the work zone and their proximity to traffic, and
- advance notification of the upcoming work zone.

Outside of enforcement efforts, agencies used several methods and devices to motivate drivers to comply with work zone speed limits. Most of these were intended to increase driver awareness of the work zone, the reduced speed limit, and/or the presence of workers. Other methods used roadway design elements to encourage or force drivers to slow down as they approached or traveled through a work zone. Outcalt (2009) conducted a study on work zone speed control and found that the most dependable method of ensuring compliance with posted work zone speed limits is the presence of law enforcement in the work zone.

CHAPTER THREE

3. FIELD DATA COLLECTION AND METHODOLOGY

The selection of an appropriate work zone for this study was crucial to evaluate the drivers' preferred speeds. The work zones had to have free flow conditions throughout the data collection period. Work zone sites were selected based on availability and in consultation with MoDOT. All sites were located on four-lane sections of I-44 in Missouri. They included two right-lane-closed work zones in the Waynesville and Rolla areas, one left-lane-closed work zone near Cuba, and one left-lane-closed zone in the Pacific area. In total, nine different datasets were collected for the periods of both construction activity and no construction activity. The data collection locations were at or near work activity within the work zone. The data collection times were determined based on the feasibility of collecting three to five hours of speed data. The normal regulatory speed limit of the highway was 70 mph.

The data were collected during daytime using high-definition video cameras to capture the traffic stream. The cameras were placed at locations where drivers would not spot them and reduce their speeds accordingly. Speed, traffic volume, and time headway data were extracted from the videos using Autoscope® software, a computer video processing program. This software uses a video image processing system and detects the vehicle speeds by calibrating the video snapshot of the location. The speeds are time mean speeds measured by placing a speed detector on the calibrated snapshot. The extracted speeds were validated by the speeds that were captured randomly using a laser speed gun at the time of video data collection. If the data extracted from the videos were not statistically the same as those measured by laser speed gun, an adjustment factor was used with the software to ensure statistically consistent data. The modified file configuration was then used to extract the data.

From the video data, free flowing vehicles were identified based on 5 seconds of headway (Benekohal and Shu, 1992; Bella, 2005; Wang et al., 2003) and extracted. FFSs were used in this study as FFS represents the desired speed of drivers not affected by the preceding vehicle, and can be used in the evaluation of work zone speed limit compliance. The vehicles were classified as either passenger cars or heavy vehicles. The extracted data included periods during which the construction activity was atypical; the data were classified as pertaining to periods of either construction activity or no construction activity. The no-construction group was further categorized into one lane open and two lanes open (with a reduced posted speed limit). The work activity at the Rolla site did not allow removal of lane closures during the peak hour or when queues were formed. At the Pacific site, the lane closures were removed when the traffic was heavy and as queues began to form, however the work zone signs were not removed. For the Rolla work zone site, the lane width was reduced by tubular markers, which were a contributing factor in the analyses. Also, the lane width in Pacific work zone was reduced by pavement markings while the construction activity was not adjacent to the open lane, that is, a lane was present between the activity area and the open lane. The minimum, mean, and maximum speeds, standard deviation, frequency distribution, and percentage of vehicles exceeding the speed limit by at least 5 mph, and 10 mph were then determined, and 95% confidence intervals were established for the mean, median, and standard deviation. The lengths of data collection periods varied by location, but enough FFSs were extracted to allow comparison. The 85th percentile of FFS values was also determined and used as a compliance criterion to compare with the speed limit.

For the work zone near Rolla, the open lane width was reduced because tubular markers were placed about 1.5 ft inside the open lane. The lane width in the Pacific work zone was reduced by pavement markings. Table 3.1 presents the number of open lanes, the speed limit, the percentage of trucks, the duration of the work zone, and the type of work activity at each work zone.

Table 3.1 Work zones studied

Work zone	Config ^	Mile marker	Speed limit (mph)	Truck (%)	Type[*] (term)	Date	Type of activity
Construction							
Waynesville WB	1	152.8	60	27.5	Short	08/13/09	Asphalt resurfacing
Rolla WB[†]		185.0		19.7	Long	10/02/09	
Pacific WB[†††]		253.0	50	28.0	Long	06/09/10 06/16/10 06/24/10	Addition of new lane
Pacific EB[†††]				25.1			
No Construction							
Waynesville WB	1	152.8	60	27.5	Short	08/13/09	Asphalt resurfacing[#]
Cuba WB		202.6		24.1	Short	11/06/09	Rumble striping[Δ]
Rolla WB[†]		185.0		19.7	Long	10/02/09	Asphalt resurfacing
Pacific WB[††]	2	253.0	50	26.8	Long	06/09/10 06/16/10 06/24/10	Addition of new lane
Pacific EB[††]				22.3			

† Reduced lane width by tubular marker, †† Reduced lane width by pavement marking, ††† Reduced lane width by pavement marking: construction not adjacent to open lane

^ One lane open = 1, Two lanes open = 2

* Duration of the work zone type

Δ Cuba work zone site was classified as no construction as rumble striping was a moving operation

The determination of work zone posted speed limit was not an issue in this study. The speed limit for the Rolla, Waynesville, and Cuba site were reduced by 10 mph to 60 mph and at the pacific site it was reduced by 20 mph to 50 mph. the construction activity at the Pacific site was much heavier than the other sites and required a higher reduction in speed limit in addition to a reduction in lane width. Also, at this site much of the construction was conducted during night time and lower speed limit was more beneficial in terms of the safety of drivers at night time. The consideration of the intensity of the construction activity justifies the amount of reduction in normal speed limit of the highway.

The nature of activity at the Rolla site did not allow removal of lane closure during peak hours and when queues formed. At the Pacific site, the lane closure was removed when the traffic was heavy and queues began to form. There, data were collected in both eastbound and westbound directions. These data were analyzed separately because i) traffic conditions were different, and ii) the geometry of the highway was also different as the eastbound highway beyond the data collection point was curved here.

The data from the Pacific work zone were collected in both the westbound and eastbound directions for three days, and they were combined for analysis. The total length of video data collection for all sites was nearly 40 hours. Schematics of the work zone sites are presented in the appendix.

Initially, speed data were extracted from those portions of video for which corresponding laser gun data were available. Data were validated to determine whether the configuration file was properly calibrated. Two sample t-tests and F-tests with a 95% confidence level were used to test the mean and variance of extracted speeds, respectively. After the data were validated, the configuration file was used for the total time of data collection. No significant difference was found in terms of the mean speed and the variance between the extracted speed and the laser gun speed.

Speed detectors were placed at an appropriate point in the video image. The angle from which the video was taken at a work zone site meant that some vehicles coming from the other side of the road also passed the speed detector, occluding the subject vehicles; therefore, the poll data of the software were not used. In these cases, all the traffic characteristics were recorded manually to exclude data on the occluding vehicles. The FFS data were read manually from the software output on the screen, assuming a time headway of 5 seconds or more from the time stamp of the video. Figure 3.1 shows a typical screen view of the Autoscope software configuration.

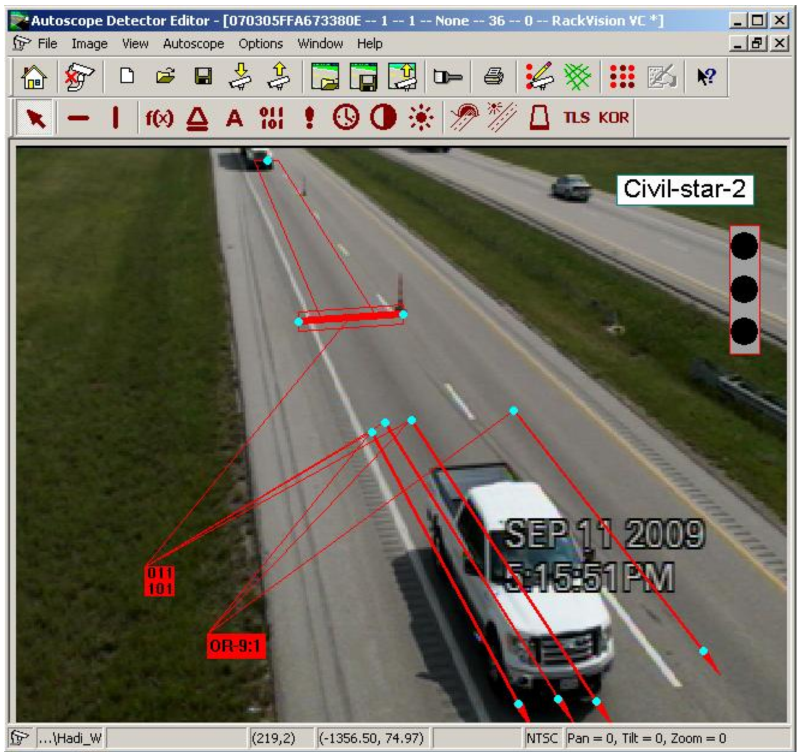

Figure 3.1 Screenshot of Autoscope software used to extract the speed and count data

In work zones with speed limits of 50 mph and 60 mph, vehicle speeds of less than 35 mph and 45 mph, respectively (mostly as a result of stop-and-go conditions with time headway of more than 5 seconds) were deemed too slow to represent FFS, and they were excluded from the extracted data. FFS distributions were tested for normality using the Anderson-Darling test; The Anderson-Darling test (Stephens, 1974) is used to determine whether a sample dataset comes from a population with a certain distribution. It modifies the Kolmogorov-Smirnov (K-S) test and gives more weight to the tail than does the K-S test. The K-S test is distribution free in the sense that the critical values do not depend on the specific distribution being tested. The

Anderson-Darling test, which is an alternative to the K-S and Chi-Square goodness-of-fit tests, makes use of the specific distribution (here, normal distribution) in calculating critical values. The Anderson-Darling normality test was defined as: H_o: data follows the normal distribution, and H_a:data does not follow the normal distribution. The Anderson-Darling test statistic is defined as:

$$A^2 = -N - S \tag{3.1}$$

where:

$$S = \sum_{i=1}^{N} \frac{2i-1}{N} \left[\ln F(Y_i) + \ln\left(1 - F(Y_{N+1}\right.\right. \tag{3.2}$$

where: F is the cumulative distribution function of the specific distribution (here, normal distribution) and Y_is are the ordered data. By comparing the test statistic with the normal distribution's critical values, the null hypothesis is evaluated. If the test statistic is smaller than the critical value, the null hypothesis is rejected. Then, the datasets can be assumed to be normally distributed because of the relative insensitivity of the t-test to normal distribution (11). The Anderson-Darling normality test was carried out using Minitab® software that provides the test statistic and the p-values. It should be noted that FFS may not necessarily follow the normal distribution. Throughout the remainder of this report, all speeds are free-flowing speeds.

Speed data were used to study the compliance of cars and trucks with the posted speed limit, and the effects of several variables. Various statistical analyses were performed: A t-test was used to determine the significance of differences in the speeds of trucks and passenger cars and to evaluate the effects of construction activity on speeds. Speed compliance was evaluated based on the difference between the mean speed and the posted speed limit. This evaluation identified statistically significant differences based on the vehicle type, lane width, lane closure configuration, and presence of construction activity.

A two-sample t-test was used to determine any significant difference between the mean value of the speed of cars and that of trucks. The null hypothesis H_0 was $\mu_C \leq \mu_T$ where μ_C indicates mean speed of cars and μ_T indicates the mean speed of trucks; the alternative hypothesis, H_a, was $\mu_C > \mu_T$.

For work zones with construction activity, a two-sample t-test was performed to evaluate the effect of construction activity on the speeds of cars and trucks. The null and alternate hypotheses were $S_{nc} - S_c \geq 0$ and $S_{nc} - S_c < 0$ respectively where S_{nc} is speed during periods of no activity and S_c is speed during periods of activity.

To evaluate the driver compliance with the work zone speed limits, a one-sample t-test was used. For each vehicle type and level of construction activity, mean speeds were compared with the posted speed limits of 50 and 60 mph in the work zones. The null and alternate hypotheses for both cars and trucks $S = 50\ or\ 60\ mph$ and $S > 50\ or\ 60\ mph$, depending on the work zone speed limit, where 'S' indicates the mean speed of either cars or trucks.

Fifty DOTs were contacted to complete a survey on their current and previous work zone practices out of which 27 DOTs responded. The DOTs were surveyed on factors determining the posted speed limit, the type of signs used to post speeds, compliance, and the measures taken to evaluate the effectiveness of these policies. Also as part of the subjective evaluation, a driver survey was conducted. Questionnaires were handed to drivers near the data collection sites over the course of the study, and the responses were recorded. Except for demographic questions, all were multiple choice questions. Most of the speed-related questions asked drivers to indicate their agreement or disagreement with various statements. Drivers were asked to take the survey if they had traveled through the work zone. The responses were analyzed to determine drivers' perception of reduced work zone speed limits, their compliance, and any hazards present within a work zone.

CHAPTER FOUR

4. RESULTS

The following section presents the results of both the objective and subjective evaluations. The objective evaluation determined the speed characteristics of cars and trucks and the effects of lane closure, lane width, construction, and speed compliance. The subjective evaluation summarizes common practices in regard to work zone speed limits based on the DOT survey. It also reports drivers' attention to the posted speed limit and work zone signage such as "Road Work Ahead," "Left/Right Lane Closed," and "Speed Limit," and the effect of such alerts on driver behavior, perceived delay, and drivers' perceptions of their own speed, the speeds of other drivers, speed limit compliance, and the effects of construction activity.

4.1 Objective Evaluation

The results of the objective evaluation are presented by work zone sites.

4.1.1. Speed Characteristics Analysis

4.1.1.1 Waynesville Site

Speeds from the Waynesville work zone site were classified based on two criteria: vehicle type and construction intensity. Table 4.1 summarizes the speed characteristics of each group. The results of this analysis indicate that the mean speed for all vehicles, both cars and trucks was higher than the speed limit; however, only statistical tests can determine whether the difference is significant. Further, for both levels of construction activity, the mean speed of cars was higher than that of trucks. Consideration of construction activity and its effects on the free flow of vehicles demonstrates that when there was no construction activity in the work zone, both the number of free flowing vehicles and their speeds increased. For example, when there was no construction, the proportion of vehicles traveling at least 10 mph above the posted speed limit of 60 mph was greater than 10% of the total (29% for cars and 16% for trucks). On the other hand, during periods of construction, this figure was lower (9% for cars and 7% for trucks).

Table 4.1 Speed characteristics (Waynesville site)

Speed Characteristics (speed limit: 60 mph)	No Construction		Construction	
	Car[1]	Truck[2]	Car[3]	Truck[4]
Mean	66.6	63.6	62.6	61.4
95 % C.I. for mean	65.2-67.9	62.0-65.1	60.0-65.1	59.5-63.4
Median	66	64	63	61.5
95 % C.I. for median	65-68	62-66	59.4-65.1	60-63
Standard deviation	7.01	7.49	5.83	6.30
95 % C.I. for standard deviation	6.18-8.09	6.52-6.78	4.51-8.25	5.18-8.03
Range	34	36	23	29
Minimum	48	47	49	46
Maximum	82	83	72	75
Count	107	89	23	42
% above speed limit	80	67	65	59
% At least 5 mph above speed limit	62	44	30	24
% At least 10 mph above speed limit	29	16	9	7

1 Passenger cars for the period with no construction
2 Trucks for the period with no construction
3 Passenger cars for the period with construction
4 Trucks for the period with construction

Table 4.2 Anderson-Darling normality test for speeds (Waynesville site)

Test parameters	No Construction		Construction	
	Car[1]	Truck[2]	Car[3]	Truck[4]
Mean	66.6	63.57	62.57	61.43
Standard Deviation	7.005	7.486	5.83	6.298
Count	107	89	23	42
AD value	0.169	0.323	0.274	0.41
p-value	0.933	0.522	0.633	0.329

1 Passenger cars for the period with no construction
2 Trucks for the period with no construction
3 Passenger cars for the period with construction
4 Trucks for the period with construction

Table 4.2 presents the results of the Anderson-Darling test. Table 4.3 presents the results of two-sample t-tests comparing the mean speeds of cars and trucks, and Table 4.4 provides the results of a t-test comparing speeds during periods of construction activity with those during periods of no construction. The results demonstrate that the speed distribution for cars and trucks was normal because the p-values were greater than 0.05, failing to reject the null hypothesis (H_0: speed distribution is normal).

Table 4.3 t-Test comparing the mean speeds of cars and trucks (Waynesville site)

Test parameters	Car vs. Trucks	
	No Construction	Construction
Difference of mean speeds	3.03	1.14
95% lower bound for difference	1.31	-1.52
t-statistic	2.92	0.71
p-value	0.002***	0.239

*** Significant at 99% level of confidence

Table 4.4 shows that with no construction activity, the difference between the speed of cars and trucks was statistically significant; however, it was insignificant during construction. Both cars and trucks had lower speeds during periods of construction than during periods of no construction (Table 4.2). As indicated in Table 4.4 the difference in the mean speeds of cars during periods of construction and no construction was significant at a 99% level of confidence; that of trucks was significant at a 90% level of confidence.

Table 4.4 t-Test comparing mean speeds during periods of construction and no construction (Waynesville site)

Test parameters	No Construction vs. Construction	
	Car	Truck
Difference	4.03	2.14
95% lower bound for difference	1.44	-0.07
t statistic	2.57	1.61
p-value	0.006***	0.055*

*** Significant at 99% level of confidence; * Significant at 90% level of confidence

4.1.1.2 Rolla Site

As at the Waynesville site, speeds at the Rolla work zone site were classified based on two criteria, vehicle type and construction activity. Table 4.5 summarizes the speed characteristics of each group. The results of this analysis indicate that the mean speed for all vehicles was lower than the speed limit of 60 mph, and the significance of this difference was determined by statistical tests. Further, for both levels of construction activity, the mean speed of cars was higher than that of trucks.

Table 4.5 Speed characteristics (Rolla site)

Speed characteristics (speed limit: 60 mph)	No Construction		Construction	
	Car[1]	Truck[2]	Car[3]	Truck[4]
Mean	56	51.9	51.5	48.9
95 % C.I. for mean	54.9-57.1	50.3-53.5	50.3-52.7	47.1-50.8
Median	56	52	52	50
95 % C.I. for median	55-57	50-53	51-53	48-51
Standard deviation	7.07	6.4	6.11	6.39
95 % C.I. for standard deviation	6.37-7.94	5.45-7.75	5.4-7.05	5.31-8.02
Range	34	31	28	26
Minimum	37	38	38	36
Maximum	70	69	65	61
Count	162	64	110	47
% above speed limit	24	8	5	2
% At least 5 mph above speed limit	11	5	0	0
% At least 10 mph above speed limit	0	0	0	0

1 Passenger cars for the period with no construction

2 Trucks for the period with no construction

3 Passenger cars for the period with construction

4 Trucks for the period with construction

Table 4.6 presents the results of the Anderson-Darling test. Table 4.7 presents the results of two-sample t-tests comparing the speeds of cars and trucks, and Table 4.8 provides the results of another t-test comparing speeds during periods of construction activity with those during periods of no construction. The results demonstrate that all of the speed distributions for cars and trucks were normal because the p-values were greater than 0.05; thus, the null hypothesis (H0: speed distribution is normal) is accepted. For both construction levels, the difference between the speed of cars and trucks was statistically significant. The p-values obtained from the two-sample t-tests show that construction activity had a significant effect on the speed of vehicles at a 95% level of confidence. The speeds of both cars and trucks dropped significantly when there was construction activity in the work zone.

Table 4.6 Anderson-Darling normality test for speeds (Rolla site)

Test parameters	No Const Car	No Const Truck	Const Car	Const Truck
Mean	56	51.9	51.5	48.9
Standard deviation	7.07	6.4	6.11	6.39
Count	162	64	110	47
AD value	0.377	0.552	0.402	0.588
p-value	0.406	0.149	0.353	0.119

Table 4.7 t-Test comparing the mean speeds of cars and trucks (Rolla site)

Test parameters	Car vs. Trucks	
	No Construction	Construction
Difference	4.162	2.55
95% lower bound for difference	2.548	0.72
t-statistic	4.27	2.32
p-value	< 0.001***	0.011**

*** Significant at 99% level of confidence; ** Significant at 95% level of confidence

Table 4.8 t-Test comparing mean speeds of construction and no construction (Rolla site)

Test parameters	No Construction vs. Construction	
	Car	Truck
Difference	4.528	2.92
95% lower bound for difference	3.198	0.88
t-statistic	5.62	2.38
p-value	< 0.001***	0.010**

*** Significant at 99% level of confidence; ** Significant at 95% level of confidence

4.1.1.3 Cuba Site

Construction activity at the Cuba site involved rumble striping, a moving operation, and activity was minimal over the whole data collection period; thus, all the data collected at this site were classified as no construction. Speeds were extracted from the data for all vehicles and classified as either car or truck speeds. Table 4.9 presents the speed characteristics of each class.

The mean speeds of both cars and trucks were higher than the speed limit; however, the significance of this difference must be determined statistically. Compared to the Waynesville work zone, the number of free flowing vehicles was low because the Cuba work zone was more congested. Table 4.9 presents the results of the Anderson-Darling normality test for the data from the Cuba site. The distribution of free flowing cars and trucks was normal, as indicated by p-values greater than 0.05 for both tests.

Table 4.9 Speed characteristics (Cuba site)

Speed Characteristics (speed limit: 60 mph)	No Construction	
	Cars	Trucks
Mean	62.8	60.6
95 % C.I. for mean	62.2-63.4	59.8-61.4
Median	63	60
95 % C.I. for median	62-63	59-62
Mode	61	59
Standard Deviation	4.72	4.93
95 % C.I. for standard deviation	4.31-5.20	4.40-5.60
Range	30	24
Minimum	46	48
Maximum	76	72
Count	221	133
% Above speed limit	71	46
% At least 5 mph above speed limit	28	17
% At least 10 mph above speed limit	4	2

Table 4.10 Anderson-Darling normality test for speeds (Cuba site)

Test parameters	Cars	Trucks
Mean	62.8	60.6
Standard Deviation	4.72	4.93
Count	221	133
AD value	0.702	0.641
p-value	0.066*	0.093*

* Significant at 90% level of confidence

Two-sample t-tests were performed to determine whether the difference between the mean values of the speeds of cars and trucks was statistically significant. Table 4.11 presents the results, indicating that the difference between the speeds of cars and trucks was statistically significant. As in the Waynesville work zone during periods of no construction, the speed of cars was significantly greater than the speed of trucks.

Table 4.11 t-Test comparing the mean speeds of cars and trucks (Cuba site)

Test parameters	Cars vs. Trucks
Difference	2.20
95% lower bound for difference	1.33
t statistic	4.18
p-value	0.000***

*** Significant at 99% level of confidence

4.1.1.4 Pacific Westbound Site

Data for the westbound pacific site were collected for three days and combined because the location and traffic flow states were almost the same in terms of percentage of trucks, weather conditions, and congestion. When there was construction activity, only one lane was open to traffic but this lane closure was removed during peak-hour congestion, when construction activity ceased. That is, for this work zone site, two lanes were open to traffic when there was no construction activity. Speeds extracted from the data were classified as either car or truck speeds. Table 4.12 presents the speed characteristics of each class. The results demonstrate that the speeds of cars and trucks were above the speed limit, and vehicles traveled faster when there was no construction in the work zone. These results seem reasonable, although the significance of the differences must be statistically tested. Table 4.13 presents the results of the Anderson-Darling normality test for the data from the Pacific westbound site.

Table 4.12 Speed characteristics (Pacific WB site)

Speed Characteristics (speed limit: 50 mph)	No Construction		Construction	
	Car[1]	Truck[2]	Car[3]	Truck[4]
Mean (mph)	55.8	54	52.3	50.5
95 % C.I. for mean (mph)	55-1-56.4	53.1-54.9	51.8-52.8	49.9-50.9
Median (mph)	56	54	52	51
95 % C.I. for median (mph)	56-57	53-55	52-53	50-51
Standard deviation (mph)	6.56	6.71	5.35	5.29
95 % C.I. for standard deviation (mph)	6.15-7.03	6.13-7.40	5.03-5.72	4.95-5.68
Range (mph)	36	32	29	27
Minimum (mph)	34	38	37	37
Maximum (mph)	70	70	66	64
Count	423	220	462	412
% Above speed limit	79	71	64	50
% At least 5 mph above speed limit	55	42	27	19
% At least 10 mph above speed limit	25	17	6	2

1 Passenger cars for the period with no construction

2 Trucks for the period with no construction

3 Passenger cars for the period with construction

4 Trucks for the period with construction

Table 4.13 Anderson-Darling normality test for speeds (Pacific WB site)

Test parameters	No Construction		Construction	
	Car	Truck	Car	Truck
Mean (mph)	55.8	54	52.3	50.5
Standard Deviation	6.56	6.71	5.35	5.29
Count	423	220	462	412
AD value	0.809	0.928	2.14	0.37
p-value	0.036	0.018	<0.005	0.42

The results indicate that the data did not follow the normal distribution. P-values are smaller than 0.05; therefore, the null hypothesis must be rejected. When the number of data points is large, normal probability tests are more powerful and detect even small deviations from normal distribution. Appendix C presents the distribution of speeds at this site. The distribution has an acceptable normal bell-shaped curve, although the normality test did not confirm that. For the purposes of this study, the datasets were assumed to be normally distributed and the t-test was used in speed evaluation due to its relative insensitivity to normal distribution (Benekohal and Shu, 1992). Table 4.14 presents the results of the t-test comparing speeds during periods of construction activity with those during periods of no construction. For both periods, the difference between the speed of cars and trucks was statistically significant. Table 4.15 provides the results of the t-test comparing speeds during construction activity with those during no construction. The p-values obtained from the two-sample t-tests show that construction activity had significant effect on the speed of vehicles at a 99% level of confidence. The speeds of cars and trucks dropped significantly when there was construction activity in the work zone.

Table 4.14 t-Test comparing the mean speeds of cars and trucks (Pacific WB site)

Test parameters	Car vs. Trucks	
	No Construction	Construction
Difference of mean speeds (mph)	1.7	1.8
95% lower bound for difference (mph)	0.83	1.21
t-statistic	3.15	2.01
p-value	0.001***	<0.001***

*** Significant at 99% level of confidence

Table 4.15 t-Test comparing mean speeds of construction and no construction (Pacific WB site)

Test parameters	No Construction vs. Construction	
	Car	Truck
Difference	3.5	3.5
95% lower bound for difference	2.84	2.7
t-statistic	8.67	6.84
p-value	<0.001***	<0.001***

*** Significant at 99% level of confidence

4.1.1.5 Pacific Eastbound Site

Speeds for the Pacific site were extracted from the video collected in eastbound direction on three data collection days and combined for analysis. As at the westbound site, with construction activity, only one lane was open to the traffic, but two lanes were open with no construction activity. Speeds were classified as either car or truck speeds. Table 4.16 presents the speed characteristics of each class. The results indicate that the speeds of cars and trucks were much higher than the speed limit of 50 mph, and vehicles traveled faster with no construction in the work zone. Similar to those for the westbound direction, these results seem reasonable. Statistical test can determine whether the differences are significant. Table 4.17 presents the results of the Anderson-Darling normality test for the data from the Pacific eastbound site.

Table 4.16 Speed characteristics (Pacific EB site)

Speed Characteristics (speed limit: 50 mph)	No Construction		Construction	
	Car[1]	Truck[2]	Car[3]	Truck[4]
Mean (mph)	57.1	53.2	52.3	50.4
95 % C.I. for mean (mph)	56.6-57.5	52.6-53.9	51.7-53.0	49.7-51.1
Median (mph)	57	53	53	50
95 % C.I. for median (mph)	56-58	52-54	52-53	50-51
Standard deviation (mph)	5.38	4.1	4.06	4.53
95 % C.I. for standard deviation (mph)	5.07-5.72	3.68-4.62	3.63-4.60	4.12-5.05
Range (mph)	28	19	19	23
Minimum (mph)	42	44	42	38
Maximum (mph)	70	63	61	61
Count	537	151	137	187
% Above speed limit	88	73	69	50
% At least 5 mph above speed limit	61	28	23	13
% At least 10 mph above speed limit	27	6	1	1

1 Passenger cars for the period with no construction

2 Trucks for the period with no construction

3 Passenger cars for the period with construction

4 Trucks for the period with construction

Table 4.17 Anderson-Darling normality test for speeds (Pacific EB site)

Test parameters	No Construction		Construction	
	Car	Truck	Car	Truck
Mean (mph)	57.1	53.2	52.3	50.4
Standard Deviation	5.38	4.1	4.06	4.53
Count	537	151	137	187
AD value	1.13	0.88	0.61	0.64
p-value	0.006	0.024	0.111	0.095

It can be observed that the data were not normal for no construction period. P-values are smaller than 0.05 for periods with no construction activity; therefore, and the null hypothesis is rejected. With a large number of data points normal probability tests are more powerful and detect even small deviations from normal distribution. Appendix C presents the distributions of speeds on this site. This distribution has a very acceptable, normal bell-shaped curve, although the normality test does not confirm that. For the purposes of this study, the datasets were assumed to be normally distributed, and the t-test was used in speed evaluation due to its relative insensitivity of to normal distribution.

Table 4.18 provides the results of the t-test comparing speeds during periods of construction activity with those during periods of no construction. For both periods, the difference between the speed of cars and trucks was statistically significant. Table 4.19 provides the results of the t-test comparing speeds during construction activity with those for speeds when there was no construction. The p-values obtained from the two-sample t-tests show that construction activity had a significant effect on the speeds of vehicles at a 99% level of confidence. The speed of cars and trucks dropped significantly when there was construction activity in the work zone.

Table 4.18 t-Test comparing the mean speeds of cars and trucks (Pacific EB site)

Test parameters	Car vs. Trucks	
	No Construction	Construction
Difference of mean speeds (mph)	3.9	1.9
95% lower bound for difference (mph)	3.2	1.1
t-statistic	9.51	4.04
p-value	<0.001***	<0.001***

*** Significant at 99% level of confidence

Table 4.19 t-Test comparing mean speeds of construction and no construction (Pacific EB site)

Test parameters	No Construction vs. Construction	
	Car	Truck
Difference	4.7	2.8
95% lower bound for difference	4.0	2.0
t-statistic	11.33	5.95
p-value	<0.001***	<0.001***

*** Significant at 99% level of confidence

4.1.2 Speed Compliance

To evaluate driver compliance with work zone speed limits, speeds were statistically compared with the posted speed limit, and the significance of the differences was determined. The speed limit for the Waynesville, Rolla, and Cuba work zone sites was 60 mph and that for the Pacific site was 50 mph. The speed data were subjected to t-tests, and the results were analyzed based on the p-values obtained.

Table 4.20 presents the results of the t-tests. Those for the datasets from work zones with a 60-mph speed limit and standard lane width (Waynesville and Cuba) demonstrate that during periods of both construction and no construction, the speeds of cars and trucks were statistically higher than the posted speed limit. Construction was not heavy enough to prompt vehicles to travel below the speed limit. As noted above, construction prompted drivers to slow down significantly, but not below the speed limit of 60 mph.

The results of the tests for the work zone with a 60-mph speed limit and reduced lane width with tubular markers (Rolla) demonstrate that the speeds of cars and trucks were statistically lower than the posted speed limit at a 99% confidence level. For the Rolla site, all vehicle speeds, whether with or without construction, were significantly lower than the speed limit. A comparison of these results with those for the Waynesville site demonstrates that the reduced lane width reduced vehicle speeds more than the construction itself.

The results of the statistical tests for the Pacific work zone with a 50-mph speed limit indicate that when there were two open lanes, the speeds of both cars and trucks were statistically higher than the speed limit (significant at 99% confidence level). Similarly, with construction activity and only one lane open to traffic, the speeds were also statistically higher than the speed limit. Here, however, lane width was reduced with pavement markings, and construction activity was not adjacent to traffic. These results agree with those for the Waynesville site, demonstrating that construction reduced the speed of the vehicles significantly but not to below the speed limit. They also suggest that reduced lane width is not a significant factor in reducing speeds when it is applied by pavement marking and when construction is not adjacent to traffic.

Except in the Rolla work zone, the mean speeds were statistically higher than the speed limit. Thus, the 85^{th} percentile speed of both cars and trucks was much higher than the speed limit, and the difference is statistically significant. For the Rolla work zone with construction, the 85^{th} percentile speeds for cars and trucks were 57 and 55 mph; with no construction, they were 64 and 57 mph respectively. When there was construction activity in the work zone and the lane width was reduced with tubular markers, the 85^{th} percentile of the speed was less than the speed limit. When there was no construction, only the 85th percentile of the car speed was higher than the speed limit.

Table 4.20 Work zones characteristics, speed characteristics, and speed limit compliance

Work Zone	Configuration^	Speed limit (mph)	Type	Mean (mph)	t-Statistic
Construction					
Waynesville WB	1	60	Car	62.6	+2.11**
			Truck	61.4	+1.47*
Rolla WB†			Car	51.5	-14.56***
			Truck	48.9	-11.85***
Pacific WB†††		50	Car	52.3	+9.11***
			Truck	50.5	+1.78**
Pacific EB†††			Car	52.4	+6.78***
			Truck	50.4	+1.38*
No Construction					
Waynesville WB	1	60	Car	66.6	+9.74***
			Truck	63.6	+4.5***
Cuba WB			Car	62.8	+8.85***
			Truck	60.6	+1.43*
Rolla WB†			Car	56.0	-7.13***
			Truck	51.9	-10.16***
Pacific WB††	2	50	Car	55.8	+18.11***
			Truck	54.0	+8.91***
Pacific EB††			Car	57.1	+30.50***
			Truck	53.2	+9.63***

† Reduced lane width by markers, †† Reduced lane width, ††† Reduced lane width, construction not adjacent to open lane.

^ One lane open = 1, two lanes open = 2

*** Significant at 99% level of confidence; ** Significant at 95% level of confidence; * Significant at 90% level of confidence

To illustrate more clearly, the number of vehicles traveling above the speed limit, Figure 4.1 presents the percentages of vehicle speeds above the speed limit by at least 0, 5, and 10 mph. Generally, when there was construction activity, the percentage of drivers traveling faster than the speed limit was lower than when there was no construction, an observation that agrees with the results of statistical tests addressing the effects of construction on speed. The width of the open lane at the Rolla site was reduced using tubular markers; therefore only a small percentage of traffic exceeded the speed limit in the work zone during periods of construction and no construction, and no vehicles traveled more than 10 mph above the speed limit.

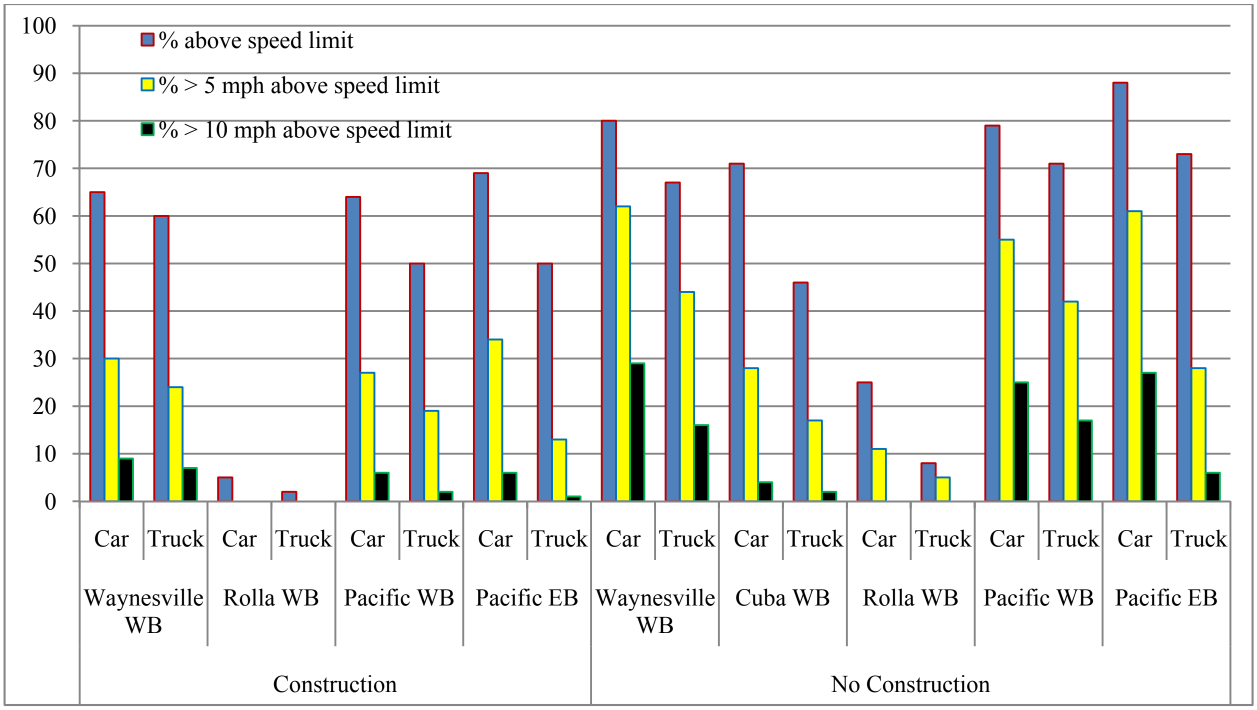

Figure 4.1 Percentages of speeds higher than speed limit by at least 0, 5, and 10 mph

Figure 4.1 also demonstrates that the percentage of drivers traveling above the speed limit, the percentage of drivers traveling more than 5 mph above the speed limit, and the percentage of drivers traveling more than 10 mph above the speed limit were higher when the speed limit was lower (50 mph rather 60 mph). This suggests drivers comply less readily with the speed limit as the speed limit drops, an observation confirmed by t-statistics that show very high values (Table 4.20). These statistics also confirm the results of Outcalt (2009) showing that drivers are more likely to exceed the speed limit in a work zone with a greater speed limit reduction.

4.2 Subjective Evaluation

The subjective evaluation is divided in two sections: common practices of state DOTs and driver survey.

4.2.1 Common Practices of States

A survey questionnaire was sent to 50 DOTs via email; 27 responded. The complete questionnaire is included in Appendix B. It posed questions on work zone speed management policies, the nature of work activities that warrant reduced speed limits, factors determining the posted speed limit, the type of signs used to post speed limits, compliance levels, and the measures taken to evaluate the effectiveness of these policies. The following summarizes the responses to each question.

4.2.1.1 Policy on Reducing Speed Limits in Work Zones

DOTs were asked if their state has a policy on reducing traffic speeds in work zones. Ninety percent of the states responding to the survey said that their agency does have such a policy. Seven state DOTs (Illinois, Michigan, Montana, Washington, Nebraska, Kentucky, Oregon) indicated that their policies had been established legislatively, and 17 indicated that policy was determined by the transportation agency.

4.2.1.2 Work Activity locations that Warrant a Reduced Speed Limit

The DOTs were asked what activities warrant work zone speed limit reductions. Figure 4.2 shows the number of states that reduce speed limits at various locations in work zones. Eighty-six percent responded that they reduce speed limits for activities within 2 ft of the road; 65% consider speed limit reductions for activities 2-10 ft from the road, and 28% consider a reduction in speed limit for activities occurring more than 10 ft from the edge of the road. For activities between the centerline and the edge on the roadway, 26 out of 27 agencies post reduced speed limits. Finally, for activities that require temporary detours, 80% of the respondents would consider a reduction in the speed limit.

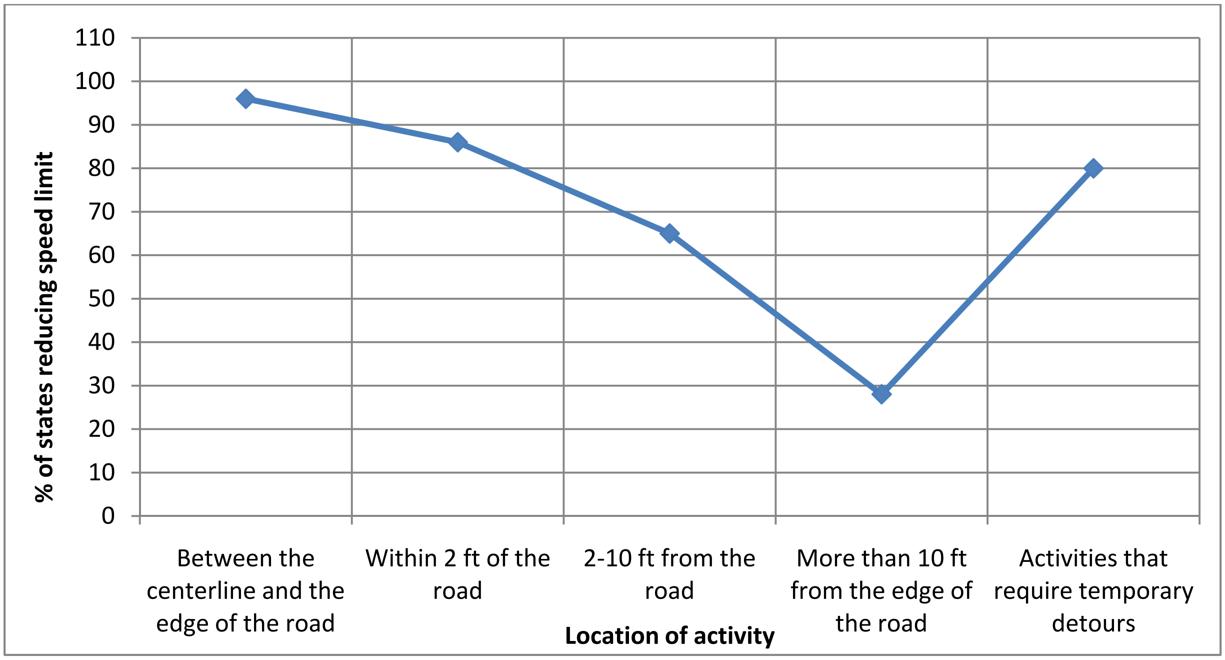

Figure 4.2 Percentages of states that reduce the speed limits in various locations in work zones

4.2.1.3 Factors Determining the Reduced Speed Limits in Work Zones

Agencies were asked about various factors that determine the magnitude of a speed limit reduction for work zones. Respondents consider the following factors in determining the magnitude of a speed limit reduction: presence of workers in the work area (93% of respondents), lane width (87%), roadway alignment (87%), type of activity (87%), existing speed limit (83%), sight distance (77%), presence of a barrier (77%), roadway type (77%), prevailing speeds (70%), and traffic volume (70%). Accident history (46%) and percentage of trucks (40%) are less commonly considered.

4.2.1.4 Maximum Speed Reduction

The DOTs were surveyed about the maximum speed reduction in work zones. The majority of the respondents (70%) impose a maximum speed limit reduction of 10 mph in work zones. The remaining states reduce the speed limit more than 10 mph. Minnesota and West Virginia permit a maximum reduction of 15 mph, Illinois and Colorado a 20-mph reduction, and South Carolina a 25-mph reduction. Oregon uses a 10-mph reduction for freeways and a 20-mph reduction on other roads in two increments of 10 mph. The Michigan DOT requires the approval of the chief operations officer to implement any speed reductions greater than 10 mph. Indiana has a state statute that permits a reduction of 10 to 45 mph.

4.2.1.5 Devices Used to Alert Drivers to Reduced Speed Limits

The most common means of alerting drivers to reduced speed limits in work zones was found to be static speed limit signs. Some DOTs also use PCMSs. The placement of signs is commonly determined based on MUTCD guidelines (2003) or agency-specific policy guidelines.

4.2.1.6 Strategies Used to Encourage Compliance

DOTs were asked to indicate which of several strategies they currently use (or have used) to control speed or improve compliance, and to estimate the effectiveness of each. Of the 27 states that responded, 24 (89%) reported that police enforcement has been the most mentioned effective strategy. Regulatory signs were found to be effective by only 25% of respondents; 72% found them partially effective. Advisory speed limit signs were found to be partially effective by 77% of respondents; 15% found them ineffective. Incremental speed limit reductions upstream of the work zone and within the work zone are imposed by 13 states, and they have proved partially effective. CMSs were deemed effective by 36% of respondents, partially effective by 54%, and ineffective by 4%. Flagging operations have been effective for 27% of respondents and partially effective for 39%. Pilot vehicles have been used by 16 DOTs, 56% of which have found them effective and 44% of which have found them partially effective. Increased fines for infractions have been deemed effective by 33% of respondents, partially effective by 59%, and ineffective by 7%.

4.2.1.7 Measures of Effectiveness

DOTs were surveyed about the measures of effectiveness they use (or have used in the past) to evaluate speed control and/or compliance. The 85th percentile speed within the work zone was found to be the most popular measure used by DOTs to determine the effectiveness of speed reduction strategies. Other measures include mean speeds within work zones, speed variance with a work zone, percentage compliance, and crash data. Some DOTs also use citation data collected from law enforcement agencies. A few states indicated that they have never formally evaluated the effectiveness of speed reduction strategies, relying instead on engineering judgment and personal perceptions. When asked if the work zone speed limit signs are posted only when work is actually underway, 63% of respondents answered affirmatively. Some DOTs indicated that movement of signs depends on the type of work activity and thus varies from one project to another.

4.2.1.8 Adverse Effects of Reduced Speed Limits in Work Zones

When asked about the adverse effects of work zone speed limit reductions in terms of capacity, LOS, and user delays, the majority of survey respondents stated that there have been no adverse effects. The Michigan DOT stated that traffic operations in work zones have improved (i.e., delays have been reduced) as a result of reductions in speed limits. However, reduced speed limits in work zones have had negative effects in some states. The Illinois DOT reported a reduction in LOS and increased delays. The New York DOT has noted a reduction in freeway capacity, and the Colorado DOT has observed that traffic slowdowns resulted in user delays, especially during morning and evening peak periods. The Hawaii DOT indicated that a reduction in speed limits usually had no adverse effects; however, a special bridge project for which speed limits were reduced to substantially below normal operating speeds did result in a lower LOS.

The speed reduction was intended mainly to reduce vibration on the bridge deck and thus to minimize the segregation of concrete.

4.2.2 Driver Survey

A survey was administered to study drivers' perception of driving through work zones. The survey questions covered three general areas: demographic information, driving behavior in work zones, and drivers' perception of speed limit compliance. Drivers were surveyed on type of vehicle driven, driver's attention to the posted speed limit, driver's opinion regarding posted speed limit, effects of work zone signage on driver behavior, perceived delay, and the effects of construction activity on their own driving behavior.

The questionnaire was distributed to drivers near data collection sites over the course of the study. Drivers were asked to take the survey if they had passed through the work zone. The responses were analyzed to determine drivers' perceptions of reduced work zone speed limits, and speed limit compliance. The results were divided into two categories: i) work zones with a speed limit of 60 mph near the Rolla site, and ii) work zones with a speed limit of 50 mph near the Pacific site. A total of 118 drivers were surveyed, 61 in the first category and 57 in the second. The categorization was used to analyze the responses to the speed related questions and to compare them with the objective evaluation. The first category was collected with the work zone in place, and the second was conducted after the lane closure had been removed that day.

4.2.2.1 Demographics

Participants in the survey ranged from 18 to 81 years old (see Figure 4.3); 75% of respondents were male and 25% were female. They had driving experience ranging from 1 year to more than 20 years (see Figure 4.4). Vehicle types included passenger cars (both sedans and SUVs) and trucks (single-unit trucks, single and double trailer trucks, and RVs) (see Figure 4.5). Sixty percent of the participants drove on the highway regularly or at least once a week.

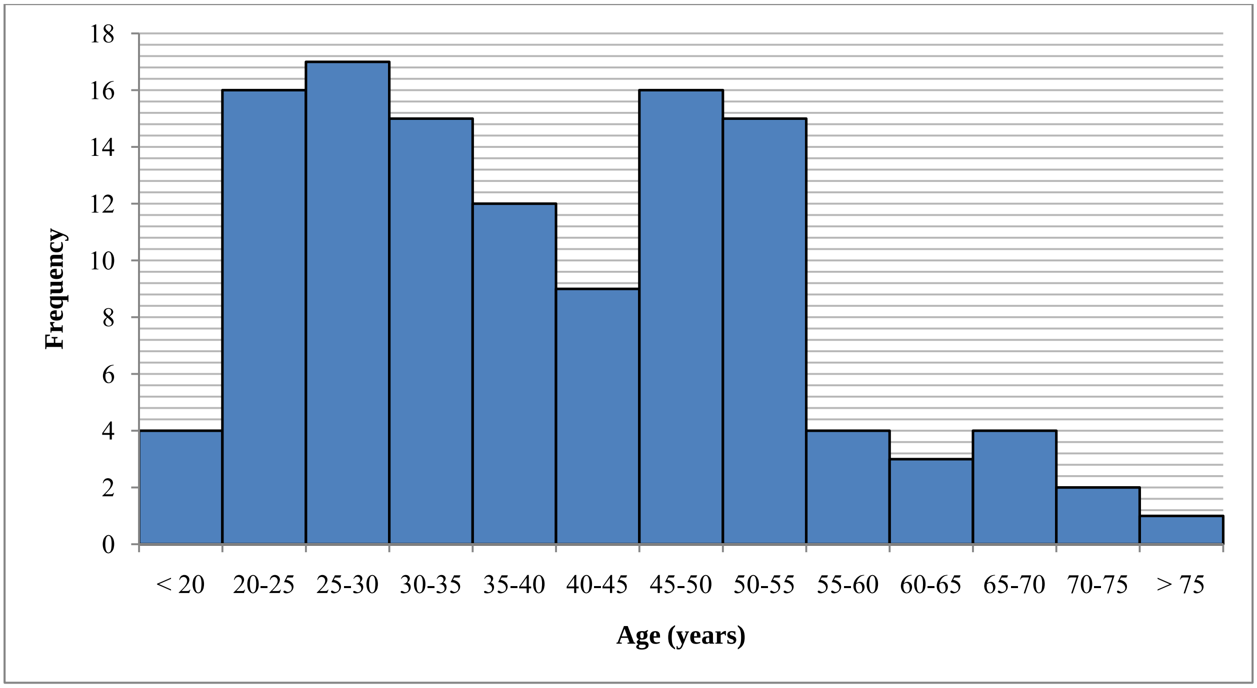

Figure 4.3 Age distribution of surveyed drivers

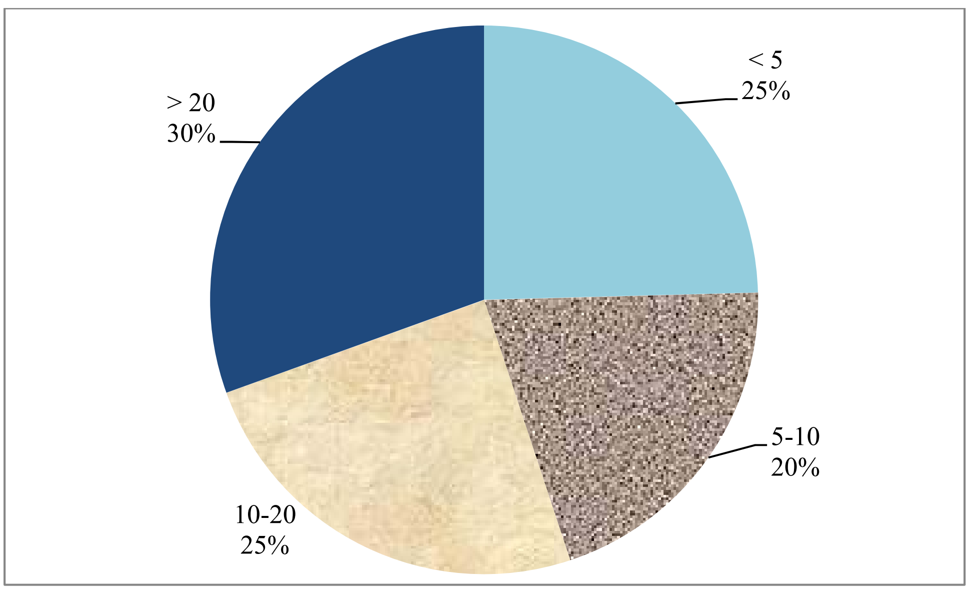

Figure 4.4 Driving experience of participants (in years)

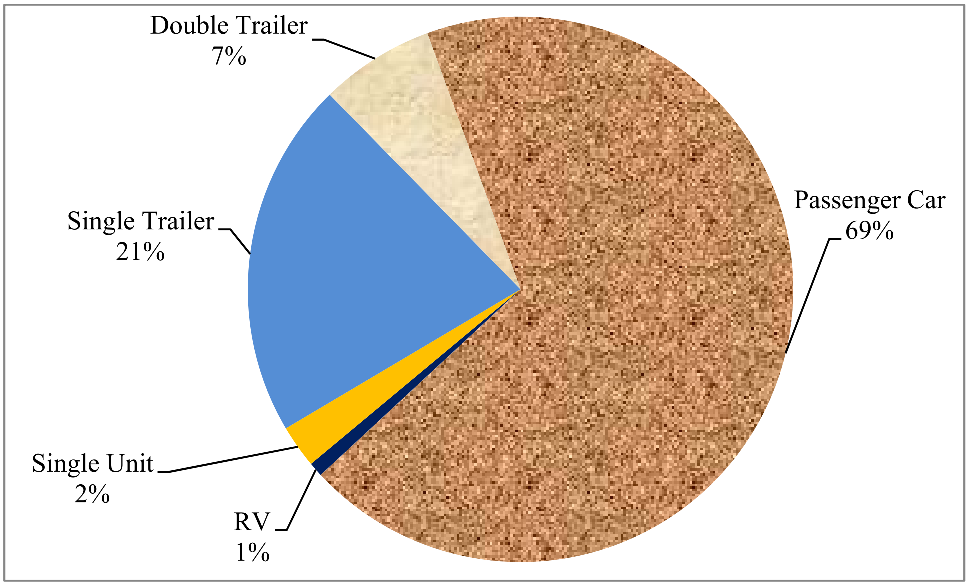

Figure 4.5 Types of motor vehicles

4.2.2.2 Driving Behavior

The signs used in the work zones were placed sequentially in the following order as drivers approached the construction zone: Fine Sign (the fine driver should pay if they hit a worker in work zone), “Road Work Ahead,” “Left/Right Lane Closed Ahead,” “Do Not Pass,” “Speed limit 50/60,” and “Left/Right Lane Closed.” Drivers were asked how far in advance of the work zone signs should appear.

All participants indicated a strong desire to be alerted to a work zone more than a mile in advance. Figure 4.6 shows the drivers’ preferences. Only 13% of respondents wished to see the “Left/Right Lane Closed Ahead” sign 0.5-1 mile before the work zone. Only about 1% preferred to see it less than 0.5 miles from the work zone; these were likely the most aggressive drivers in the sample. This figure is in accordance with the driving behavior observed in response to the "Road Work Ahead" sign. Similarly, drivers were asked about their preference regarding the “Speed limit 50/60 mph” sign; very few indicated a desire to see this sign less than 0.5 miles before the work zone, and more than 75% preferred to see it more than a mile before the work zone.

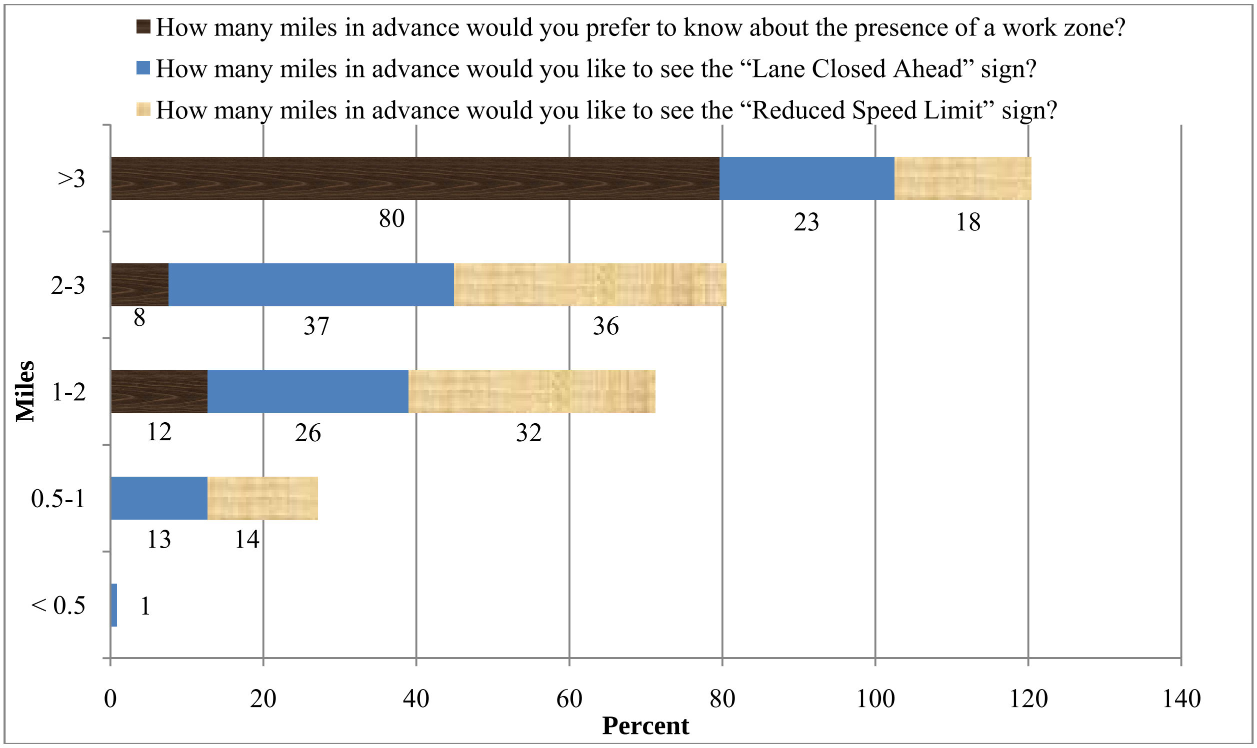

Figure 4.6 Drivers' preference regarding location of work zone signs

To evaluate lane change behavior, drivers were asked, "When do you move out of the closed lane?" Figure 4.7 presents their responses. More than 87% of participants stated they move out of the closed lane "prior to when they actually see the work zone," of these, 62% preferred to take action "immediately after the 'Lane Closed Ahead' sign," indicating conservative behavior. Of the remaining participants, 10% and 3% preferred to move out of the closed lane "after they saw the work zone", and "immediately before the transition taper," figures showing once again that aggressive drivers are a small sample of the population.

When drivers were surveyed about appropriateness of the speed limit, about 80% said they found the work zone speed limit safe. Drivers were asked about the delay experienced while driving through the work zone; about 70% indicated some delay. When surveyed about the impact of construction activity on driving speed, 92% of respondents indicated that they reduced their speed when there is construction activity. The high percentage of agreement with this statement corresponds to the small percentage of aggressive behaviors as suggested by responses to previous questions. The data shows that this small portion of aggressive drivers indicated that construction activities had no effect on their speed, and they preferred to change lanes just before the taper area.

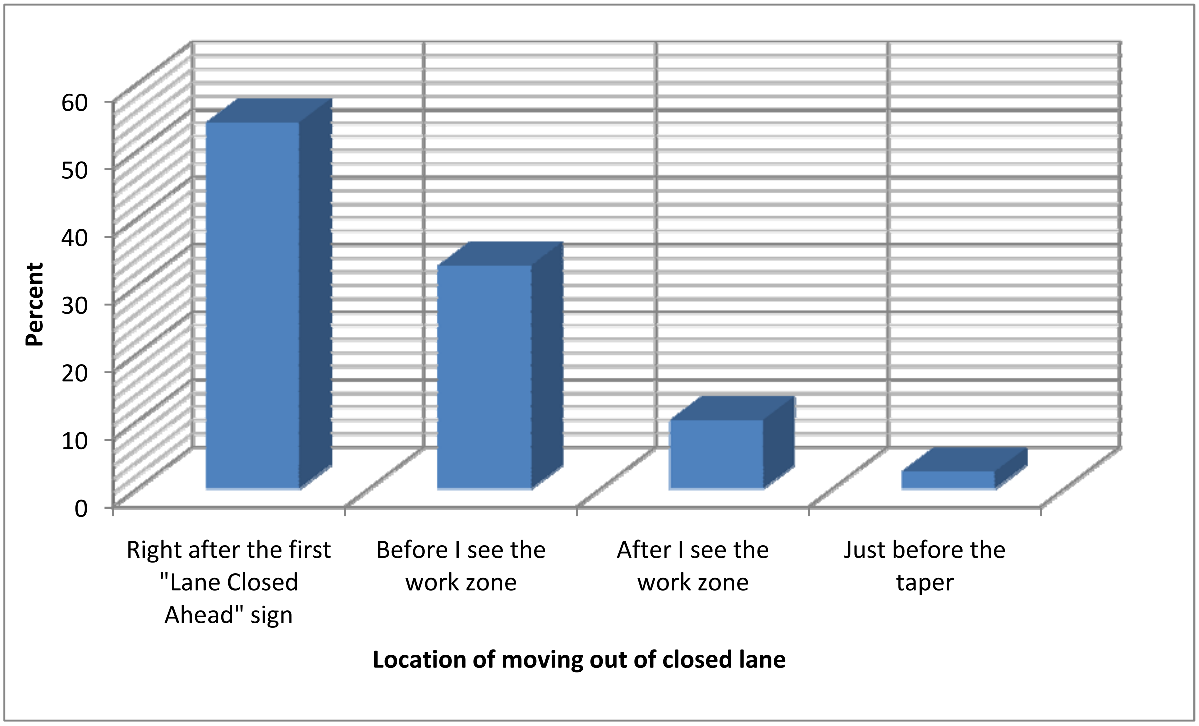

Figure 4.7 Points at which where drivers move out of the closed lane

4.2.2.3 Speed-Related Questions

Drivers were asked if operating their vehicle among various types of vehicles posed any safety risks. Seventy-five percent of drivers said it did not. This statistic shows that the majority of drivers (more than 70%) have few safety concerns about driving among other types of vehicles. Although this question was not directly related to the speed limit in work zones, answers to it can be regarded as a factor influencing driver behavior. Drivers whose answers were positive may have reduced their speed because of reasons other than the reduced speed limit. Since most of the drivers did not show concern about other vehicle types, speed reduction can be assumed to be independent of vehicle composition in the traffic stream. To compare the results of the subjective evaluation to those of the objective evaluation, the responses to speed related survey questions were analyzed separately for passenger car drivers and truck drivers.

4.2.2.3.1 Passenger Car Driver Survey

Passenger car drivers constituted 64% and 74% from the first (60 mph speed limit) and second (50 mph speed limit) categories, respectively. When asked their opinion of the speed limit compliance of other drivers, about 36% from the first category and 40% from the second category disagreed that other drivers followed the speed limit in the work zone. These figures should be interpreted in the light of responses to the asked about vehicle speed and the posted speed limit, discussed below. Figure 4.8 presents drivers' opinions about the speed limit compliance of other drivers.

When drivers were surveyed regarding their own speed (see Figure 4.9), 12% in the first category and 53% in the second category indicated that they drove above the speed limit within the work zone. The Rolla site which had a 60-mph speed limit, had congested conditions, and the lane width was reduced. Compared to the other sites, speeds in that zone were, on average, below the posted speed limit. The Rolla site was also permanent and long-term. For the second category, the lane closures were removed when queues formed, and the speed limit was lower. As a result, the speed limit compliance was lower, and the results of the subjective survey were consistent with those of the objective survey. The t-statistics presented in Table 4.20 confirm the consistency of the subjective and objective evaluation of speed limit compliance at the Rolla and Pacific sites.

Another multiple choice question asked drivers to indicate the speed they believed should be posted as the speed limit. Their choices were 45, 50, 55, 60, 65, and 70 mph. Ninety-three percent of participants in the first category suggested a speed limit less than or equal to 55 mph, the rest suggested 60 mph. Thus, all participants in the first category suggested a speed limit equal to or below the posted speed limit. In the second category, about 93% of the participants suggested a speed limit of above or equal to 55 mph, and the rest suggested 45 and 50 mph (see Figure 4.10). These responses indicate that drivers generally suggested a speed limit based on their own traveling speed. This can be confirmed by comparing responses to the questions asking about drivers' own speeds and their suggestions for a speed limit. Most drivers in the first category traveled below the actual speed limit and most suggested a reduced speed limit. Similarly, more than half of drivers in the second category were traveling faster than the actual speed limit, and most suggested a limit higher than the actual speed limit. The speed limit in the first category was 60 mph, however, and that in the second category was 50 mph. Therefore, the results are consistent with the actual conditions.

4.2.2.3.2 Truck Driver Survey

Truck drivers comprised 36% and 26% in the first and second categories, respectively. When surveyed about the speed limit compliance of other truck drivers, about 16% in the first category (60 mph speed limit) and 20% in the second category (50 mph speed limit) indicated that other drivers did not follow the speed limit in the work zone (see Figure 4.8).

When drivers were surveyed regarding their own speed (see Figure 4.9), all participants in the first category indicated that they drove below the 60-mph speed limit. About 73% of the drivers in the second category indicated that they drove below the 50-mph speed limit within the work zone.

When surveyed about their preferred speed limit (see Figure 4.10), all truck drivers in the first category suggested a speed limit between 45 and 55 mph as appropriate for work zones.

About 74% of the participants in the second category suggested a speed limit of more than 50 mph, and the rest suggested 45-50 mph. Similar to passenger car drivers, truck drivers generally suggested a speed limit consistent with their own traveling speed.

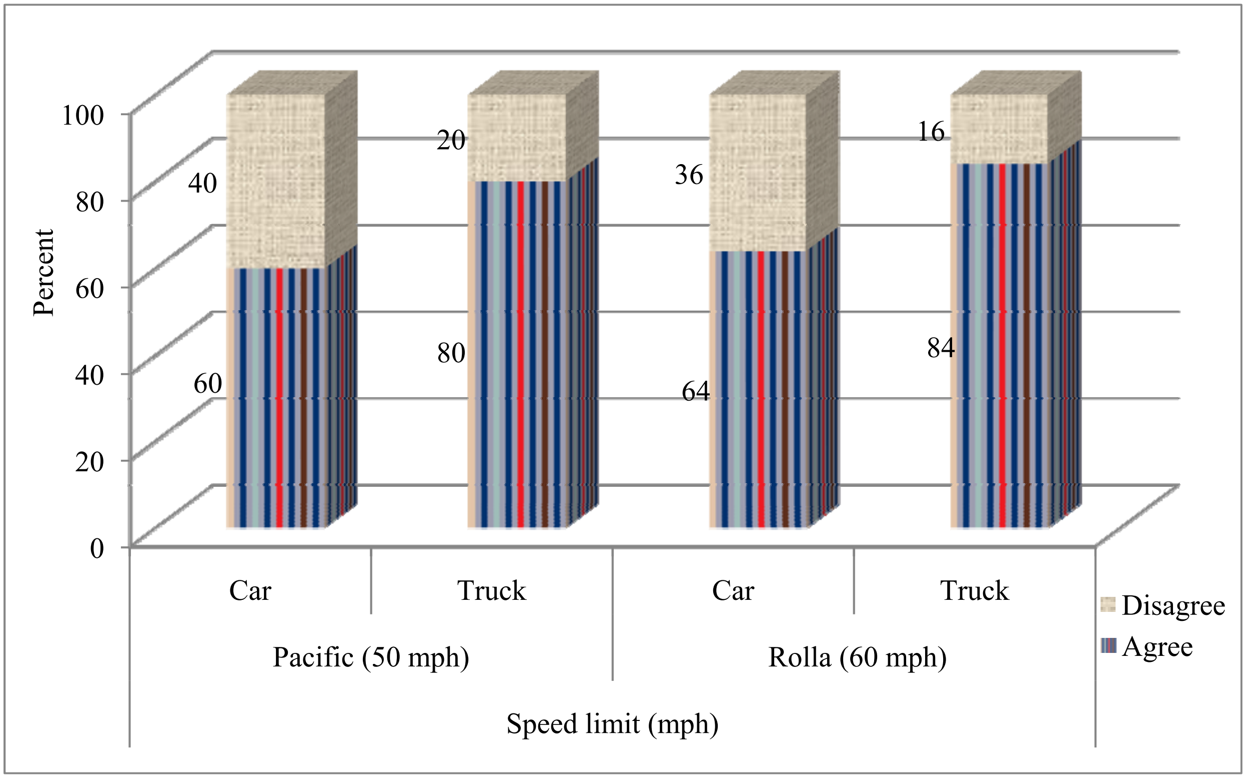

Figure 4.8 Car and truck drivers' opinions about the speed limit compliance of other drivers: "Did other drivers follow the speed limit?"

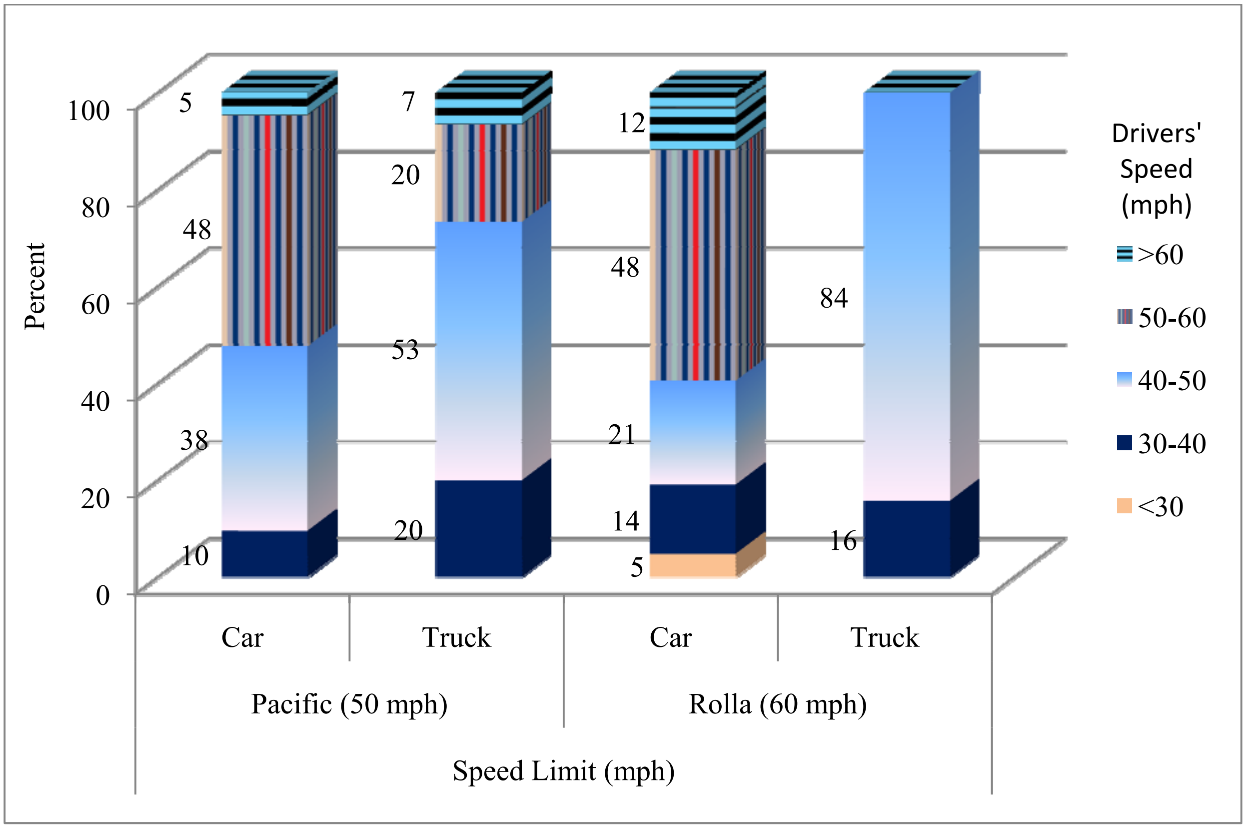

Figure 4.9 Drivers' speed while traveling through the work zone

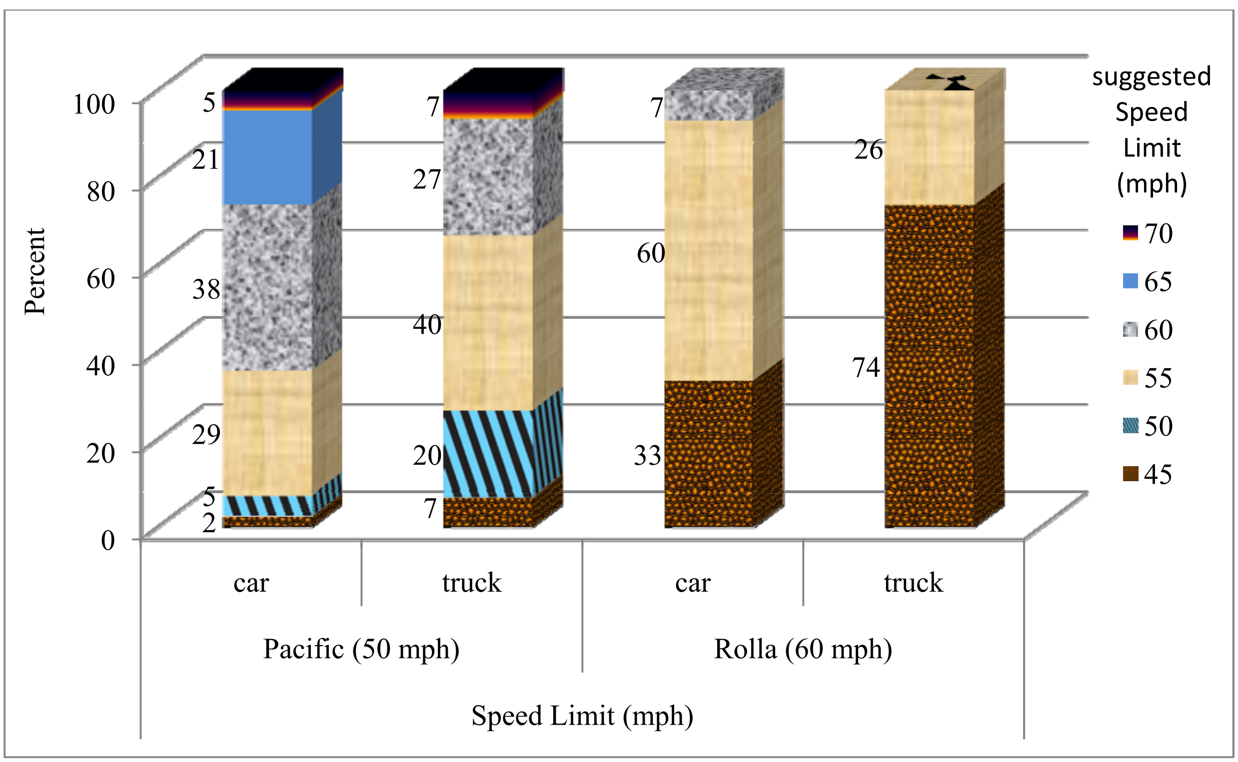

Figure 4.10 Speed limit suggested by surveyed drivers

CHAPTER FIVE

5. DISCUSSION OF RESULTS

This section presents the results from the objective and subjective evaluation that require further clarification. It includes a brief discussion on the DOT survey, comparisons of the effects of reduced lane widths, construction, and lane closure on speed of vehicles, and an evaluation of the consistency of the results of the objective and subjective evaluations.

A 10-mph reduction in the posted speed limit is desirable in work zones when work activity is on or near the highway (Outcalt, 2009; Agent et al., 2005). The survey of DOT practices showed that most states impose a maximum speed limit reduction of 10 mph in work zones, based on the presence of workers, reduced lane width, roadway alignment, type of activity, and the existing speed limit. The variables that prompt a 20-mph reduction in speed limit include all of those variables, plus narrower lanes and higher traffic volume. The DOT survey indicated that regulatory static speed limit signs are considered effective by only 25% the respondents. Based on the results of the t-tests for comparing the vehicle speeds for two levels of construction activity (Table 4.4, Table 4.8, Table 4.15, and Table 4.19) the objective evaluation indicated that the mean speed of passenger cars and trucks in work zones with no construction was significantly higher than those with construction. Static signs, therefore, were ineffective at reducing speeds unless construction activity was in place. This observation agrees with the results of the subjective evaluation, which indicated that more than 90% of respondents agree that construction causes them to reduce their speeds.

The speed limit for the Rolla, Waynesville, and Cuba sites was 60 mph and at the Pacific site was 50 mph. The construction activity at the Pacific site (addition of a new lane) was heavier than the other sites and the lane width (10 ft) was reduced, which required a higher reduction in speed limit in addition to a reduction in lane width (10 ft). Much of the construction at the Pacific site was performed at night time and a lower speed limit was more beneficial for the safety of travelers. The consideration of the type and intensity of the construction activity justifies the amount of reduction in normal speed limit of the highway.

Lane width in the Rolla and Pacific work zones were reduced by tubular markers and pavement markings, respectively. The mean speeds of vehicles (with or without construction) at the Rolla site were below the speed limit; those at the Pacific site were higher than the speed limit. In both cases, the differences were statistically significant. These results indicate that the effect of reduced lane width was much greater when tubular markers were used.

The number of vehicles traveling at least 5 mph or 10 mph above the speed limit was considerably larger for periods of no construction activity in the work zone. While the work zone signs were in place and drivers saw no worker or construction activity, they speed up to their desired speed. On the other hand, some drivers comply with the speed limits. This causes higher speed variation during no construction which increases the risk of crashes.

Passenger car speeds were generally higher than truck speeds except at the Waynesville site with construction (Table 4.3). At the Waynesville site, the mean speed of passenger cars was 1.14 mph higher than that of trucks, but the difference was not statistically significant. For the Pacific WB site, either with or without construction, however, the small difference between passenger car and truck speeds (1.7 mph for no construction and 1.8 mph for construction) was statistically significant at a 99% level of confidence. These results should be interpreted carefully because of the sample size, which has an important effect on the test results. The larger the sample size, the higher the power of the test. A test with higher power detects even very small differences as statistically significant. For the Waynesville site (with construction), the sample size was about 10% of the sample size for the Pacific WB site (without construction) (Table 4.1 and Table 4.12).

For the Rolla site, the reduced lane width indicated by tabular markers on the open lane significantly affected the mean speeds of vehicles, even with no construction, reducing them to much lower than the 60 mph speed limit, and this difference was statistically significant at a 99% level of confidence. Further, construction activity significantly reduced the speeds of both cars and trucks, a finding echoed by the results of the subjective evaluation, in which more than 90% of the respondents indicated that they would reduce their speed if they observed construction activity.

The objective evaluation determined that, with no construction activity in the work zone, or with construction activity not adjacent to the open lane, vehicles drove faster than the speed limit. These results agree with previous findings (Migletz et al, 1998; Migletz et al, 1999). Additionally, the objective results agree with those of the subjective analysis. The survey for the Pacific work zone with a 50-mph speed limit was conducted when the lane closure had been removed as a result of congestion and no construction was observed; as a result, most of the passenger car and truck drivers were traveling faster than the speed limit. Only 40% of drivers drove indicated that they below the speed limit under those conditions. On the contrary, for work zones with a 60-mph speed limit, the survey was conducted with one lane closed and on-going construction. In this case, 95% of the participants indicated that they drove below the speed limit. In addition, about 92% of all participants indicated that construction activity causes them to reduce their speed.

Passenger car surveys conducted for work zones with 60-mph and 50-mph speed limits, 36% and 40% of car drivers, respectively, indicated that other drivers do not follow the speed limit. On the same surveys, 5% and 60% of car drivers respectively indicated that they drove faster than the speed limit. Thus, when the minority of drivers (5%) drove faster than the speed limit, they overestimated the number of other drivers that travel faster than the speed limit (36%). When appreciable number of drivers (60%) traveled faster than the speed limit, they underestimated the number of other drivers they estimated traveled faster than the speed limit (40%). Further, drivers generally suggest a speed limit higher than their actual speed, regardless of the existing speed limit or of roadway or environmental conditions. This result is expected; drivers are unlikely to suggest a speed limit that they violated. A similar result was observed for truck driver survey, which indicates that all the drivers behave in a similar manner.

CHAPTER SIX

6. CONCLUSIONS AND RECOMMENDATIONS

This study analyzed the effects of lane closures (closed versus open lanes within the work zone), construction activity, and lane width on free flow speeds of passenger cars and heavy vehicles in work zones. Speeds referred to in this section and elsewhere in the report indicates the free flow speeds unless otherwise stated. It also evaluated drivers' compliance with the posted speed limit, both objectively and based on drivers' perceptions of their own speeds. Moreover, it surveyed US DOTs to identify common work zone practices related to posted speed limit.

From the objective evaluation, passenger cars were found to travel at significantly higher speeds than trucks. For all work zone sites, the speed of cars was at least 1.2 and 1.8 mph higher than trucks during no construction and construction, respectively. Construction activity significantly reduced the speeds of passenger cars and heavy vehicles; however, their speeds were still higher than the posted speed limit. During periods of no construction, passenger car speeds were at least 3.5 mph higher than during periods of construction. Truck speeds were also found to be at least 2.2 mph higher during periods of no-construction compared to construction. With no-lane width reduction and no-construction activity, drivers drove faster than the speed limit; mean speed of cars and trucks were found to be at least 2.8 and 0.6 mph higher than the speed limit, respectively. Reduced lane width as a result of tubular markers was most effective factor in terms of reducing the speeds of vehicles. It resulted in a mean speed of cars and trucks, 4.0 and 8.1 mph less than the speed limit, respectively during no-construction activity, and 8.5 and 11.1 mph less than the speed limit during construction activity. Based on the discussion in this report about the safety risks of low speed limits with no work zone activity, the use of variable speed limits is recommended since it adjusts the speed limit according to the state of traffic and may reduce the risk of crashes in work zones.

Drivers' compliance with the speed limit dropped with lower speed limits, 50 versus 60 mph. The number of drivers traveling at a speed of at least 5 or 10 mph above the speed limit was considerably higher for sites with 50-mph speed limit compared to sites with 60-mph speed limit during both periods of construction and no-construction activity. Drivers exceeding the speed limit by more than 10 mph were found to be less than 10% with construction, however, this percentage increased to more than 25% and 17% for cars and trucks, respectively, with no construction activity.

From the state DOT survey, twenty seven responses were received. Of these, 86% of DOTs reduce the speed limit for activities within 2 feet of the road edge. For activities between the centerline and the edge, 26 out of 27 agencies reduce the speed limit. The dominant factors in determining the reduced speed limit were presence of workers, lane width, roadway alignment, and type of activity. Seventy percent of respondents indicated a maximum speed limit reduction of 10 mph in work zones. Also, static speed limit signs are most commonly used. Most DOTs agree that the best strategy to increase compliance with the speed limit in work zones is the use of police patrol. Only 25% of respondents found regulatory signs effective and another 72% indicated that the regulatory signs were partly effective.

The subjective evaluation determined that drivers prefer to be informed of an upcoming work zone more than a mile in advance when workers are present. Fourteen percent of drivers, however, were found to be aggressive in terms of lane changing behavior as they prefer to see the "Lane Closed Ahead" and "Reduced Speed Limit" sign less than 1-mile before the work zone. A similar percentage of drivers exceeding the speed limit by more than 10 mph were found from the objective analysis when no construction was in place. Most drivers indicated that they experienced delay in the work zone, and more than 90% agreed that construction activity reduced their speeds, a figure that agrees with the results of the objective analysis. Comparison of the responses to the survey questions on speed limit suggests that when most drivers are traveling faster than the speed limit, they underestimate the number of other drivers by 20% that do not comply with the speed limit. Conversely, when most other drivers are traveling below the speed limit, they overestimate the by 31%. Also, drivers generally suggest a speed limit consistent with their own speed, irrespective of the existing speed limit, roadway or environmental factors, a tendency that is predictable of human behavior.

The survey results related to the posted speed limit are particularly important. An overwhelming majority of drivers (92% of car drivers and all of the truck drivers) suggested a reduction in speed limit during periods when the work zone is congested. Conversely, 92% of car drivers and 73% of truck drivers suggested increasing the posted speed limit (from 50 mph) when the work zone is not congested. A possible solution to this issue could be the use of a variable speed limit system.

This study found that tubular markers were effective in reducing the speeds of vehicles in work zones. Therefore, the study recommends the use of tubular markers rather than pavement markings for reducing the lane width, and separating the construction area from the open lanes. When there is no construction activity in the work zone or there is no lane closure, reduced speed limit results in higher variance in the vehicle speeds and indicated the risk of crashes. This study strongly recommends the use of variable speed limit for work zones with short-term construction periods. Speed limits can be adjusted in real time based on the traffic speed and construction activity. This will help in the mobility and safety of traffic during periods with no-construction activity.

Future studies should consider the effects of different lane widths i.e., reduced using tubular markers on vehicle speeds in work zones. Work zones on freeways with more than two lanes in each direction and the effects of different types of construction activities on vehicle speeds should be studied as well. In terms of subjective analysis, the difference in the behavior of male and female drivers should be investigated with a much larger database. As many drivers travel across state boundaries, the results of a survey conducted over a region could reveal interesting outcomes.

CHAPTER SEVEN

7. REFERENCES

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CHAPTER EIGHT

8. APPENDICES

APPENDIX A Aerial Views of Work Zone Sites

Following are aerial views of video data collection sites in the work zones studied here. The circle in figures A1-A3 shows where the camera was positioned.

Figure A1. Waynesville work zone site, August 13, 2009.

Figure A2. Rolla work zone site, October 2, 2009.

Figure A3. Cuba work zone site, August 13, 2009.

APPENDIX B State DOT Survey Questionnaire

1. Please mention the name of your organization?
2. Does your state have a policy on reducing or managing traffic speeds in work zones?
   - Yes
   - No

   If yes, please specify whether it is a legislative or transportation agency wide policy
3. Do you reduce speed limits for the following conditions?(Please choose all that apply)
   - Activities that are more than 10 ft from the edge of the traveled way
   - Activities that encroach on the area closer than 10 ft but not closer than 2 ft to the edge of the traveled way
   - Activities that encroach on the area from the edge of the traveled way to 2 ft from the edge of the traveled way
   - Activities that require an intermittent or moving operation on the shoulder
   - Activities that encroach on the area between the centerline and the edge of the traveled way
   - Activities requiring temporary detour to be constructed
4. If you answered yes to any part of the above question, do you consider any of the following factors before deciding on appropriate work zone speed limit?(please check all that apply)
   - Lane width
   - Alignment
   - Type of work zone
   - Sight distance

- Prevailing speeds
- Worker's present
- Accident experience
- Presence of barrier
- Roadway type
- Traffic volume
- Design speed
- Engineering judgment
- Duration of work
- Existing speed limit
- Vehicle mix (truck composition)

5. What is the maximum speed reduction you use for work zone? (Please mark beside the appropriate option)
    - 5 mph
    - 10 mph
    - 20 mph
    - Others (please specify)
6. What devices do you use to notify the driver of a lower work zone speed limit? At what distance from work zone are these devices placed? If multiple devices are used, what is the spacing between them? (These devices may include post-mounted static signs, portable changeable message signs, speed display trailers, flashing beacons, and other devices.)

7. Which of the following strategies in work zone do you currently use (or have used in the past) for speed control and/or improved compliance, and how effective are they, if used? Please mark in the appropriate box?

    - Regulatory signs – Effective, Partially Effective, Not Effective
    - Advisory signs – Effective, Partially Effective, Not Effective
    - Staggered speed reduction* – Effective, Partially Effective, Not Effective
    - Changeable message signs – Effective, Partially Effective, Not Effective
    - Police Enforcement – Effective, Partially Effective, Not Effective
    - Flagging – Effective, Partially Effective, Not Effective
    - Pilot vehicle – Effective, Partially Effective, Not Effective
    - Flashing lights on signs – Effective, Partially Effective, Not Effective
    - Longer speed zone transition – Effective, Partially Effective, Not Effective
    - Increased fines for infraction – Effective, Partially Effective, Not Effective
    - Pavement markings – Effective, Partially Effective, Not Effective
    - Lane narrowing – Effective, Partially Effective, Not Effective
    - Rumble strips – Effective, Partially Effective, Not Effective
    - Any other combinations – Effective, Partially Effective, Not Effective
    - If any other combination, please specify

    * Note: Staggered speed reduction means different speed reductions just upstream of the work zone and within the work zone. (Example: 10mph reduction just u/s of work zone and 20 mph reduction within the work zone)

8. Which of the following measures of effectiveness are used to determine the effectiveness of the speed reduction strategy in the work zone? (Please choose all that apply)
    - Mean speed within the work zone
    - Speed variance within the work zone
    - 85th percentile speed within the work zone
    - Percentage of vehicles complying with the speed limit
    - Crash data
    - Other (please specify)
9. Has your agency's policy on reducing speed limit in work zones had any adverse impacts on work zone operations in terms of work zone capacity, LOS, user delays, etc.? Please provide details.

If you like to share any additional information about work zone speed limit please do mention below?

APPENDIX C Speed Distribution Curves for the Pacific Work Zone

This appendix presents speed distributions of cars and trucks at various levels of construction activity in the Pacific work zone. The figures show that these distributions follow an approximately normal bell-shaped curve; however, the normality test can detect very small deviations from the standard normal distribution.

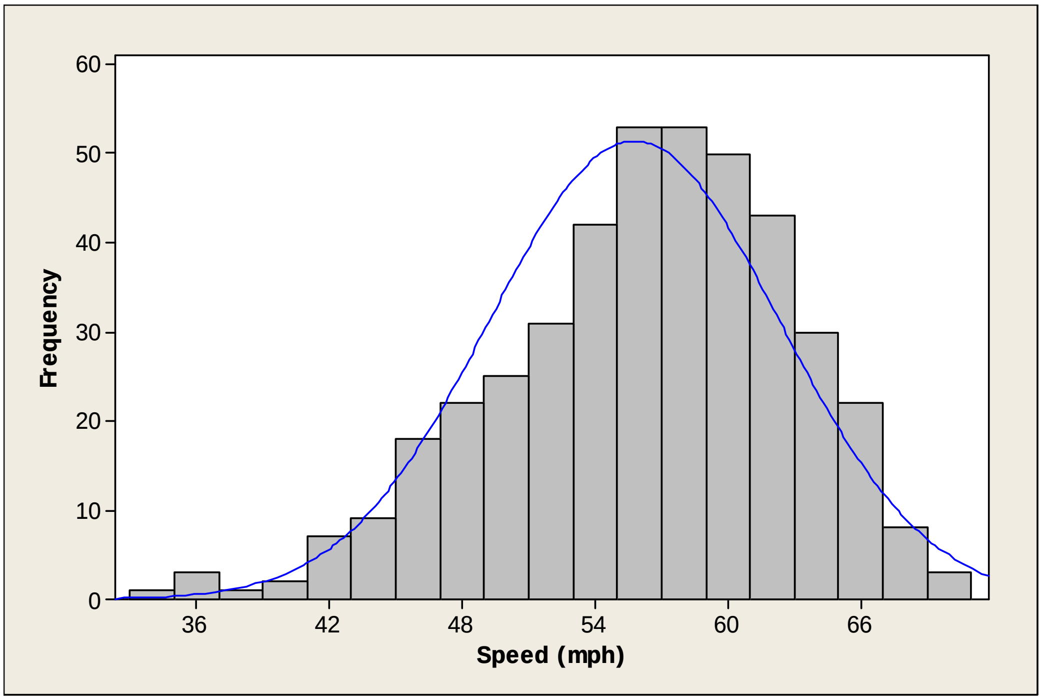

Figure C1. Car speed distribution in the Pacific WB work zone with no construction

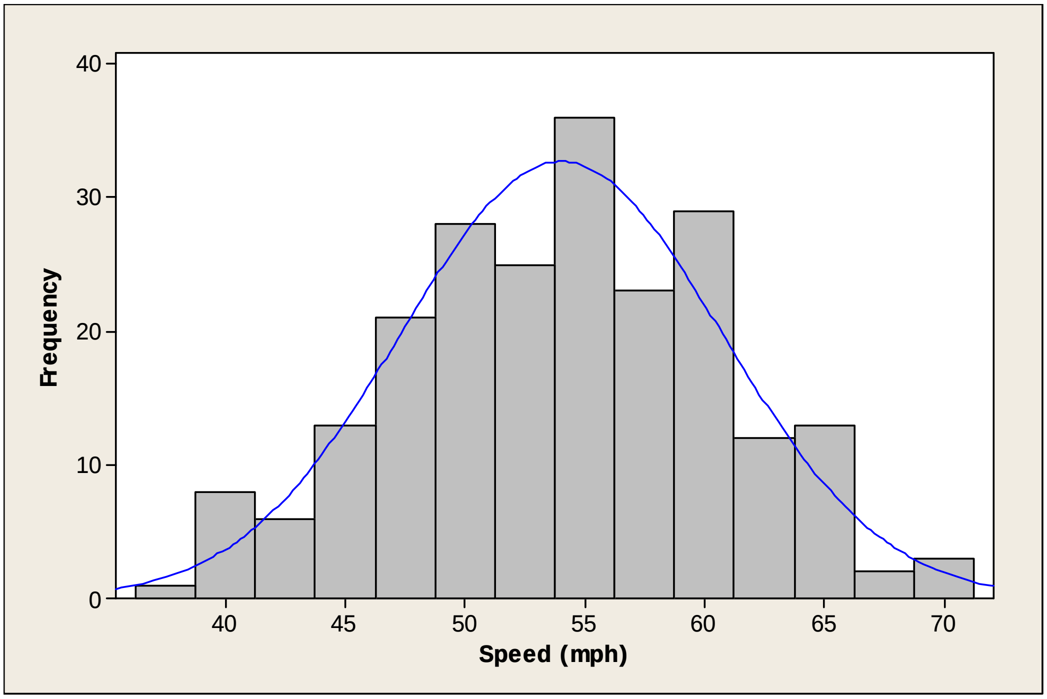

Figure C2. Truck speed distribution in the Pacific WB work zone with no construction

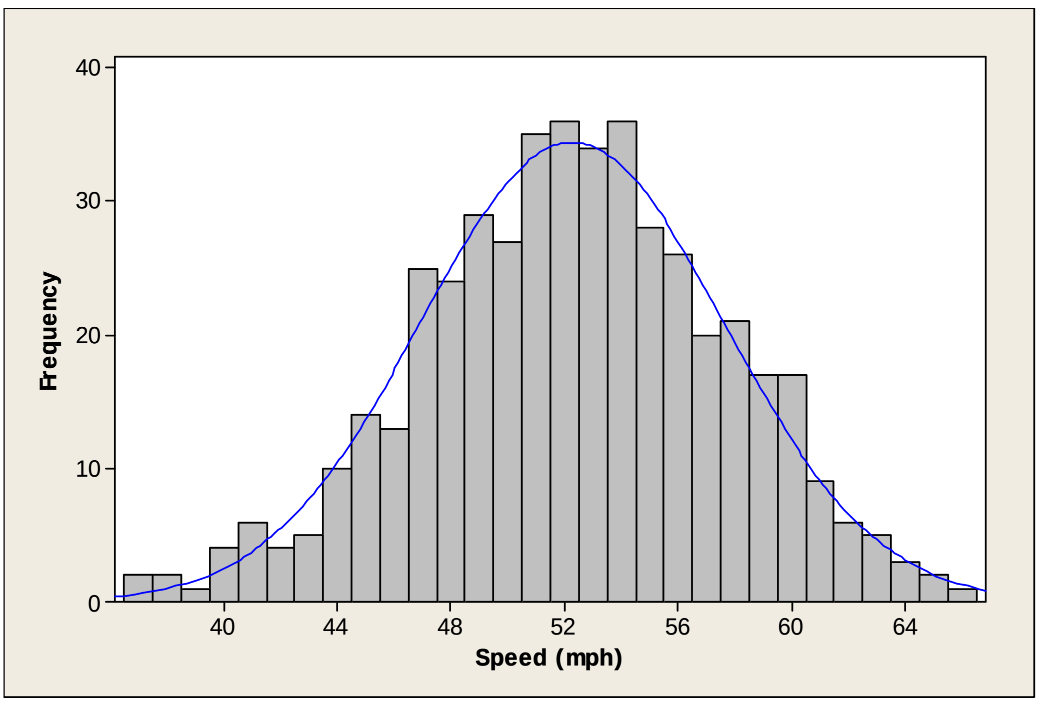

Figure C3. Car speed distribution in the Pacific WB work zone with construction

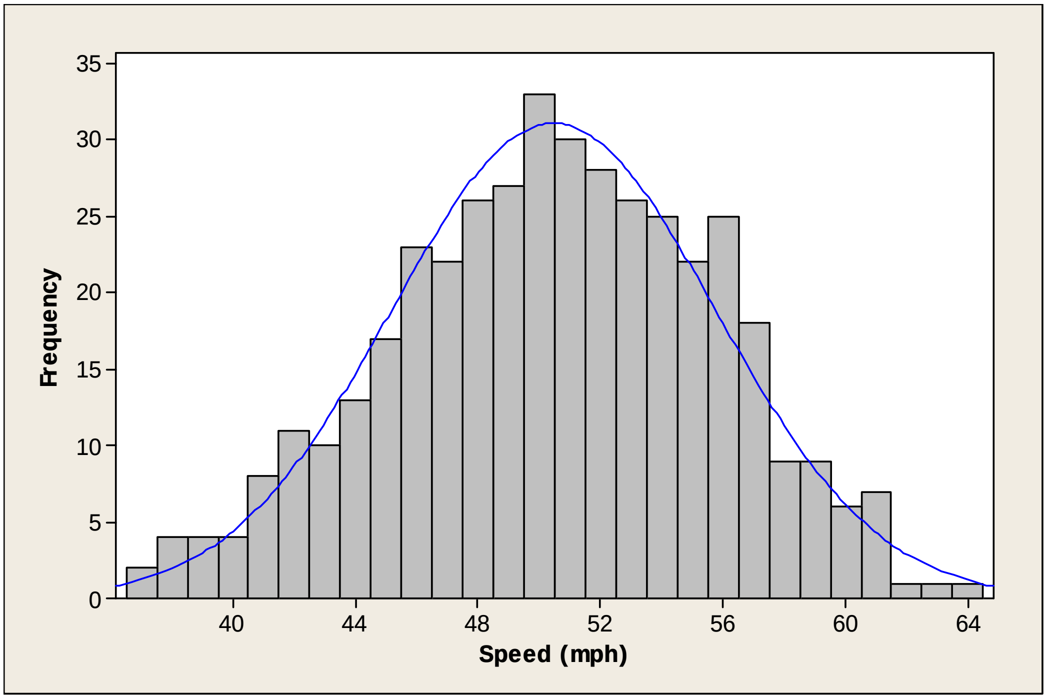

Figure C4. Truck speed distribution in the Pacific WB work zone with construction

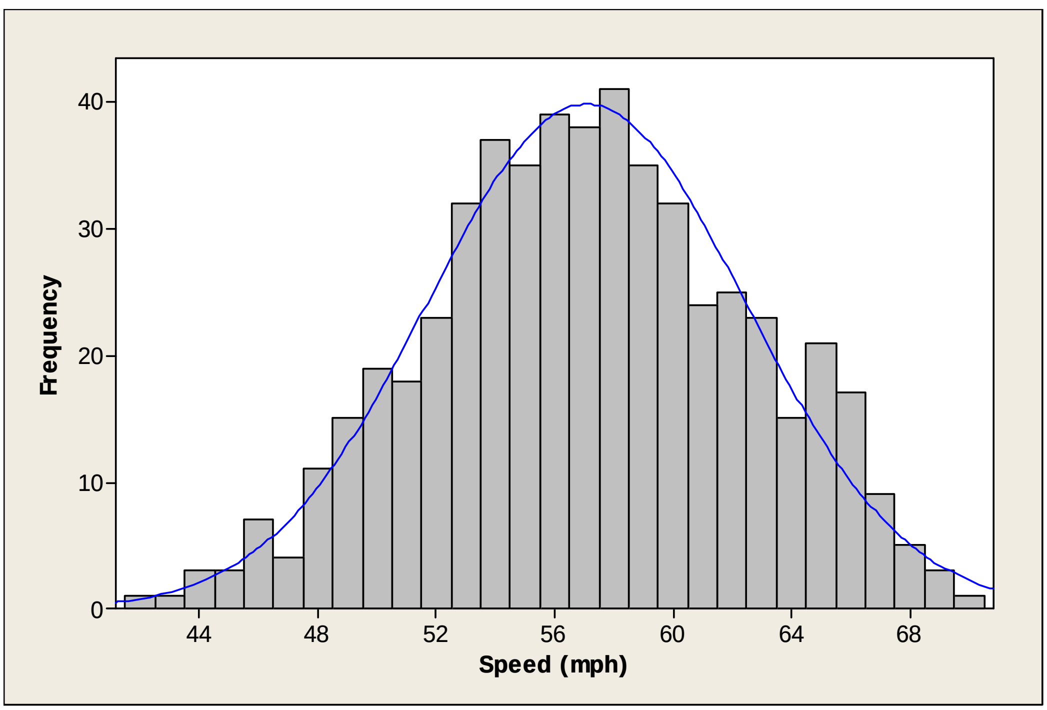

Figure C5. Car speed distribution in the Pacific EB work zone with no construction

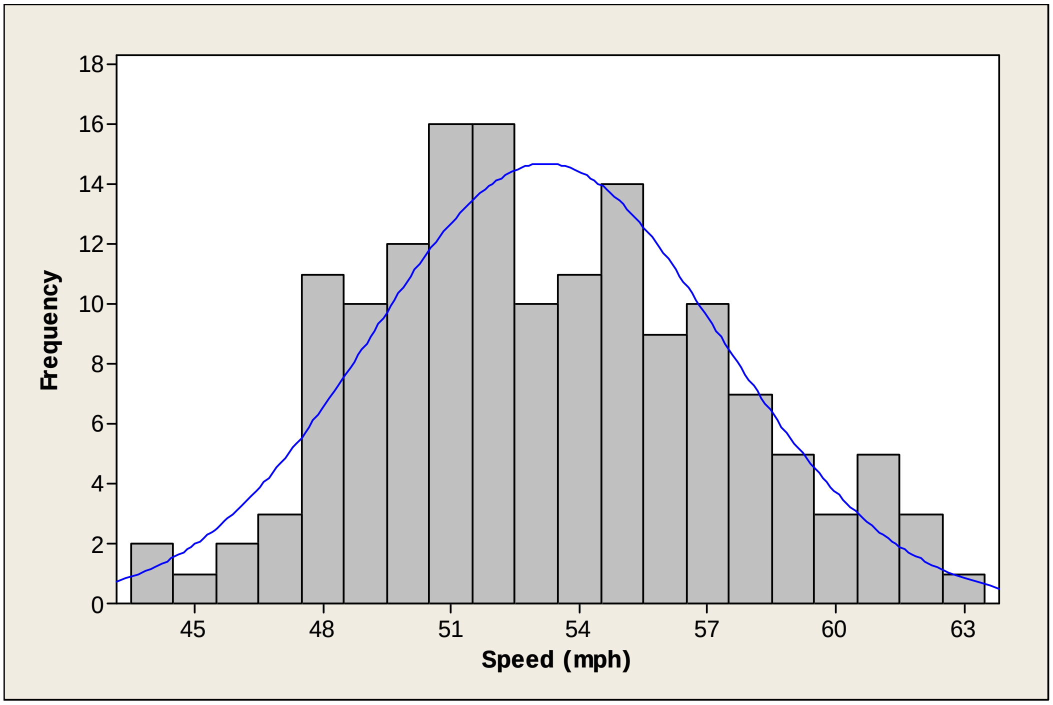

Figure C6. Truck speed distribution in the Pacific EB work zone with no construction

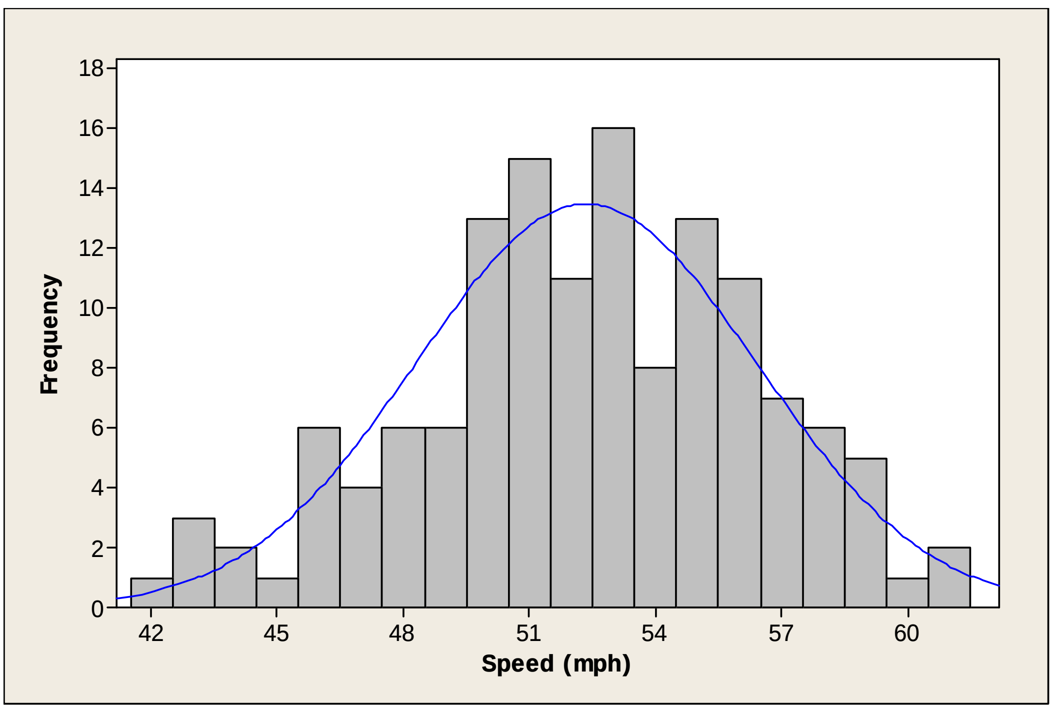

Figure C7. Car speed distribution in the Pacific EB work zone with construction

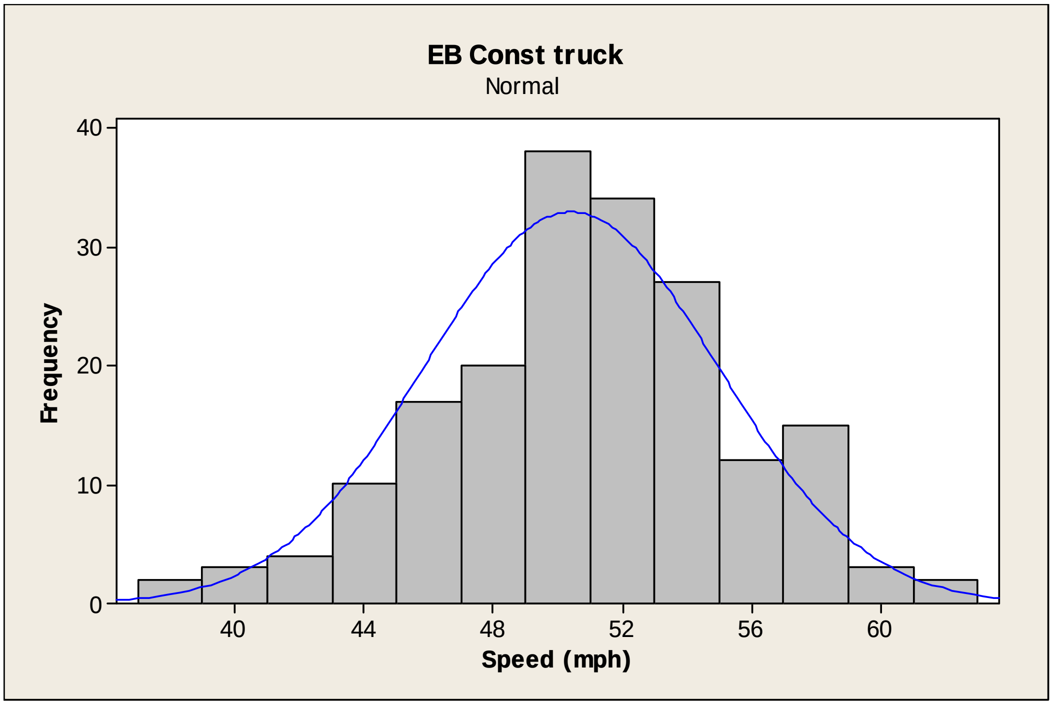

Figure C8. Truck speed distribution in the Pacific WB work zone with no construction

SPEED LIMIT PROJECT QUESTIONNAIRE

Please answer the following questions. Your answers will help Missouri University of Science and Technology, Rolla working with Missouri Department of Transportation to evaluate & make work zones safer.

APPENDIX D **Driver Survey Questionnaire**

Date MM/DD/YEAR_________ Age: ______ Gender: 1. M 2. F

1) What type of motor vehicle do you most commonly drive?

   A. Passenger Vehicle B. RV C. Single unit D. Single-trailer

   E. Double-trailer

2) Number of years you have been driving? _________ years

3) Operating my vehicle in traffic among Passenger Vehicles, RV, and Trucks poses a safety hazard to me. A. Disagree B. Agree

4) When do you drive most often?

   A. Daytime B. Nighttime C. All times

5) How often do you drive on I-44? A. Daily B. Regularly
   C. Once a week D. Once a month E. Once a year

6) Did you notice the reduced speed limit on I-44 when traveling through the work zones? A. Yes B. No

7) How many miles in advance would you prefer to know about the presence of a work zone?
   A. less than 1 B. 1-2 C. 2-3 D. 3-4 E. more than 4

8) How many miles in advance would you like to see the "lane closed ahead" sign?
   A. less than 0.5 B. 0.5-1 C. 1-2 D. 2-3 E. more than 3

9) When do you usually move out of the closed lane of a work zone?
   A. Right after the first "lane closed ahead" sign
   B. Before I see the work zone
   C. After I see the work zone
   D. Just before the start of taper

10) How many miles in advance would you like to see the "reduced speed limit" sign?
    A. less than 0.5 B. 0.5-1 C. 1-2 D. 2-3 E. more than 3

11) I made it through the work zone in a timely manner?

    A. Disagree B. Agree

12) Other passenger car / truck drivers followed the posted speed limit while driving through the I-44 work zone.
    A. Disagree B. Agree

13) At what speed did you drive through the I-44 work zone?
    <30 30-40 40-50 50-60 >60

14) What speed limit do you suggest for this work zone? (circle the answer)

    45 50 55 60 65 70

15) I felt safe driving at the work zone's speed limit.

    A. Disagree B. Agree

16) I experienced significant delays while driving through the work zone.

    A. Disagree B. Agree

17) Construction activity in the work zone makes me reduce my travel speed. A. Disagree B. Agree

18) Please provide any comments on improving work zone operations.

____

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THANK YOU VERY MUCH FOR COMPLETING THIS SURVEY
Research conducted by Missouri University of Science and Technology
Sponsored by Missouri Department of Transportation