# SPEED-BASED SAFETY ANALYSIS FOR WORK ZONES

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By

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The undersigned, appointed by the dean of the Graduate School,

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Presented by Yi Hou

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And hereby certify that, in their opinion, it is worthy of acceptance.

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# EXECUTIVE SUMMARY

Speed is one of the characteristics of traffic flow that affect accident rates and severity near work zones. Approximately 25% fatal crashes in work zones involved high speed. In speed-related work zone traffic safety studies, $85^{th}$ percentile speed, mean speed, speed variance, the percentage of driver compliance and speed distribution are usually considered as the measures of effectiveness in evaluating speed management strategies. In order to determine the significance of the improvements of these measures of effectiveness, statistical methodology is applied. The t-test is the most common statistical tests for mean speed. F-test is employed to test the statistical significance of the difference in speed variance. Binomial proportion test is used in evaluating the statistical significance of difference of the percentage of driver compliance. Two commonly used statistical tests, Chi-Square test and Kolmogorov-Smirnov test can be applied to determine if the differences of speed distributions are statistically significant. However, in spite of the wide use of the 85th percentile speed, statistical test for comparing percentile speeds from different groups of speed population is not as common as t-test and ANOVA for the mean speed. In this thesis, a standard normal Z statistical test for quantiles is derived based on Crammer's asymptotic distribution of sample quantiles. In addition, two research projects that motivated this methodology are presented as case studies of speed-based safety analysis for work zones, as well as excellent illustrations of this new methodology.

One is the evaluation of the effectiveness of work zone speed limits. An appropriate policy for work zone speed limits has to delicately balance the safety and the efficiency impacts. If speeds are set too low, then avoidable congestion and speed violations might result. If speeds are set too high then, again, safety may be compromised. Field studies were conducted on three Interstate 70 maintenance short-term work zones in rural Missouri for three different speed limit scenarios: 1) no posted speed limit reduction, 2) a 10 miles per hour (mph) posted speed limit reduction and 3) a 20 miles per hour posted speed limit reduction. The 85$^{th}$ percentile speeds and speed variance were found to be 81 mph and 10 mph; 62 mph and 8 mph; and 48 mph and 6 mph, respectively for the three scenarios. The differences in the 85$^{th}$ percentile speed and speed variance among all three scenarios were statistically significant. The percent of drivers who exceeded speed limit by over 10 mph were 15.4%, 4.8%, and 0.9%, respectively. Thus a reduction in posted speed limit was effective in reducing prevailing speeds and speed variances.

The other one is analysis of the sequential warning lights in night time work zone. Improving safety at nighttime work zones is important because of the extra visibility concerns. The deployment of sequential lights is an innovative method for improving driver recognition of lane closures and work zone tapers. Sequential lights are wireless warning lights that flash in a sequence to clearly delineate the taper at work zones. The effectiveness of sequential lights was investigated using controlled field studies. The speeds of approaching vehicles were used to determine the impact of sequential lights on safety. Traffic speeds were collected at the same field site with and without the deployment of sequential lights. The results of this study indicate that sequential warning lights had a net positive effect in reducing the speeds of approaching vehicles and enhancing driver compliance. Statistically significant decreases of 2.21 mph mean speed and 1 mph 85$^{th}$ percentile speed resulted with sequential lights. The shift in the cumulative speed distributions to the left (i.e. speed decrease) was also found to be statistically significant using the Kolmogorov-Smirnov tests. But a statistically significant increase of 0.91 mph in the speed standard deviation also resulted with sequential lights. Also, an economic analysis of Missouri nighttime work zones and historical crash data resulted in a benefit-cost ratio of around 5.

# CHAPTER 1: INTRODUCTION

The major motivation for speed analysis is safety. Safety is usually analyzed by evaluating crash rate and crash severity. One characteristic of traffic flow that affects crash rate and severity near work zones is speed (*1*). High traffic speeds could be a major safety concern in highway work zones and a potential risk to both motorists and workers. According to Li and Bai (*2*), up to 25% of fatal crashes in work zones involved high speeds. On the other hand, a large speed variance coupled with hazardous conditions at work zones (e.g., workers' presence, lane closure, and narrow lanes) could also lead to higher crash rates at work zones. The study of Migletz and Graham (*3*) showed that crash rates increase as speed variance increases. The main focus in this thesis is to examine work zone safety based on vehicle speed data.

In speed-related work zone safety study, $85^{th}$ percentile speed, mean speed, speed variance, the percentage of driver compliance and speed distribution are usually considered as the measure of effectiveness in evaluating speed management strategies. But $85^{th}$ percentile speed is usually considered as the most frequently used measures of effectiveness in evaluating speed management strategies in work zones. In the speed limit study, the $85^{th}$ percentile speed is an important descriptive statistic. The MUTCD *(4)* guidelines on setting speed limits say, "When a speed limit is to be posted, it should be the 85th percentile speed of free-flowing traffic, rounded up to the nearest 10 km/h (5 mph) increment". The theory behind $85^{th}$ percentile speed concept is that traffic engineers have assumed the large majority of drivers are rational and cautious, and desire to select a maximum safe speed based on roadway conditions to minimize their travel time *(5)*. Results of a large number of before-and-after studies indicate that a speed not above which 85 percent of people drive at any particular location may be the maximum safe speed at that location *(5)*. In traffic speed studies, the measured random sample of traffic speeds usually has a normal distribution *(6)*. From the cumulative speed distribution curves, traffic engineers discovered that a small portion of drivers exceed greatly over the prevailing traffic speed and a small portion of drivers drive at an extremely slow speed relative to the majority. Most of the time, break points of the cumulative speed distribution curves occur at approximately the 15$^{th}$ percentile and the 85$^{th}$ percentile *(5)*. According to Solomon *(7)*, the crash risk is least around the 85$^{th}$ percentile speed, and rises sharply above the 90$^{th}$ percentile speed. But the slowest driver has the similar risk as the fastest. Thus, a speed at or below which 15 percent of drivers drive is considered to be unreasonable slow, while a speed above which 85 percent of drivers drive is also supposed to be unsafe.

In most speed-related work zone safety studies, traffic engineers compare the 85$^{th}$ percentile speeds numerically to evaluate the effectiveness of a particular safety countermeasure. For example, For example, Sorrell, et al.*(8)*, only tested the significant differences in the change of mean speed with two sample t-test and change in percentage of vehicle speeding in their study of portable changeable message sign. No test was performed on the difference in 85$^{th}$ percentile speed. In Ullman and Rose's *(9)* study, they evaluated the effectiveness of dynamic speed display sign by comparing mean speed, 85$^{th}$ percentile speed, and percentage exceeding posted speed limit. No statistical inference was made on $85^{th}$ percentile speed. Often, the t-test or ANOVA are employed to test the significance of mean speeds from two or more independent speed populations. Binomial proportion test is used to test the significance of difference in the percentage of driver compliance. Additionally, the F-test is used to investigate changes in the variance of speeds, and the K-S test is used to investigate changes in speed distributions. Although the $85^{th}$ percentile speed is frequently used as a measure of effectiveness to assess if the safety device or treatment was effective in reducing traffic speed in work zones, much fewer discussions on the statistical significance of the 85th percentile exist. These discussions are listed in the literature review section. A few studies established methodologies that suffered from complicated statistical procedures. Some researchers either applied statistical test on the $85^{th}$ percentile speeds inappropriately, or presented statistical test for $85^{th}$ percentile speed without details and references. None of them developed a methodology that provided a simple test statistic which were widely accepted and applied by traffic engineers.

This thesis proposes simpler statistical methodology with easy applicability to determine whether the change of the $85^{th}$ percentile speed in traffic safety analysis is statistically significant. The statistical test is explicitly derived from the theory of asymptotic distribution of sample quantiles. This new methodology was originally motivated by two different empirical work zone safety projects. In conducting the research on both projects, it became clear that an easy methodology for analyzing 85 percentile speed was lacking. Thus these two projects are presented in this thesis as empirical case studies of speed-related safety analysis for work zones, and also as excellent illustrations of this new methodology.

The first empirical case study is the investigation of short-term rural work zone speed limits which was presented on the 90th annual Transportation Research Board (TRB) conference. Many states have enacted temporary speed reduction regulations and a variety of speed limits are in place across the country. The most commonly used speed limits are 0 mph, 5 mph, 10 mph, and 20 mph reductions. This variation in speed limits also exists in terms of type of work zone activity, type of roadway, type of traffic control device used, method of enforcement, penalties, type of work and construction zone, and others. Several studies have been conducted on work zone speed limits. Richards and Dudek *(10)* researched work zone speed limits in Texas. Their study recommended that existing speeds, work zone design speed, and work zone conditions be considered when selecting the speed limits and recommended speed reductions by different roadway types. Finley et al. *(11)* studied motorist perceptions and reactions to reduced work zone speed limits and other work zone conditions, and concluded that work zone speed limit reduction should be selected based on work zone conditions such as lane encroachment, lane closure, and temporary diversion.

NCHRP Project 3-41 developed a uniform procedure for determining work zone speed limits *(12)*. The NCHRP Research Results Digest 192, noted that work zones with advisory and regulatory speed limits had higher crash increases than those without speed reductions *(12)*. The Manual of Uniform Traffic Control Devices (MUTCD) *(13)* states, “Research has demonstrated that large reductions in the speed limit, such as a 30 mph reduction, increase speed variance and the potential for crashes. Smaller reductions in the speed limit of up to 10 mph cause smaller changes in speed variance and lessen the potential for increased crashes. A reduction in the regulatory speed limit of only up to 10 mph from the normal speed limit has been shown to be more effective.” According to Garber and Gadiraju *(14)*, large speed differentials occur at work zones where speed limits have been considerably reduced from normal speed limits because most drivers tend to drive at a speed that in their opinion is suitable for the prevailing conditions regardless of the posted speed limit. Therefore, in order to increase safety at work zones, it is important to establish an appropriate work zone speed limit that will achieve high driver compliance as well as low speed variance.

Field studies were conducted on three Interstate 70 maintenance short-term work zones in Missouri for three different speed limit scenarios: 1) no reduction in the posted speed limit (i.e., the speed limit in the segment is the same with or without the work zone), 2) a 10 miles per hour (mph) reduction in the posted speed limit, and 3) a 20 miles per hour in the posted speed limit.

The second one of empirical case studies is the analysis of the sequential warning lights in nighttime work zone. Sequential warning lights are designed to dynamically enhance the visibility of the work zone entrance and to improve driver lane discipline by providing a directional guide. Nowadays, sequential warning lights combine the latest LED lamp and lens technology with intelligent synchronization wireless communications technology to enable longer cone taper deployment. SynchroGUIDE and Empco-Lite LWCSD are the two latest production models. The flash rate is 60 flashes per minute. Each lamp requires two 6V batteries. When the lamps are placed in line, they give the impression of a single light source traveling along the lamps from front to back. Each lamp has a low output steady light to aid direction indication. **FIGURE 1-1** is an example of such sequential lights.

In order to minimize traffic impacts due to work zones, Departments of Transportation (DOTs) have increased off-peak and nighttime work. For example, the Missouri Department of Transportation has a recommendation for off-peak and/or nighttime work when the traffic volumes exceed 75 to 80 percent of the open-lane capacity *(15).*

**FIGURE 1-1 Sequential warning light (HA, 2005).**

There is some evidence that nighttime crash characteristics might differ from daytime. According to a comprehensive Canadian work zone study *(16)*, fatal crash ratio for day is 1.8 fatalities per 100 crashes as compared to 2.6 fatalities per 100 crashes under dark conditions. Another study found that there were more fixed-object crashes and fewer angle and rear-end crashes during the nighttime but no difference in severity *(17)*. In discussing the nighttime fixed-object crashes, Garber and Zhao explained that “problems may exist in the lighting conditions at work zones or in the illumination conditions of channelizing devices during nighttime.” The primary motivation for using sequential warning lights is to improve safety in the work zone by alerting drivers of the upcoming taper and work zone.

The controlled field studies were performed on Interstate 70 maintenance short term work zones to evaluate the effectiveness of sequential lights in enhancing the safety of nighttime work zones. The traffic speeds were used to determine the impact of sequential lights on safety. Also, an economic analysis was conducted to monetize the safety benefits and costs of deploying sequential lights at nighttime work zones.

# CHAPTER 2: LITERATURE REVIEW

The literature review includes three sections, the existing discussion on methodologies employed for making inference on the 85$^{th}$ percentile speed, work zone speed limits, and sequential warning lights for nighttime work zones.

## 2.1. Statistical Test for the 85$^{th}$ Percentile Speed

In most speed related safety studies, traffic engineers only compare the 85$^{th}$ percentile speeds numerically without any statistical analysis. Currently, not too much research has yet been conducted to make inference on the 85$^{th}$ percentile speed. The main findings of existing literatures are summarized as follow.

Spiegelman and Gates *(18)* described a nonparametric double bootstrapping procedure for comparison of quantiles from two or more sample populations. Nonparametirc bootstrapping procedure is a method of resampling existing data by using simulation. Two nonparametric double bootstrapping procedures were included in their methodology. The first bootstrapping experiment is to estimate the standard errors for desired quantiles. The second bootstrapping simulation produces the confidence interval for the test of hypothesis. The statistical test does not require populations to follow specific distributions, to have balanced sample sizes or equal variances. Brewer, et al. *(19),* conducted a statistical test on the 85$^{th}$ percentile speed in their work zone speed limit study by applying the post hoc quantile test developed by Spiegelman and Gates.

Voigt, et al. *(20)*, investigated the current dual-advisory speed signing practice on freeway-to-freeway connectors in Texas. In their study, they did statistical significance testing on $85^{th}$ percentile speed by employing the percentile bootstrapped data analysis technique which is similar to Spiegelman and Gates's methodology. However, the procedure of this methodology is too complicated to gain the prevalence among traffic engineers.

Hewson *(21)* demonstrated a method of making inference on $85^{th}$ percentile speed by employing quantile regression which is a widely used econometric technique. Quantile regression extends the least squares estimate of conditional means to conditional quantiles. The methodology builds a linear model relating desired percentile speed to intervention factors in experiment, then estimate the standard error of desired percentile speed through estimating the standard error of model parameters. This method has no restriction to two group comparisons. However, in the practice of this method, the rounding of speed data is problematic in the process of quantile regression. Also, this methodology is still too complicated to become a common statistical test for $85^{th}$ percentile speed.

In some speed-related empirical safety studies, the significance of the $85^{th}$ percentile speed change was also analyzed statistically. For example, Knoblauch, et al. *(22)*, conducted a statistical test on 15th percentile speed in the field study of pedestrian walking speed. In their study, the test statistic was presented, and is similar to the one derived in the thesis, but the estimated value of standard error is different. Also, their methodology is lacking details and references.

In the study of Pesti and McCoy's *(23)* evaluation of speed monitoring displays, they applied the binomial proportion test on evaluating the statistical significance of the differences in both the $85^{th}$ percentile speeds and the percentage of driver compliance. $85^{th}$ percentile speed is the speed bellow which 85% of motorist travel, not a percentage or proportion. Based on the definition of percentile, binomial proportion test is an appropriate test for percentage of driver compliance, but might not be an appropriate test for $85^{th}$ percentile speed. Pesti and McCoy misapplied the proportion test.

In some studies, researchers perform statistical analysis on the change in the average of 85th percentile speeds of several speed data sets. Hildebrand, et al. *(24)*, analyzed the $85^{th}$ percentile speed statistically in their study of speed management strategies for rural work zones. But no statistical test was performed directly between $85^{th}$ percentile speeds from two populations. Instead, they applied t-test on the average $85^{th}$ percentile speed of many work zone sites. Agent, et al. *(25)*, performed statistical test on the average change in the $85^{th}$ percentile speed at several data collection sites in their speed limit study in Kentucky without performing statistical test directly on $85^{th}$ percentile speeds from two populations. Mattox, et al. *(26)*, evaluated the effectiveness of speed-activated sign in work zones by comparing mean speed, $85^{th}$ percentile speed, and percentage exceeding posted speed limit. In their study, they performed statistical test on the average reduction of $85^{th}$ percentile speed of several speed data sets to determine the change in 85$^{th}$ percentile speeds. This methodology requires a significant amount of data sets, or the accuracy of the test may be decreased. Also, many other factors such as geometric design, traffic composition, and driver population, may result in the speed difference across the data sets.

Eckenrode, et al. *(27)*, studied the use of drone radar to reduce speed in work zones. They did not perform any statistical analysis on 85$^{th}$ percentile speed, but they pointed out that a parametric hypothesis test could not be used to test statistical significance of the change in 85$^{th}$ percentile speed.

In Summary, only a few methodologies were developed for testing significance on 85$^{th}$ percentile speed in previous studies. The nonparametric double bootstrapping procedure and quantile regression are too complicated for wide application in the practice of traffic engineering. The application of binomial proportion test is not appropriate for 85$^{th}$ percentile speed. The accuracy of testing the average of 85$^{th}$ percentile speed of different speed data sets is affected by many other factors. Thus, a simple statistical test for 85$^{th}$ percentile speed with easy applicability is still in desire.

### 2.2. Work Zone Speed Limits

A number of studies has been conducted on speed control techniques currently used by state DOTs in the U.S. These include the posting of regulatory and advisory speed limit signs, using the latest radar technologies and the involvement of law enforcement.

In Maze and Kamyab's evaluation of work zone speed reduction measures, they found out that while important for conveying information to the public, regulatory and advisory speed limit signs alone have been shown to have minimal impact on reducing traffic speeds *(28)*.

There have been studies showing that augmenting static signs with other techniques might increase driver compliance to speed limits. Benekohal and Shu *(29)* studied the speed reduction effects of speed limit signs augmented with strobe lights. Their results indicated that the average speeds of cars and trucks were reduced by 1.9–7.1 mph and 1.3–6.0 mph, respectively. The study concluded that, in general, the percentages of vehicles with excessive speeds at work zones decreased when strobe lights were flashing.

Brewer, et al. *(30)*, conducted evaluation on variable speed limits. In their study, motorists respond better to variable speed limits and can result in better driver compliance, lower speed variability, and higher safety as they are considered more realistic compared to static speed limits.

McMurtry et al. *(31)* investigated the applicability and effectiveness of variable speed limits (VSL) signs at work zone in Utah. The study showed that the standard deviation of speed and the percentage of vehicles exceeding speed limits have reduced significantly when VSL signs were used.

According to Outcalt *(32)*, for situations requiring speed reductions of 15 mph or more, it is effective to add message signs and law enforcement vehicles and officers. The study also concluded that a speed reduction of more than 20 mph probably needs the presence of law enforcement to be effective.

Benekohal, et al. (*33*), evaluated the effectiveness of speed photo-radar enforcement (SPE). The study found that SPE was effective to reduce the mean speeds of work zones as well as the percentage of vehicles exceeding speed limit.

**2.3. Sequential Warning Lights for Nighttime Work Zones**

Since the sequential warning lights is relatively a new technology, only two studies were conducted to analyze its effectiveness.

The Texas Transportation Institute (TTI) conducted a study of sequential lights in *(34)*. The sequential lights were a prototype and were wired. In addition to controlled sample studies, they also performed field studies on a rural two to one lane work zone and an urban interstate with lanes closed for re-striping work. They measured the occupancy of the closed lane near the taper at: 0 ft, 300 ft, and 1000 ft. They found that such lights may encourage motorists to vacate the closed lane further upstream than normal.

The British Highway Agency *(35)* conducted a trial that involved wireless production-model sequential lights. The trial site was the M42 carriageway which is approximately the equivalent of a U.S. interstate highway. Existing loops were placed 100 m apart and data was collected starting from 1100 m upstream of the taper. The configuration was three lanes to a two lanes closure. HA reported that the "effect of sequential lamps is seen consistently from a point 500m before the taper, but also has an effect at a point 600m before the taper in half the cases".

Both of the studies on sequential warning lights only focused on the traffic merging data. In their studies, neither traffic speed data were analyzed statistically, nor were measures of effectiveness translated into quantifiable benefits.

# CHAPTER 3: METHODOLOGY

## 3.1. Statistical Test for Mean Speed

### *3.1.1. T-test*

The t-test is the most common statistical tests for mean speed. The test statistic is given by

$$\frac{(\overline{X}_1 - \overline{X}_2) - 0}{\sqrt{S_1^2 / n_1 + S_2^2 / n_2}}$$

where $\overline{X}_1$ , $\overline{X}_2$ are the sample means and $S_1^2$, $S_2^2$ are the sample variances of the two independent populations, and $n_1$ and $n_2$ are the sample sizes *(36).*

### *3.1.2. ANOVA*

In some speed-related traffic safety studies, more than two speed population means are compared. Instead of making comparisons between each speed population means via t-test, another statistical methodology analysis of variance (ANOVA) is employed. The test statistic is

$$\frac{SS_{Tr} /(k-1)}{SS_E /(N-k)}$$

where $SS_{Tr}$ is the measure of variability in data attributed to the fact that different factor levels or treatments are used; $SS_E$ is the measure of variability in data attributed to random fluctuation among subjects within the same factor level; $k$ is the number of populations; and $N$ is the number of homogeneous experimental units*(36).*

### 3.2. Statistical Test for Speed Variance

F-test is employed to test the statistical significance of the difference of speed variance. The test statistic of F-test is specified as

$$\frac{S_1^2}{S_2^2}$$

where $S_1^2$ and $S_2^2$ are the sample variances of two populations to be compared *(36).*

### 3.3. Statistical Test for the Percentage of Driver Compliance

Binomial proportion test is used in evaluating the statistical significance of difference of the percentage of driver compliance. The test statistic is

$$\frac{(\hat{p}_1 - \hat{p}_2) - 0}{\sqrt{\hat{p}_1(1-\hat{p}_1)/n_1 + \hat{p}_2(1-\hat{p}_2)/n_2}}$$

where $\hat{p}_1$ and $\hat{p}_2$ are the sample proportions of two populations, and $n_1$ and $n_2$ are the two sample sizes *(36).*

### 3.4. Statistical Test for Speed Distribution

To determine if the differences of speed distributions are statistically significant, The Kolmogorov-Smirnov test can be applied. The test statistic of two-sample Kolmogorov-Smirnov test is

$$|D|\sqrt{\frac{n_1 n_2}{n_1 + n_2}}$$

where $n_1$ and $n_2$ are the two sample sizes; and $D$ is the maximum vertical deviation between the two curves of sample distributions *(37)*.

### 3.5. Statistical Test for the 85th Percentile Speeds

The statistical test for the 85$^{th}$ percentile speed is developed in this thesis based on the asymptotic distribution of sample quantiles. First, Crammer *(38)*'s derivation of the general sample quantile distribution will be outlined. Then the standard error of 85$^{th}$ sample quantile from a normal distribution will be calculated. Last, the statistical test for comparison of two 85$^{th}$ sample quantiles from independent normal distribution will be developed.

#### *3.5.1. Asymptotic Distribution of Sample Quantiles*

Suppose $X_1, X_2, \ldots, X_n$ are $n$ independent and identically distributed random variables from a continuous one-dimensional distribution with cumulative distribution function $F(x)$ and probability density function $f(x)$. Let $\zeta_p = F^{-1}(p)$ denote the quantile of the distribution of order $p$. The random variables $X_1, X_2, \ldots, X_n$ are arranged in ascending order of magnitude: $X_{(1)} \le X_{(2)} \le X_{(3)} \ldots \le X_{(n)}$, where random variable $X_{(i)}$ is defined as the $i^{th}$ smallest value in $X_1, X_2, \ldots, X_n$. Then, $X_{([np]+1)}$ is denoted as the quantile of the sample of order $p$, where $[np]$ is denoted as the greatest integer smaller or equal to $np$.

Let $g(x)$ denoted the probability density function of random variable $X_{([np]+1)}$. The marginal probability $g(x)dx$ that $X_{([np]+1)}$ is located in the interval $[x, x+dx]$ is equal to the probability that $[np]$ sample values are smaller than $x$, $n-[np]-1$ sample values are greater than $x+dx$, and 1 sample value located in the interval between $x$ and $x+dx$ among $n$ sample values. According to order statistics,

$$g(x)dx = \binom{n}{[np]}(n-[np])(F(x))^{[np]}(1-F(x))^{n-[np]-1} f(x)dx. \tag{3-1}$$

Making use of the *DeMoivre-Laplace* Central Limit Theorem which states that a binomial distribution is approximately normal for large $n$, as $n \to \infty$,

$$X_{([np]+1)} \sim N(\zeta_p, \frac{1}{f(\zeta_p)^2} \cdot \frac{p(1-p)}{n}). \tag{3-2}$$

Crammer’s derivation of the sampling distribution of quantiles is equivalent to other derivations that apply the Delta method. The Delta method is considered a general central limit theorem that approximates a complex analytical variance computation by using a Taylor series *(39).*

### *3.5.2. Asymptotic Distribution of 85th Sample Quantile from Normal Distribution*

In traffic studies, traffic speed distribution tends to have a normal distribution *(6)* and 85th percentile speed is of particular interest for traffic studies, thus the distribution of 85th sample quantile from normal distribution is further investigated. The theory of asymptotic distribution of sample quantiles is then applied to the distribution of the 85th sample quantile from a normal distribution. Suppose $X_1, X_2, \ldots, X_n$ are $n$ independent and identically distributed random variables from a normal distribution with probability density function

$$f(x) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(1/2)[(x-\mu)/\sigma]^2} . \tag{3-3}$$

The 85th sample quantile is denoted as $X_{([n0.85]+1)}$. The 85th distribution quantile is denoted as $\zeta_{0.85} = 1.036\sigma + \mu$ (85th distribution quantile for standard normal is 1.036). Then,

$$f(\zeta_{0.85}) = \frac{1}{\sqrt{2\pi}\sigma} e^{-(1/2)[((1.036\sigma+\mu)-\mu)/\sigma]^2} = \frac{1}{\sqrt{2\pi}\sigma} e^{-(1/2)(1.036)^2} = 0.233/\sigma . \tag{3-4}$$

Based on the conclusion of asymptotic distribution of sample quantiles, for large $n$,

$$X_{([n0.85]+1)} \sim N(\zeta_{0.85}, \frac{1}{f(\zeta_{0.85})^2} \cdot \frac{0.85(1-0.85)}{n}) . \tag{3-5}$$

By substituting (3-4) to (3-5),

$$X_{([n0.85]+1)} \sim N(\zeta_{0.85}, 2.342\sigma^2 / n) . \tag{3-6}$$

Thus, the random variable $X_{([n0.85]+1)} - \zeta_{0.85} /(1.530\sigma / \sqrt{n})$ is approximately standard normally distributed for large $n$.

### *3.5.3. Comparing Two 85th Population Quantiles from Independent Normal Distributions*

One objective of this study is to develop a statistical significance test for comparing 85th percentile speeds of two speed samples. Let random variables $X_{([n0.85]+1)}$ and $Y_{([n0.85]+1)}$ be the 85th sample quantiles of independent random samples of size $n_X$ and $n_Y$ drawn from normal distributions with 85th distribution quantiles $(\zeta_{0.85})_X$ and $(\zeta_{0.85})_Y$ and variances $\sigma_X$ and $\sigma_Y$ , respectively. Based on the conclusion of previous section, for large $n_X$ and $n_Y$ , $X_{([n0.85]+1)}$ and $Y_{([n0.85]+1)}$ are approximately normally distributed with means $(\zeta_{0.85})_X$ and $(\zeta_{0.85})_Y$ and variances $1.530^2 \sigma_X^2 / n_X$ and $1.530^2 \sigma_Y^2 / n_Y$ , respectively. Therefore, the random variable $X_{([n0.85]+1)} - Y_{([n0.85]+1)}$ is also approximately normally distributed with mean $(\zeta_{0.85})_X - (\zeta_{0.85})_Y$ and variance $1.530^2 \sigma_X^2 / n_X + 1.530^2 \sigma_Y^2 / n_Y$ *(36)*. This implies that the random variable

$$\frac{(X_{([n0.85]+1)} - Y_{([n0.85]+1)}) - ((\zeta_{0.85})_X - (\zeta_{0.85})_Y)}{1.530\sqrt{\sigma_X^2 / n_X + \sigma_Y^2 / n_Y}}$$

is standard normal. The unknown population variance $\sigma_X^2$ and $\sigma_Y^2$ can be substituted by sample variance $S_X^2$ and $S_Y^2$, since in this case the sample sizes are large enough that there is very little difference between population variance and sample variance. Then the random variable

$$\frac{(X_{([n0.85]+1)} - Y_{([n0.85]+1)}) - ((\zeta_{0.85})_X - (\zeta_{0.85})_Y)}{1.530\sqrt{S_X^2 / n_X + S_Y^2 / n_Y}}$$

is still standard normal. In order to test null hypothesis $H_0: (\zeta_{0.85})_X = (\zeta_{0.85})_Y$, which is equivalent to $H_0: (\zeta_{0.85})_X - (\zeta_{0.85})_Y = 0$, the random variable

$$\frac{(X_{([n0.85]+1)} - Y_{([n0.85]+1)}) - 0}{1.530\sqrt{S_X^2 / n_X + S_Y^2 / n_Y}}$$

can be served as the standard normal test statistic for testing the difference in 85th population quantiles.

# CHAPTER 4: EMPIRICAL ANALYSIS AND RESULTS

## 4.1. Work Zone Speed Limits

### *4.1.1 Data Collection*

Short-term maintenance work zones on Interstate 70 were selected for studying the relationship between posted speed limits and traffic behavior. Two sites were located in Boonville and one site in Kingdom City, Missouri. **FIGURE 4-1** shows a map of these study locations. Kingdom City and Booneville are roughly forty miles apart, and these rural locations of Interstate 70 are fairly similar in terms of terrain, geometrics, traffic composition and driver population. All three work zones involved a right lane closure with the passing lane open (2 to 1 work zone). The speeds of vehicles approaching the work zone were measured using two methods, 1) a radar speed gun, and 2) video cameras in conjunction with video processing software. Speed gun data was used for calibrating the speeds extracted from videos. In the field, the delineators were often aligned with centerline stripes to assist in the post-processing of the video. Missouri highway centerline stripes are spaced 40 feet apart *(40)*. The layout of delineator setting of work zone is showed in **FIGURE 4-2**.


**FIGURE 4-1 Location of study work zones (Google, 2010).**

Details of each field study scenario are described below:

- **Scenario 1**: No speed limit reduction

  The posted speed limit was 70 mph. Data was collected east of Kingdom City, Missouri at mile marker 148.4 on Interstate 70 on June 2, 2009. Approximate times of collection were from 9:00 a.m. to 4:30 p.m. Westbound traffic was monitored.

- **Scenario 2**: 10 mph speed limit reduction

  The posted speed limit was 60 mph. Data was collected near Boonville, Missouri at mile marker 105.1 on Interstate 70 on September 15 and 16, 2009. Approximate times of collection were from 12:20 p.m. to 4:00 p.m. for September 15, and from 9:40 a.m. to 2:10 p.m. for September 16. Eastbound traffic was monitored.

- **Scenario 3**: 20 mph speed limit reduction

The posted speed limit was 50  mph. Data was collected near Boonville, Missouri at mile marker 102.0 on Interstate 70 on August 12, 2009.  Approximate times of collection were from 7:30 p.m. to 10:15 p.m. (only data during day light hours was processed). Westbound traffic was monitored.

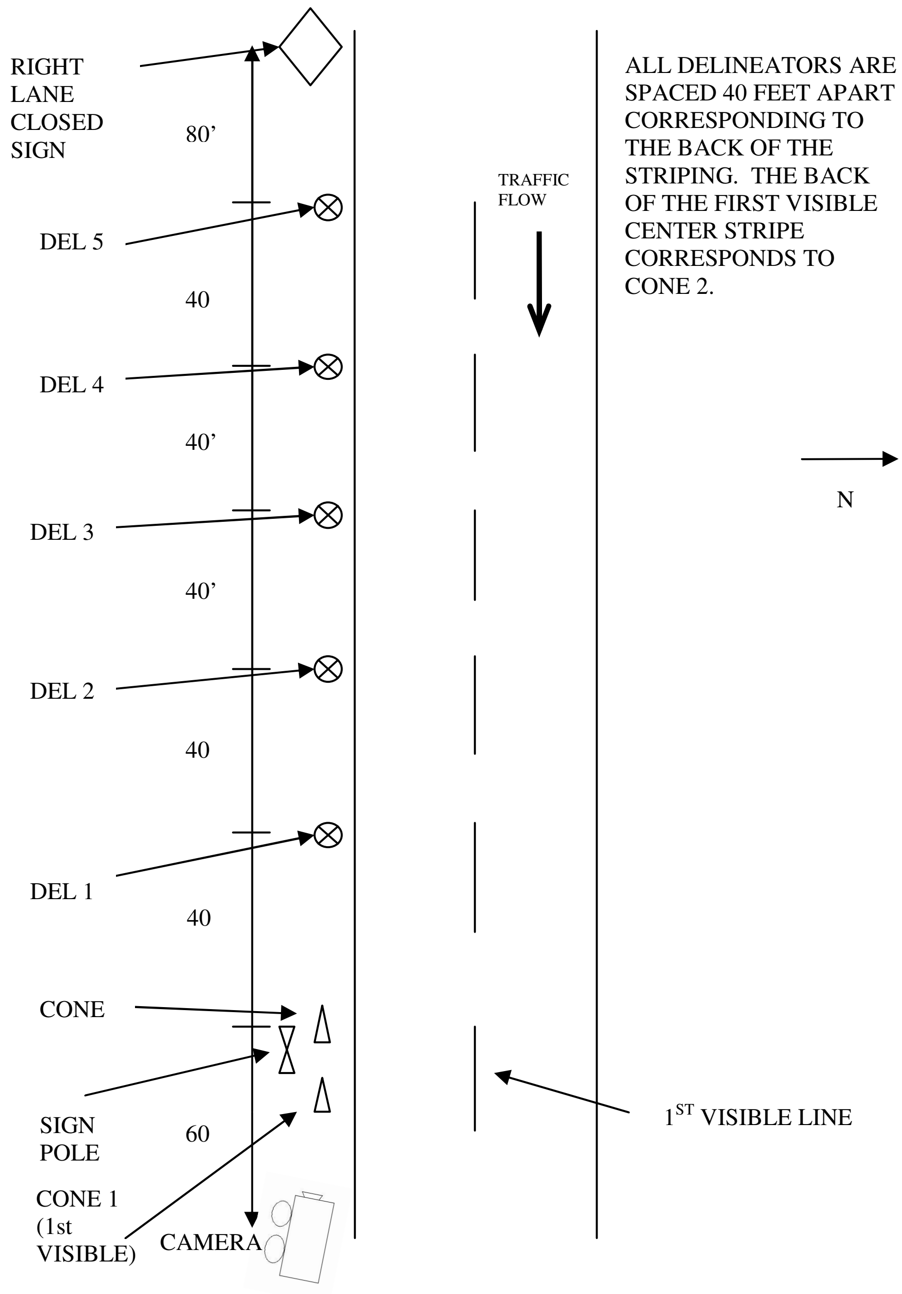



**FIGURE 4-2 Layout of delineator setting in the field.**

### *4.1.2 Data Analysis and Results*

Automated video processing software was used in processing video for traffic parameters. The software was capable of recognizing vehicles by detecting the pixel changes on screen generated by moving vehicles. Since the video software did not produce reliable speeds, a pair of virtual detectors were set up in a speed trap configuration to compute more accurate speeds. Two count detectors were set at known distances corresponding to the delineators deployed in the field. Additionally, 5 minutes worth of speed radar data was also used for calibrating speeds. The calibration adjusted the speed trap distance to minimize the average absolute difference of speeds. In this research, only free flow vehicles were considered. Vehicles in platoons were constrained by the speed of the platoon leader which could be at a slower speed than desired. Therefore, the speeds of the followers in a platoon were not considered as their desired speeds and were dropped from further analysis.

**TABLE 4-1** is an example of a portion of data obtained from video processing software for scenario 1. The "Detector ID" is the number of the virtual detector where 102 means upstream detector and 101 means downstream detector. "Time MS" is the numerical value of time recorded in milliseconds. After processing the complete video tape in each scenario with software, software scripts were used to automate the calculation of all speeds by filtering out platooned vehicles, outliers and errors. Speeds that were less than 30 mph and greater than 90 mph were considered outliers but were rare. The descriptive statistics of speeds for each scenario is shown in **TABLE 4-2.**

**TABLE 4-1 Automated Video Processing Data**

| Detector ID | Date | Time | Time MS |
|---|---|---|---|
| 102 | 2010-2-28 | 12:38:18 PM | 345792 |
| 101 | 2010-2-28 | 12:38:20 PM | 347828 |
| 102 | 2010-2-28 | 12:38:21 PM | 349096 |
| 101 | 2010-2-28 | 12:38:23 PM | 351098 |

**TABLE 4-2 Speed Statistics**

| Scenario | Scenario 1 | Scenario 2 | Scenario 3 |
|---|---|---|---|
| Posted speed limit (mph) | 70 | 60 | 50 |
| Mean (mph) | 70 | 56 | 41 |
| 85th percentile speed (mph) | 81 | 62 | 48 |
| Standard Error (mph) | 0.20 | 0.15 | 0.22 |
| Median (mph) | 70 | 55 | 42 |
| Mode (mph) | 71 | 62 | 40 |
| Standard Deviation (mph) | 10 | 8 | 6 |
| Range (mph) | 55 | 52 | 43 |
| Minimum (mph) | 33 | 31 | 31 |
| Maximum (mph) | 88 | 83 | 74 |
| Count (vehicles) | 2448 | 2483 | 828 |

As shown in **TABLE 4-2**, mean speeds in each scenario was found to be less than or equal to the posted speed limits. In scenario 1, mean speed was same as the posted speed limit. In scenarios 2 and 3 the mean speeds were 4 mph and 9 mph, respectively lower than the posted speed limits. The 9 mph reduction observed in scenario 3 could be partly attributed to the fact that it was approaching nighttime during the latter part of the 90 minute data collection period. It was found that the mean speed of first 30 minutes was 44 mph, the second 30 minutes was 40 mph, and the last 30 minutes dropped to 39 mph. The standard deviation decreased linearly from 10 mph to 6 mph as the posted speed limit dropped from 70 mph (scenario 1) to 50 mph (scenario 3). Lower mean speed and standard deviation are desirable for improving traffic safety.

To determine if the reduction in mean speeds was due to the posted speed limit instead of random fluctuations, an analysis of variance (ANOVA) test was conducted. **TABLE 4-3** presents the ANOVA test results and shows that the significance is almost 0 or much less than 0.05. Thus, the null hypothesis, *the three groups of speed data are from the same population,* was rejected. The results indicate that the reduction of posted speed limit has a significant impact on vehicle speed reduction.

**TABLE 4-3 Results of ANOVA Test**

| | **Sum of Squares** | **Df** | **Mean Square** | **F** | **Sig.** |
|---|---|---|---|---|---|
| Between Groups | 574658.298 | 2 | 287329.149 | 4047.694 | .000 |
| Within Groups | 408594.761 | 5756 | 70.986 | | |
| Total | 983253.059 | 5758 | | | |

The $85^{th}$ percentile speeds were further examined. The standard normal Z test developed in this thesis was applied to test the significance of difference in $85^{th}$ percentile speed. Results of the test are shown in **TABLE 4-4**. All the null hypotheses were rejected at 95% confidence interval, indicating that the difference in $85^{th}$ percentile speed were statistically significant. Thus lowering down speed limit had a positive effect on reducing $85^{th}$ percentile speeds at work zone.

TABLE 4-4 Results of Statistical Test on 85th Percentile Speed

| Hypothesis | 85% speed with lower speed limit | 85% speed with higher speed limit | Change | P-value | Reject null hypothesis? |
|---|---|---|---|---|---|
| $H_0:(\xi_{0.85})_{60}=(\xi_{0.85})_{70}$<br>$H_1:(\xi_{0.85})_{60}<(\xi_{0.85})_{70}$ | 62 | 81 | -19 | 0.000 | Yes |
| $H_0:(\xi_{0.85})_{50}=(\xi_{0.85})_{60}$<br>$H_1:(\xi_{0.85})_{50}<(\xi_{0.85})_{60}$ | 48 | 62 | -14 | 0.000 | Yes |

*Key:* $(\xi_{0.85})_{70}$ *is the 85th percentile speed with speed limit of 70mph*
$(\xi_{0.85})_{60}$ *is the 85th percentile speed with speed limit of 60mph*
$(\xi_{0.85})_{50}$ *is the 85th percentile speed with speed limit of 50mph*

The cumulative distributions of speeds observed in all three work zones followed S-shaped curves as shown in **FIGURE 4-3**. It was evident that there were three distinct speed curves. The Kolmogorov-Smirnov test were applied to the speed data to determine the significance of difference in speed distribution. The results are shown in **TABLE 4-5**. The cumulative speed distributions are statistically different across all three data sets, which means lowering down speed limit at work zone reduced speeds of vehicles in all speed range.

TABLE 4-5 Results of K-S Test

| | P-value | Statistical Significant? |
|---|---|---|
| 70mph vs. 60mph | 0.000 | Yes |
| 60mph vs. 50mph | 0.000 | Yes |

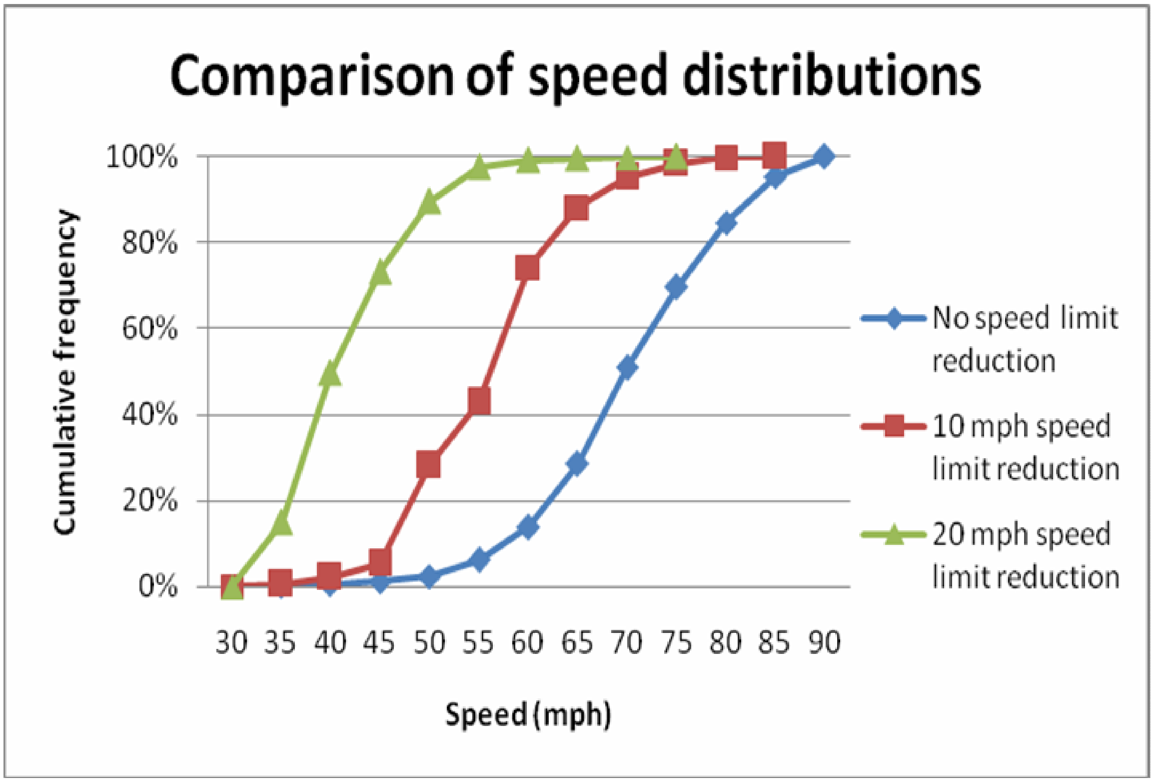



**FIGURE 4-3 Comparison of speeds distribution under different speed limits.**

The standard deviations of vehicle speeds were also analyzed statistically at a 90% confidence level. F-test can be used to compare scenario 1 (70 mph) with scenario 2 (60 mph), and scenario 2 with scenario 3 (50 mph). The results are shown in **TABLE 4-6**. The F-test results indicated that speed variance differences were statistically significant in both comparisons. Thus any safety improvement was the result of systematic and not random factors.

**TABLE 4-6 Result of F-Test on Speeds Standard Deviation**

**A. Result of F-Test on Speeds Standard Deviation Under Speed Limit 50 mph and 60 mph**

| | **Standard deviation** | **Calculated F-value** | **Critical region** | **Statistical Significant?** |
|---|---|---|---|---|
| Speed limit 50 mph | 6 | 1.778 | >1.077 | Yes |
| Speed limit 60 mph | 8 | | | |

**B. Result of F-Test on Speeds Standard Deviation Under Speed Limit 50 mph and 60 mph**

| | **Standard deviation** | **Calculated F-value** | **Critical region** | **Statistical Significant?** |
|---|---|---|---|---|
| Speed limit 60 mph | 8 | 1.563 | >1.053 | Yes |
| Speed limit 70 mph | 10 | | | |

In addition to analyzing the effect of speed limits on speed distribution and speed variance, drivers' compliance was also computed from speed data. The following five indicators of speed limit compliance were computed: 1) 85$^{th}$ percentile speed, 2) percent of traffic not exceeding (or complying with) posted speed limit, 3) percent of traffic exceeding posted speed limit by 5 mph or less, 4) percent of traffic exceeding posted speed limit by more than 5 mph but less than 10 mph and 5) percent of traffic exceeding posted speed by 10 mph or more. The 85$^{th}$ percentile speeds were previously discussed in **TABLE 4-4**. Except for scenario 1 for which the 85$^{th}$ percentile speed was 11 mph higher than speed limit, the 85$^{th}$ percentile speeds in other two scenarios were within 2 mph of the speed limits.

The percentage of traffic complying with posted speed limit increased with the lowering of speed limit in work zone. When the speed limit was not reduced, 50.8% of vehicles complied with the posted limit whereas 74.1% and 89.5% of vehicles complied when the speed limit was lowered by 10mph and 20mph, respectively.

The amount of speed by which speeders exceed speed limits were further examined, because speeders who exceed speed limit more than 10 mph may exert more serious consequences than those who exceed speed limit by 5 mph or less. In scenario 1, 18.8% of drivers speeded by 5 mph or less, 15.0% speeded between 5 to 10 mph, and 15.4% speeded by 10 mph or more. In scenario 2, 13.9% speeded by 5 mph or less, 7.1% speeded between 5 to 10 mph, and 4.8% speeded by 10 mph or more. In scenario 3, 8.1% speeded by 5 mph or less, 1.6% speeded between 5 to 10 mph, and 0.9% speeded by 10 mph or more. As shown in **FIGURE 4-4**, when speed limit was reduced to 50 mph, the percentage of driver exceeding speed limit by between 5 to 10 mph and by over 10 mph decreased drastically. The significance of differences in the percentages of drivers exceed speed limit by 5 mph or less, 5 mph to 10 mph, and 10 mph or more was tested by binomial proportion test. As shown in **TABLE 4-7**, the differences across all three speed limits are all statistically significant.

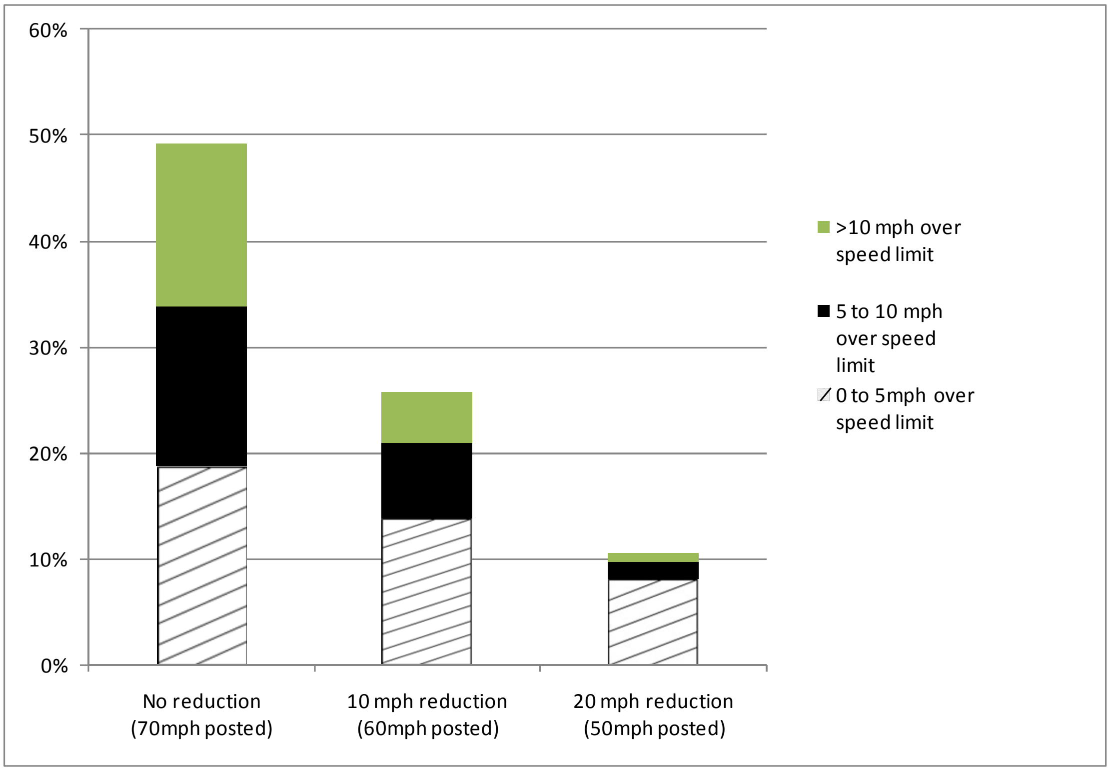



**FIGURE 4-4 Percentage of driver speeding by less than 5 mph, between 5 to 10 mph, and over 10 mph.**

**TABLE 4-7 Results of Proportion Test on the Percentage Exceeding Speed Limit**

**A. Results of Proportion Test on the Percentage Exceeding Speed Limit by 5 mph or less**

| | Percentage with lower speed limit | Percentage with higher speed limit | Change | P-value | Statistically Significant? |
|---|---|---|---|---|---|
| 70 mph vs. 60 mph | 13.9% | 18.8% | -4.9% | 0.000 | Yes |
| 60 mph vs. 50 mph | 8.1% | 13.9% | -5.8% | 0.000 | Yes |

**B. Results of Proportion Test on the Percentage Exceeding Speed Limit by 5 mph to 10 mph**

| | Percentage with lower speed limit | Percentage with higher speed limit | Change | P-value | Statistically Significant? |
|---|---|---|---|---|---|
| 70 mph vs. 60 mph | 7.1% | 15.0% | -7.9% | 0.000 | Yes |
| 60 mph vs. 50 mph | 1.6% | 7.1% | -5.5% | 0.000 | Yes |

**C. Results of Proportion Test on the Percentage Exceeding Speed Limit by 10 mph or more**

| | Percentage with lower speed limit | Percentage with higher speed limit | Change | P-value | Statistically Significant? |
|---|---|---|---|---|---|
| 70 mph vs. 60 mph | 4.8% | 15.4% | -10.6% | 0.000 | Yes |
| 60 mph vs. 50 mph | 0.9% | 4.8% | -3.9% | 0.000 | Yes |

## 4.2. Sequential Warning Lights

### *4.2.1 Data Collection*

In field studies, three short-term maintenance work zones with speed limit of 60 mph on Interstate 70 which all involved a right lane closure with the passing lane open (2 to 1 work zone) were selected for speed data collection. Two rural work zones data was collected on May 17th and 18th, 2010 and one urban work zone data was collected on May 23rd. The speeds with and without the sequential lights were recorded. The details of data collection periods are shown in the **TABLE 4-8**. Road sections in the study sites had minimal horizontal and vertical curves in order to control for geometric factors and to achieve an optimal field-of-view for the speed data collection equipment. Instead of using loops, video data collection was used. The video data allows automated post-processing of the video and preserves a visual record in case there are anomalies with the data. In addition, the video footage was useful for presenting the results of the study. **FIGURE 4-5** shows snapshots of sample work zone video footages. It shows a set of equally spaced delineators with reflective tops that was used for calibrating distances on the video. The photo also shows the sequential lights mounted on channelizers and the arrow board near the end of the taper.

**TABLE 4-8 Data Collection Schedule**

| | May 17th | May 18th | May 23rd |
|---|---|---|---|
| With lights | 10:00PM-11:30PM | 11:40PM-1:10AM | 9:30PM-11:00PM |
| Without lights | 11:30PM-1:00AM | 9:30PM-11:00PM | 11:15PM-12:45AM |

**FIGURE 4-5 Video data collection and spatial reference points.**

### *4.2.2 Data Analysis and Results*

**TABLE 4-9** is a snippet of the radar speed data. Column 1 shows the five-minute chapter indices that were added for ease of reference. Column 2 shows the speed. Column 3 shows the vehicle type where T stands for commercial trucks and P stands for passenger vehicles. Column 4 indicates the presence and size of a platoon which is determined visually by observing video evidence of vehicles following one another. Only unconstrained vehicle speeds were considered for further analysis, because the speeds of platoon vehicles were constrained by the leading vehicle. The goal was to isolate the effect of the sequential lights on vehicle speed.

**TABLE 4-10** presents the descriptive statistics of speeds for total vehicles, passenger cars, trucks, vehicles at rural work zones and vehicles at urban work zones. As explained earlier, only free flow vehicles are included in this table. Thus the Count variable does not include the number of vehicles counted in the platoons. For both with and without lights, **TABLE 4-10** shows the 85$^{th}$ percentile speeds are around the speed limit for trucks and slightly higher for passenger cars. The speed limit compliance rate is similarly higher for trucks than passenger cars. The standard deviation of speeds and the speed ranges are smaller for trucks than passenger cars. The 85 percentile and mean speeds are both higher at rural work zones as compared to urban work zones. But the standard deviations of speed are higher at urban work zones as compared to rural. **TABLE 4-10** suggests that a small group of more aggressive drivers skew the overall urban work zone data.

**TABLE 4-9 Example of Radar Data from May 17, 2010**

| Chapters (5 min) | Speed (mph) | Vehicle Type (T or P) | Platoon |
|---|---|---|---|
| 1 | 54 | T | 1 |
| | 54 | T | |
| | 53 | T | |
| | 55 | T | |
| | 55 | P | |
| | 56 | T | |
| | 57 | P | |
| | 58 | T | |
| | 55 | P | 1 |
| | 60 | P | |
| | 48 | T | |
| | 49 | P | |
| | 48 | P | |
| | 52 | T | 1 |
| | 60 | P | |
| | 52 | P | |
| | 60 | P | |
| | 59 | T | |
| | 59 | T | |
| | 57 | T | 2 |
| | 50 | T | |
| | 63 | P | |
| | 64 | P | 1 |
| | 55 | P | |
| | 55 | T | |
| | 71 | P | 1 |
| | 49 | T | |
| 2 | 46 | T | 2 |
| | 41 | T | 1 |

**TABLE 4-10 Speeds Statistics**

**A. Speed Statistics for Total Vehicles**

| | **With lights** | **Without lights** |
|---|---|---|
| Mean (mph) | 55.55 | 57.76 |
| $85^{th}$ Percentile (mph) | 62 | 63 |
| Standard Deviation (mph) | 6.66 | 5.75 |
| Minimum (mph) | 32 | 34 |
| Maximum (mph) | 82 | 79 |
| Speed Limit Compliance Rate | 78.1% | 71.4% |
| Count (veh) | 1389 | 1241 |

**B. Speed Statistics for Passenger Cars**

| | **With lights** | **Without lights** |
|---|---|---|
| Mean (mph) | 56.50 | 58.70 |
| $85^{th}$ Percentile (mph) | 63 | 64 |
| Standard Deviation (mph) | 6.73 | 5.91 |
| Minimum (mph) | 32 | 37 |
| Maximum (mph) | 82 | 79 |
| Speed Limit Compliance Rate | 73.1% | 65.2% |
| Count (veh) | 900 | 750 |

**C. Speed Statistics for Trucks**

| | **With lights** | **Without lights** |
|---|---|---|
| Mean (mph) | 53.80 | 56.30 |
| $85^{th}$ Percentile (mph) | 60 | 61 |
| Standard Deviation (mph) | 6.15 | 5.17 |
| Minimum (mph) | 32 | 34 |
| Maximum (mph) | 70 | 71 |
| Speed Limit Compliance Rate | 87.3% | 80.9% |
| Count (veh) | 489 | 491 |

**D. Speed Statistics for Rural Work Zones**

| | With lights | Without lights |
|---|---|---|
| Mean (mph) | 57.65 | 58.43 |
| $85^{th}$ Percentile (mph) | 63 | 63 |
| Standard Deviation (mph) | 6.09 | 5.48 |
| Minimum (mph) | 37 | 35 |
| Maximum (mph) | 82 | 79 |
| Speed Limit Compliance Rate | 69.0% | 68.3% |
| Count (veh) | 749 | 861 |

**E. Speed Statistics for Urban Work Zone**

| | With lights | Without lights |
|---|---|---|
| Mean (mph) | 53.09 | 56.24 |
| $85^{th}$ Percentile (mph) | 60 | 62 |
| Standard Deviation (mph) | 6.45 | 6.06 |
| Minimum (mph) | 32 | 34 |
| Maximum (mph) | 69 | 75 |
| Speed Limit Compliance Rate | 88.8% | 78.4% |
| Count (veh) | 640 | 380 |

T-tests were performed on the “with lights” and “without lights” speed data. The t-test results are shown in **TABLE 4-11**. All the null hypothesis rejections indicate there is a significant difference in the mean speeds with and without sequential lights for all analysis categories (all vehicles, passenger cars, trucks, vehicles at rural work zones and vehicles at urban work zones.) The p-values were all close to a value of 0. As shown in **TABLE 4-11**, Sequential lights resulted in a statistically significant mean speed reduction of 2.5 mph for all vehicles, 2.2 mph for passenger cars and 2.5 mph for trucks. Mean speeds decreased by 0.8 mph and 3.1 mph for the vehicles in rural work zones and urban work zones, respectively due to the installation of sequential lights. The greater effect on trucks was expected as trucks have more limited performance characteristics, and truck drivers are more regulated and receive more training than non-commercial drivers.

**TABLE 4-11 T-Test Results for Mean Speeds**

| | Hypothesis | Mean w/ lights | Mean w/o lights | Change | P-value | Reject null hypothesis? |
|---|---|---|---|---|---|---|
| All vehicles | $H_0 : \mu_{with} = \mu_{without}$ <br> $H_1 : \mu_{with} < \mu_{without}$ | 55.55 | 57.76 | -2.21 | 0.000 | Yes |
| Passenger cars | $H_0 : \mu_{with} = \mu_{without}$ <br> $H_1 : \mu_{with} < \mu_{without}$ | 56.50 | 58.70 | -2.2 | 0.000 | Yes |
| Trucks | $H_0 : \mu_{with} = \mu_{without}$ <br> $H_1 : \mu_{with} < \mu_{without}$ | 53.80 | 56.30 | -2.5 | 0.000 | Yes |
| Rural WZ | $H_0 : \mu_{with} = \mu_{without}$ <br> $H_1 : \mu_{with} < \mu_{without}$ | 57.65 | 58.43 | -0.78 | 0.004 | Yes |
| Urban WZ | $H_0 : \mu_{with} = \mu_{without}$ <br> $H_1 : \mu_{with} < \mu_{without}$ | 53.09 | 56.24 | -3.15 | 0.000 | Yes |

*Key:* $\mu_{with}$ *is the mean speed of vehicles at work zones with sequential warning lights*

$\mu_{without}$ *is the mean speed of vehicles at work zones without sequential warning lights*

Despite some vigorous debate over the years, it is generally accepted that vehicle speeds are correlated to crash severities *(41)*. The 85$^{th}$ percentile speed was examined more carefully as it is commonly used for establishing the speed limit. As shown in **TABLE 4-12**, the 85% speeds with sequential lights were lower than those without sequential lights for all vehicles, passenger cars and trucks. The significance of the difference in 85% speeds was tested by using the standard normal Z test developed in this thesis. **TABLE 4-12** shows the differences in the 85% speed was statistically significant. **TABLE 4-12** also shows there is no difference in the 85% speed in rural work zones while there is a statistically significant difference in the urban work zone.

**TABLE 4-12 Standard Normal Z Test Results for 85th Percentile Speed**

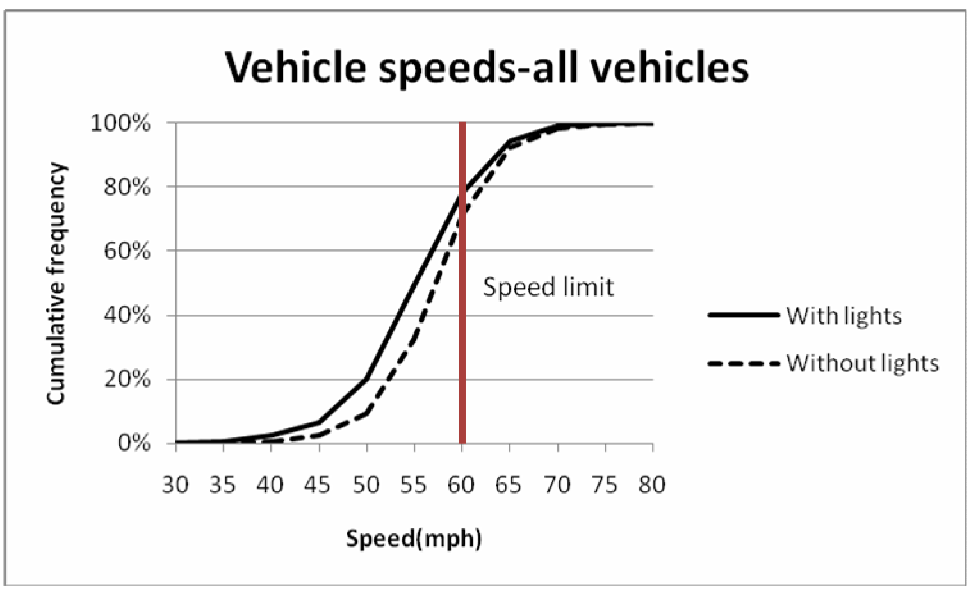
| | Hypothesis | 85% speed with lights | 85% speed w/o lights | Change | P-value | Reject null hypothesis? |
|---|---|---|---|---|---|---|
| All vehicles | $H_0:(\xi_{0.85})_{with}=(\xi_{0.85})_{without}$ <br> $H_1:(\xi_{0.85})_{with}<(\xi_{0.85})_{without}$ | 62 | 63 | -1 | 0.003 | Yes |
| Passenger cars | $H_0:(\xi_{0.85})_{with}=(\xi_{0.85})_{without}$ <br> $H_1:(\xi_{0.85})_{with}<(\xi_{0.85})_{without}$ | 63 | 64 | -1 | 0.017 | Yes |
| Trucks | $H_0:(\xi_{0.85})_{with}=(\xi_{0.85})_{without}$ <br> $H_1:(\xi_{0.85})_{with}<(\xi_{0.85})_{without}$ | 60 | 61 | -1 | 0.035 | Yes |
| Rural WZ | $H_0:(\xi_{0.85})_{with}=(\xi_{0.85})_{without}$ <br> $H_1:(\xi_{0.85})_{with}<(\xi_{0.85})_{without}$ | 63 | 63 | 0 | 0.500 | No |
| Urban WZ | $H_0:(\xi_{0.85})_{with}=(\xi_{0.85})_{without}$ <br> $H_1:(\xi_{0.85})_{with}<(\xi_{0.85})_{without}$ | 60 | 62 | -2 | 0.001 | Yes |

*Key:* $(\xi_{0.85})_{with}$ *is the 85th percentile speed with sequential warning lights*
$(\xi_{0.85})_{without}$ *is the 85th percentile speed without sequential warning lights*

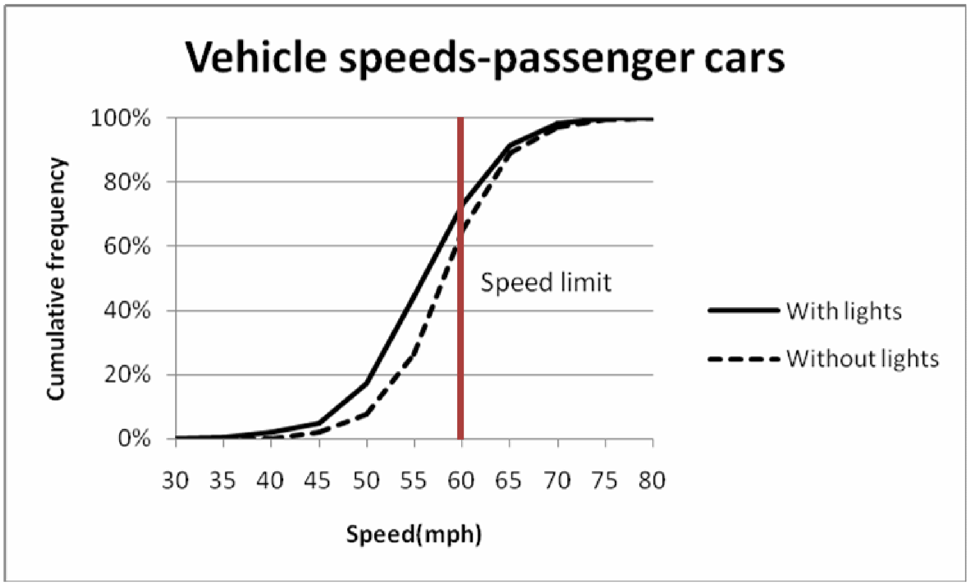
In **FIGURE 4-6**, cumulative speed distributions of free flowing vehicles with sequential lights and without sequential lights are shown and compared. The speed limit of 60 mph is shown as a red vertical line. Whether or not this line falls above or below the 85% speed has implications for speed compliance and safety. With sequential lights, the distribution curves of total vehicles, passenger cars, trucks, vehicles at rural work zones and vehicles at urban work zones were all shifted to the left, indicating a decrease in vehicle speeds. The results of the comparison of vehicle speeds at rural work zones show only vehicle speeds below 60 mph were reduced by sequential lights as shown in **FIGURE 4-6(d)**. All of the other comparisons indicate that sequential lights decrease the speeds of all vehicles in the study: passenger cars, trucks and vehicles at urban work zones in all speed ranges. To determine if the speed distributions differences (with and without lights) in the five data sets shown in **FIGURE 4-6** are statistically significant, the Kolmogorov-Smirnov test was applied. The results are displayed in **TABLE 4-13**. In all five data sets, the cumulative speed distributions with sequential lights were significantly different from those without sequential lights.

**TABLE 4-13 Results of K-S Test**

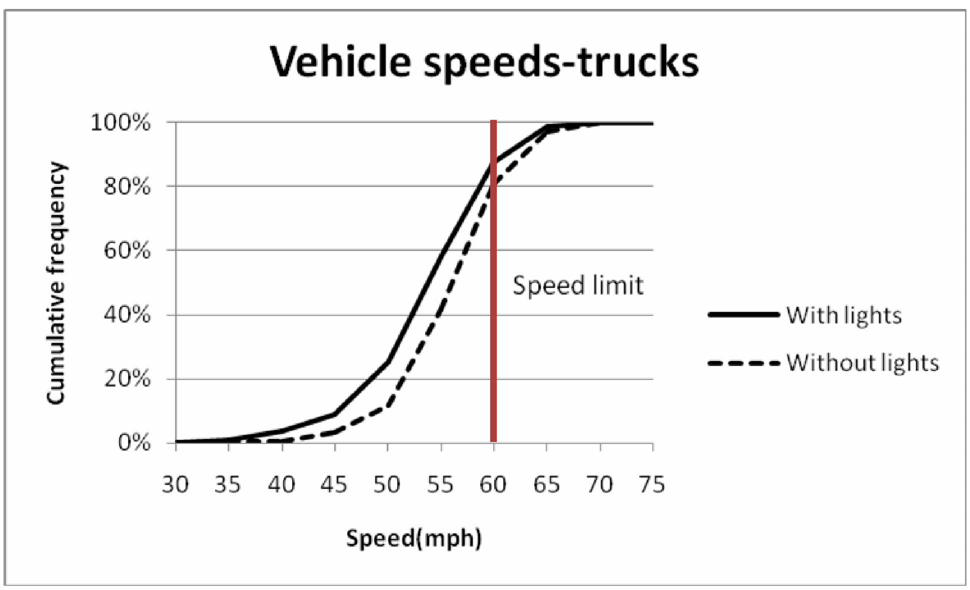
| | P-value | Statistical Significant? |
|---|---|---|
| All vehicles | 0.000 | Yes |
| Passenger cars | 0.000 | Yes |
| Trucks | 0.000 | Yes |
| Rural WZ | 0.000 | Yes |
| Urban WZ | 0.000 | Yes |



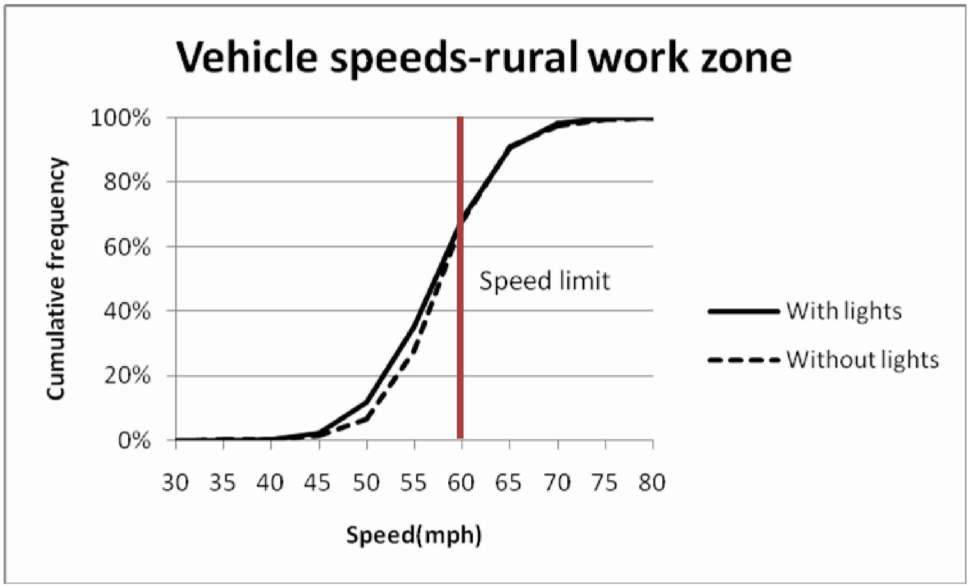

**4-6(a)**


Vehicle speeds-passenger cars
100%
80%
60%
40%
20%
0%
Cumulative frequency
30 35 40 45 50 55 60 65 70 75 80
Speed(mph)
Speed limit
With lights
Without lights

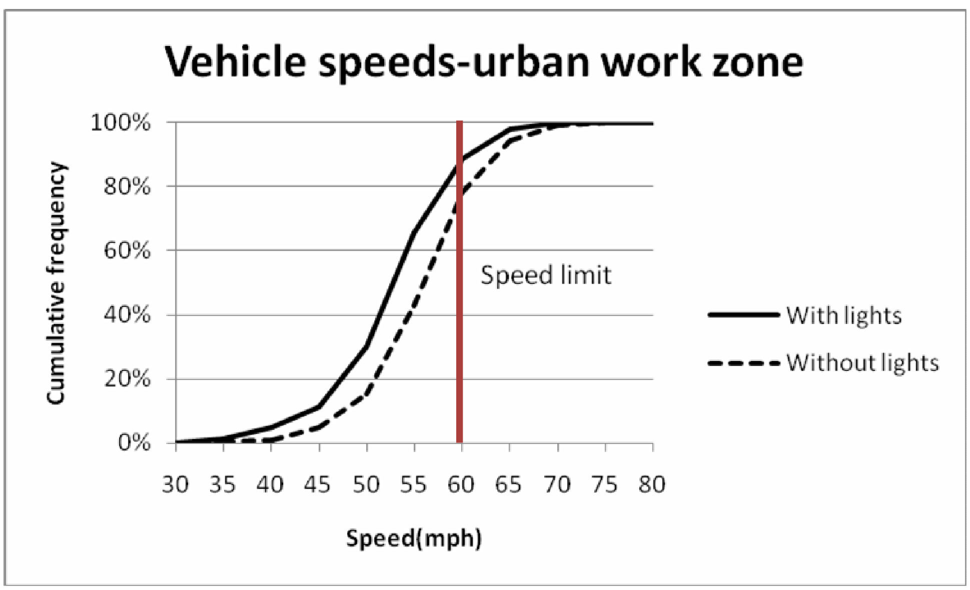
**4-6(b)**


Vehicle speeds-trucks
100%
80%
60%
40%
20%
0%
Cumulative frequency
30 35 40 45 50 55 60 65 70 75
Speed(mph)
Speed limit
With lights
Without lights

**4-6(c)**




**4-6(d)**




**4-6(e)**

**FIGURE 4-6 Comparison of cumulative speed distributions between with lights and without sequential lights: (a) Total vehicles; (b) Passenger cars; (c) Trucks; (d) Rural work zone; (e) Urban work zone.**

The standard deviations of vehicle speeds were analyzed statistically using the F-test. The results of the test are shown in **TABLE 4-14.** All null hypotheses were rejected showing that there were statistically significant differences in the standard deviations of vehicle speed for all categories of data. Thus, sequential lights slightly increased standard deviations by 0.91 mph on all vehicles, 0.82 mph on passenger cars, 0.98 mph on trucks, 0.61 mph on vehicles at rural work zone and 0.39 mph on vehicles at urban work zone.

**TABLE 4-14 F-Test Results for Speed Variances**

| | Hypothesis | Std. dev. with light | Std. dev. w/o lights | Change | P-value | Reject null hypothesis? |
|---|---|---|---|---|---|---|
| All vehicles | $H_0:\sigma_{with}=\sigma_{without}$<br>$H_1:\sigma_{with}>\sigma_{without}$ | 6.66 | 5.75 | 0.91 | 0.000 | Yes |
| Passenger cars | $H_0:\sigma_{with}=\sigma_{without}$<br>$H_1:\sigma_{with}>\sigma_{without}$ | 6.73 | 5.91 | 0.82 | 0.000 | Yes |
| Trucks | $H_0:\sigma_{with}=\sigma_{without}$<br>$H_1:\sigma_{with}>\sigma_{without}$ | 6.15 | 5.17 | 0.98 | 0.000 | Yes |
| Rural WZ | $H_0:\sigma_{with}=\sigma_{without}$<br>$H_1:\sigma_{with}>\sigma_{without}$ | 6.09 | 5.48 | 0.61 | 0.001 | Yes |
| Urban WZ | $H_0:\sigma_{with}=\sigma_{without}$<br>$H_1:\sigma_{with}>\sigma_{without}$ | 6.45 | 6.06 | 0.39 | 0.089 | Yes |

*Key:* $\sigma_{with}$ *is the standard deviation of vehicle speed with sequential warning lights*
$\sigma_{without}$ *is the standard deviation of vehicle speed without sequential warning lights*

In addition, drivers' speed limit compliance rate with and without sequential lights were examined. Binomial proportion test was used to test the significance of the difference in compliance rate.

The speed limit compliance test results are presented in **TABLE 4-15**. The test shows no significant difference in passenger car compliance rate between with and without sequential lights. However, all other null hypotheses were rejected which means sequential lights had a statistically significant effect in increasing driver compliance with posted work zone speed limit.

**TABLE 4-15 Binomial Proportion Test Results for Compliance Rate**

| | Hypothesis | Percentage with light | Percentage w/o lights | Change | P-value | Reject null hypothesis? |
|---|---|---|---|---|---|---|
| All vehicles | $H_0 : p_{with} = p_{without}$<br>$H_1 : p_{with} > p_{without}$ | 78.1% | 71.4% | 6.7% | 0.000 | Yes |
| Passenger cars | $H_0 : p_{with} = p_{without}$<br>$H_1 : p_{with} > p_{without}$ | 73.1% | 65.2% | 7.9% | 0.000 | Yes |
| Trucks | $H_0 : p_{with} = p_{without}$<br>$H_1 : p_{with} > p_{without}$ | 87.3% | 80.9% | 6.4% | 0.003 | Yes |
| Rural WZ | $H_0 : p_{with} = p_{without}$<br>$H_1 : p_{with} > p_{without}$ | 69.0% | 68.3% | 0.7% | 0.381 | No |
| Urban WZ | $H_0 : p_{with} = p_{without}$<br>$H_1 : p_{with} > p_{without}$ | 88.8% | 78.4% | 10.4% | 0.000 | Yes |

*Key:* $p_{with}$ *is the drivers' speed limit compliance percentage with sequential warning lights*

$p_{without}$ *is the drivers' speed limit compliance percentage without sequential warning lights*

### *4.2.3. Economic Analysis*

The other aspect of this study was the economic analysis of the benefits and costs of deploying sequential lights. The tangible safety benefits were estimated and valued economically. Such benefits were computed from the potential reductions in crashes at nighttime work zones in Missouri. The deployment costs included the cost of sequential warning lights and batteries, and labor costs for installation and removal.

The benefit-cost analysis involved the following assumptions. Only fatal and injury crashes were considered in computing the benefits. In contrast, the costs of property-damage-only (PDO) crashes were considerably less significant. This case study only used work zone crash data from freeways and major highways. Thus no work zones on interrupted flow facilities were considered. Also, only Missouri data was used for this study. But the results from this study could be adapted to other states by using the appropriate crash data for the other states.

Total benefits ( $B_{Total}$ dollars per year) from sequential lights were computed by taking the difference between the total costs of crashes without sequential warning lights ( $C_{Total,Without}^{Crash}$ dollars per year) and the total costs of crashes with ( $C_{Total,With}^{Crash}$ dollars per year) sequential lights. Thus, total benefits were specified as

$$B_{Total} = C_{Total,Without}^{Crash} - C_{Total,With}^{Crash} . \tag{4-1}$$

The total costs of crashes without sequential warning lights, $C_{Total,Without}^{Crash}$ , was obtained using historical crash data. This total cost of crashes was composed of the total costs of fatal crashes ( $C_{Total,Without}^{Fatal}$ dollars per year) and the total costs of injury crashes ( $C_{Total,Without}^{Injury}$ dollars per year), i.e.

$$C_{Total,Without}^{Crash} = C_{Total,Without}^{Fatal} + C_{Total,Without}^{Injury} = N_{Without}^{Fatal} \times C^{Fatal} + N_{Without}^{Injury} \times C^{Injury} , \tag{4-2}$$

where $N_{Without}^{Fatal}$ ( $N_{Without}^{Injury}$ ) is number of fatal (injury) crashes per year and $C^{Fatal}$ ( $C^{Injury}$ ) is the average cost per fatal (injury) crash.

Since sequential lights were a relatively new technology, there was no significant crash data associated with their deployment, thus crash regression models were used to estimate the crash benefits of sequential lights. The use of crash regression models is an accepted method that is used in publications such as the Redbook *(42).* Two regression models were considered in the study. One was the Power Model, originally derived by Nilsson *(43).* This model expressed the quantitative relationship between crash and speed and is given by

$$\frac{n_1}{n_0} = \left(\frac{V_1}{V_0}\right)^{\alpha}, \tag{4-3}$$

where $n_1$ was the number of fatal or injury crashes at mean speed $V_1$, $n_0$ was the number of fatal or injury crashes at mean speed $V_0$, and $\alpha = 4$ for fatal crashes and $\alpha = 2$ for injury crashes. Another model was one proposed by Garber and Ehrhart *(44)* that expressed the mathematical relationship between crash rate and several factors, including mean speed, speed variance, and flow. For freeways with speed standard deviation ranging from 8 km/h to 18 km/h, mean speed ranging from 90 km/h (55 mph) to 98 km/h (60 mph) and flow ranging from 200 veh/h/lane to 1800 veh/h/lane, the model form was

$$\begin{aligned} Crashrate = {} & (0.355) - (1.591\times10^{-3})\times(SD^2) + (8.651\times10^{-7})\times(SD^4) - (2.071\times10^{-8})\times \\ & (FPL^2) - (1.256\times10^{-10})\times(SD^2)\times(FPL^2) + (8.527\times10^{-15})\times(FPL^4) - (6.509\times10^{-5})\times \\ & (MEAN^2) + (1.725\times10^{-7})\times(SD^2)\times(MEAN^2) + (3.143\times10^{-12})\times(FPL^2)\times(MEAN^2) + \\ & (2.875\times10^{-9})\times(MEAN^4) \end{aligned} \tag{4-4}$$

where *Crashrate* was in terms of the number of crashes per hour per km per lane, *SD* was the standard deviation of speed (km/h), *FPL* was the flow per lane (veh/h/lane) and *MEAN* was the mean speed (km/h).

Both models were similar in expressing the non-linear relationship between crash rate and speed. However, Nilsson's Power Model treated fatal and injury crashes separately. In the Garber-Ehrhart model, flow and standard deviation of speed were included, but the model was developed based on speed data collected at 55 mph speed limit locations, not the 60 mph speed limit at the work zones investigated in this study. Also, crash rate in the Garber-Ehrhart model included all type of severity crashes such as fatal, injury, and property damage only (PDO). In this study, only fatal crash and injury crash were investigated for the economic analysis. In addition, the Power Model was widely used and was accepted by the European Commission *(45)* as a method to express the relationship between speed and crashes. Hence, Nilsson' Power Model was a better fit for this study.

According to the Power Model, the predicted ratio of the number of crashes with installation of sequential warning lights to the number of crashes without was given by

$$R_{Fatal} = \left(\frac{V_{With}}{V_{Without}}\right)^4 \text{ and } R_{Injury} = \left(\frac{V_{With}}{V_{Without}}\right)^2, \qquad (4\text{-}5)$$

where $R_{Fatal}$ was the ratio for fatal crashes, $R_{Injury}$ was the ratio for injury crashes, $V_{With}$ was the mean speed with sequential warning lights (mph), and $V_{Without}$ was the mean speed without sequential warning lights (mph).

The total costs of crashes with the installation of sequential warning lights ($C_{Total,With}$) were expressed as

$$C^{Crash}_{Total,With} = N^{Fatal}_{Without} \times C^{Fatal} \times R_{Fatal} + N^{Injury}_{Without} \times C^{Injury} \times R_{Injury} . \qquad (4\text{-}6)$$

By substituting (4-2) and (4-6) to (4-1), the total benefits were computed as

$$B_{Total} = N^{Fatal}_{Without} \times C^{Fatal} \times (1 - R_{Fatal}) + N^{Injury}_{Without} \times C^{Injury} \times (1 - R_{Injury}) . \qquad (4\text{-}7)$$

**TABLE 4-16** shows the fatal and injury ratios computed using speeds measured in the three work zone sites. **TABLE 4-17** presents the nighttime work zone crash history on US freeways and major interstates in Missouri for the last five years. Only nighttime work zone crashes were considered for this analysis because sequential lights could have the most impact at nighttime. **TABLE 4-18** shows the user costs of crashes from the Redbook *(42).* The total costs of fatal crashes without installation of sequential warning lights $C^{Fatal}_{Total,Without}$ were estimated to be 4.4 fatal crashes/year × \$3.72 million per fatal crash, or \$16.37 million in 2000 US dollars. Similarly, the total costs of injury crashes without installation of sequential warning lights $C^{Injury}_{Total,Without}$ were estimated to be 77.6 injury crashes/year × \$108,600 per injury crash, or \$8.43 million in 2000 US dollars.

Based on equation (4-7), the monetized annual saving from fatal crashes and injury crashes with sequential lights were \$2.36 million and \$0.63 million in 2000 US dollars, respectively. Hence, the total monetized benefits of implementing sequential warning lights were estimated to be \$3.00 million annually in 2000 US dollars, which was equivalent to \$3.65 million in 2010 US dollars using a conservative 2% discount rate.

**TABLE 4-16 The Result of Parameters**

| **Fatal Crash** ($R_{Fatal}$) | **Injury Crash** ($R_{Injury}$) |
|---|---|
| 85.6% | 92.5% |

**TABLE 4-17 Freeway and Major Highway Nighttime Work Zone Crashes in Missouri**

| | **2006** | **2007** | **2008** | **2009** | **2010** | **Total** |
|---|---|---|---|---|---|---|
| Fatal Crashes | 7 | 1 | 5 | 2 | 7 | 22 |
| Injury Crashes | 149 | 56 | 46 | 63 | 76 | 388 |

**TABLE 4-18 User Costs of Crashes (year 2000 dollars)**

| **Type of work zone crash** | **Average Perceived User Cost** | **Average Insurance Reimbursement** | **Net Perceived User Cost** |
|---|---|---|---|
| Fatal crashes | 3,753,200 | 29,500 | 3,723,700 |
| Injury crashes | 138,100 | 29,500 | 108,600 |
| Property Damage Only | 3,900 | 3,700 | 200 |

Total costs of implementing sequential warning lights ($C_{Total}$ dollars per year) were computed by adding the total costs of sequential warning lights devices in Missouri

($C_{Device}$ dollars per year), the costs of batteries ($C_{Battery}$ dollars per year) and the total labor costs of installing and removing the devices ($C_{Labor}$ dollars per year). Its mathematic form is presented as

$$C_{Total} = C_{Device} + C_{Battery} + C_{Labor}. \tag{4-8}$$

Based on the information provided by the manufacture of sequential warning lights, the current price of each lamp was approximately \$104 and each lamp consumed the equivalent of \$0.2 of electricity from two batteries every night. According to the MUTCD, each work zone could deploy approximately 20 lights at the taper area. The exact number of lights depends on site characteristics such as the speed limit. The MoDOT work zone schedules from 2010 showed that 1968 nighttime work zones were deployed on freeways in Missouri with an average of 7.6 nights duration per work zone. At most, 109 nighttime work zones were carried out on the same night, thus 109 was the maximum number of sequential light sets required if deployment were desired at all nighttime work zones. Therefore, the total costs of sequential warning lights devices $C_{Device}$ were estimated to be \$104/lights ×20 lights/WZ × 109 WZs, or \$226,760 current US dollars. The total costs of batteries $C_{Battery}$ were estimated to be \$0.2/lights × 20 lights/WZ/night × 1968 WZs × 7.6 nights, or \$59,716 current US dollars.

According to MU's estimates for each work zone, it took 2 workers about 30 minutes to install sequential lights for twenty channelizers and 30 minutes to remove them using manual tools. According to MoDOT's maintenance supervisor, a typical worker salary is approximately \$14 per hour. Thus the labor costs were estimated as \$14/worker/hr $\times$ 2 workers $\times$ (0.5+0.5)hr/WZ/nights $\times$ 1968WZs $\times$ 7.6 nights, or \$418,572 current US dollars. The total costs of implementing sequential warning lights $C_{Total}$ were \$705,008 per year. Since labor was the major component of cost, an increase in worker efficiency could significantly reduce overall deployment costs. The use of portable power wrenches could decrease labor costs. Currently, it is not possible to permanently install sequential lights on channelizers so as to eliminate the installation and removal of lights each time it is deployed. One reason is because channelizers are stacked when transported. The installation of sequential lights prohibits the stacking of channelizers. Another reason is that the handles of sequential lights are not designed to be used for picking up channelizers. Channelizers have heavy bases for stability. In the future, perhaps the sequential light function could be designed into the channelizer itself. This will eliminate significant labor costs with deployment and enable channelizers to be stacked. Re-locating batteries to the channelizer base could also help with stability and crash performance.

Common measures for economic evaluation include benefit-cost ratio, net benefits and cost effectiveness. Such measures are interrelated but serve somewhat different purposes. Using the total benefit amount of \$3.65 million and the total cost amount of \$705,008, the benefit-cost ratio of deploying sequential lights in Missouri was estimated to be around 5.18. By subtracting the total costs from the total benefits, the net annual benefits were computed to be \$2.95 million. Using the crash ratios from **TABLE 4-16** and the average annual nighttime work zones crashes from **TABLE 4-17**, the annual crash reductions were estimated to be 0.634 fatality/year and 5.84 injury/year. The cost effectiveness of sequential lights was then estimated by dividing the total cost by the expected crash reductions. Assuming an equivalency of 34.3 injuries to a single fatality, the cost effectiveness was estimated to be $17,565/injury.

# CHAPTER 5: CONCLUSION

The well-known Student t-test and ANOVA can be used to assess whether or not the means from two normally distributed populations are equal. However, in the area of transportation safety, a critical parameter is the 85$^{th}$ percentile speed and not the mean speed. The 85$^{th}$ percentile speed statistic is often described but no inference is made due to the lack of a simple statistical test. The major problem to making inference on quantiles from two populations is calculating the estimates of standard error of desired quantiles. In this thesis, a standard normal Z test for comparing the 85$^{th}$ sample quantiles is developed using Cramer's derivation of the asymptotic distribution of sample quantiles. The test provides a reasonable estimate of standard error of the 85$^{th}$ sample quantile and a simple form. The test is as easy to apply as the t-test for mean speeds and can be a useful tool for researcher to determine whether the 85$^{th}$ percentile speed changed significantly in transportation safety analysis.

In addition, two projects that motivated this new statistical methodology, the evaluation of the effectiveness of work zone speed limits and the analysis of the sequential warning lights in night time work zone tapers, were presented as empirical case studies of speed-related safety analysis for work zones. They were also excellent illustrations of this new methodology.

In the evaluation of the effectiveness of work zone speed limits, with the increase of speed limit reduction from 0 to 10 mph, the percentage of speeding was almost halved.

When speed limit was further reduced by 10 mph, the percentage of speeding was about one fifth of the percentage under the no speed limit reduction scenario. If exceeding the speed limit by more than 10 mph were considered as aggressive driving, then in the no speed limit reduction scenario about 1 in 7 was an aggressive driver, in the 10 mph speed limit reduction scenario about 1 in 21 was an aggressive driver, and in the 20 mph speed limit reduction scenario the aggressive drivers were almost non-existent.

The decline in the mean speed and 85$^{th}$ percentile speed when the posted speed limit was reduced was evidence that lowering the speed limit was successful in reducing prevailing traffic speeds in work zones. Further analysis of speed variance data showed that lower speed limit in work zone did not lead to greater variation in vehicle speeds. The standard deviation of speed decreased 2 mph with every reduction of 10 mph speed limit.

Lower speeds and speed variance in work zones result in a safer environment for both vehicles and work zone personnel. The 20 mph speed limit reduction scenario turned out to be the most effective in terms of lowering prevailing speeds and speed variance. Almost a 90% compliance rate was achieved for the 20 mph speed limit reduction scenario. Within the 10% of those who exceeded speed limit, 80% of them were by less than 5 mph. The 10 mph speed limit reduction was also effective in reducing speeds and speed variance.

In the evaluation of sequential warning lights, all speed results were also analyzed statistically. Although sequential lights caused a small increase of 0.91 mph in speed variance, it caused a statistically significant decrease of 1 mph in the 85$^{th}$ percentile speed and an increase of 6.7% in driver compliance at nighttime work zones. The cumulative speed distributions showed sequential lights reduced the speeds of both passenger cars and trucks at both rural and urban work zones for all speed ranges. That effect was more pronounced at the urban work zone than at rural work zones. In general, sequential lights appear to be effectiveness for improving safety at nighttime work zones by clearly delineating the taper area.

The monetized benefits and costs of sequential lights were evaluated. No crash analysis was performed because there was no significant crash data associated with the short sequential lights deployment. However, a crash model was used to estimate improvements in safety from the reduction in speeds. Based on Nilsson's power model and MoDOT's work zone crash data, the total annual benefits and total annual costs of $3.65 million and $705,008, respectively, were estimated. These estimates assumed that sequential lights were deployed on all nighttime interstates and major highway work zones in Missouri. The resulting benefit-cost ratio was around 5, the net benefit was $2.95 million, and the cost effectiveness was around $17,600 per injury. Because labor is a major component of sequential lights deployment, improvements in design could reduce agency deployment costs significantly.

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