EVALUATION OF RUMBLE STRIPS AT RURAL STOP-CONTROLLED INTERSECTIONS IN TEXAS

A Thesis

by

TYRELL D. THOMPSON

Submitted to the Office of Graduate Studies of
Texas A&M University
in partial fulfillment of the requirements for the degree of

MASTER OF SCIENCE

August 2004

Major Subject: Civil Engineering

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Approved as to style and content by:

Mark W. Burris (Chair of Committee)	Conrad L. Dudek (Member)
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ABSTRACT

Evaluation of Rumble Strips at Rural Stop-Controlled

Intersections in Texas. (August 2004)

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Major safety concerns are present at rural high speed intersections. When long uninterrupted tangents are located near rural intersections, the drivers can become inattentive to upcoming decision points. Traffic control devices could aid in mitigating these occurrences by warning drivers of upcoming decision points. One such device is transverse rumble strips, which act to provide motorists with an audible and tactile warning that their vehicle is approaching a decision point of critical importance to safety.

The objective of this research was to determine if the presence of transverse rumble strips were an effective warning device for drivers approaching rural stop-controlled intersections. To evaluate the effectiveness of transverse rumble strips, vehicle speeds were measured at three locations along the approach to an intersection both before and after the installation of rumble strips. Vehicle speeds were measured at nine rural stop-controlled intersection sites in Texas.

Overall, the installation of rumble strips generally produced small, but statistically significant ($p \leq 0.05$), reductions in traffic speeds. There were some negative driver behavioral impacts (i.e., speed increases) that occurred after the installation of rumble strips. There were a few instances where speed change reductions of greater than 1 mph occurred, however, the overall trend was that speed change reductions were equal to or less than 1 mph. Although the

rumble strips did not produce meaningful reductions in traffic speeds, they should still be considered based upon previous accident reductions and minimal installation costs.

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INTRODUCTION

A major safety concern in rural areas is crashes at intersections. A study of crashes on low-volume rural two-lane highways in Texas showed that 25 percent of crashes occurred at intersections (*1*). A comparison of intersection crashes between 1968 and 1988 showed an increase in crashes at urban and rural intersections of 14 percent and 5 percent, respectively. The most prevalent factor contributing to traffic crashes is speeding. There were 41,967 fatalities that occurred in 1997 and excessive speed was the primary contributing factor in 31 percent (13,036) of the crashes (*2*).

The frequency of access points, the amount of roadway lighting, and the magnitude of traffic demands are generally lower in rural areas than urban areas. The combination of these factors tends to make drivers on rural roads more relaxed and potentially less attentive. As a result, drivers are less expectant of upcoming conditions and are more prone to crashes at intersections on rural roadways (*1*, *3*).

Rural intersections could benefit from the use of a traffic control device to mitigate the number and severity of crashes by warning the drivers of upcoming decision points. Traffic control devices help insure highway safety by providing for the orderly and predictable movement of all traffic (*4*). Their primary purpose is to regulate, warn, and/or guide traffic to promote the safe and uniform operation of all motorized and non-motorized elements in the traffic stream. Transverse rumble strips are traffic control devices used to alert drivers to the possible need of action. Their purpose is to provide motorists with an audible and tactile warning that their vehicle is approaching a decision point of critical importance to safety.

This thesis follows the style and format of the *Transportation Research Record.*

Problem Statement

Crashes and accident rates are increasing at rural, high speed intersections. Rural intersections are prone to safety hazards as a result of drivers traveling at higher speeds and decreased driver expectancy.

As a part of a Texas Transportation Institute research project, a set of guidelines will be established for transverse rumble strips to help determine how to apply them if they are implemented. A need exists to fully understand and determine potential benefits of transverse rumble strips as a warning device on approaches to rural intersections. Using field data, a before and after comparison of changes in speed and approach speeds on the intersection approach can be made. By examining multiple rural stop-controlled intersections, it can be determined if the presence of transverse rumble strips affect the operational behavior of drivers.

Research Objectives

The data collected for this thesis were obtained through research conducted at the Texas Transportation Institute (TTI) as part of Project 4472, *Evaluation of Rumble Strips*. Rumble strips are intended to provide the driver with an audible and tactile warning that an operational decision is to be made or that an operational decision point is approaching. As part of this research, before and after studies were conducted to evaluate vehicle speeds at several rural stop-controlled intersections that could benefit from the use of in-lane rumble strips.

The primary objective of this research was to perform an evaluation of transverse rumble strips as a warning device to drivers approaching rural stop-controlled intersections. To determine the effectiveness of transverse rumble strips, change in approach speed was used as a surrogate measure of evaluation. The ultimate measure of effectiveness for the evaluations performed would be the number of collisions prevented by the in-lane rumble strips. However, recognizing that unbiased crash data would be difficult to obtain within the resources and timeframe of this project, the focus was placed on collection of traffic operations data to serve as surrogates for crash data. Approach speeds along the intersection were also compared. A secondary objective of this research was to determine if the transverse rumble strips were more effective during periods (Night and Weekend periods) of decreased driver expectancy.

The following tasks were performed to accomplish the objectives of this research:

- Review pertinent literature
- Select appropriate study sites
- Record speeds prior to installing in-lane rumble strips
- Install in-lane rumble strips
- Record speeds after installing in-lane rumble strips
- Conduct a before and after speed study at each location
- Format and clean the speed data
- Determine the distribution of the speed data
- Compare the mean change in speed after the installation of in-lane rumble strips case at each location
- Compare approach speeds after the installation of in-lane rumble strips at each location
- Document and discuss the results of the research

Scope

A before-and-after study design was conducted at eight rural intersections in the Bryan District of Texas and one rural intersection in the Waco District of Texas. Data were collected on rural, low-volume two lane roads at stop-controlled intersections. Speeds were obtained from vehicles as they traversed the site via automatic vehicle classifiers and pneumatic hoses.

Organization of Thesis

This thesis contains five sections that present methods and results of this research. The introduction includes the problem statement, research objectives, and scope of the research. The literature review section presents the transverse rumble strip state of practice and previous research of operational effects of transverse rumble strips. An emphasis is given to the effects of speed as a result of installation of transverse rumble strips. The literature review also includes background information on research related to the effects of traffic crash experience and traffic control device compliance as a result of installation of transverse rumble strips. The study design section provides a description of the methodology employed by this research, including data collection procedures, data collection equipment, and analysis of the data. In the data analysis and results section, the results of the before and after study are presented. Mean change of speed parameters are compared between the before and after conditions at each location. The data analysis and results section also includes an examination of rumble strips in the Day, Night, Week, and Weekend periods. The last section contains the conclusions and recommendations of this research.

LITERATURE REVIEW

This literature review contains a comprehensive description of the state of practice of rumble strips and previous studies that have examined the operational and safety effects of transverse rumble strips. The first section of this section describes the definition and types of rumble strips as well as the current practices using transverse rumble strips. The second section outlines the measures of effectiveness (MOE) used to evaluate rumble strips. The third section describes studies which have investigated the effectiveness of rumble strips on traffic accident experience, compliance with traffic control devices, and vehicle speed.

State of Practice

Definition and Types of Rumble Strips

According to the *Manual on Uniform Traffic Control Devices* (MUTCD) Millennium Edition, "Rumble strips consist of intermittent narrow, transverse areas of rough-textured or slightly raised or depressed road surface that alert drivers to unusual motor vehicle traffic conditions. Through noise and vibration they attract the driver's attention to such features as unexpected changes in alignment and to conditions requiring a stop" (*5*).

Rumble strips can imply one of three types: shoulder rumble strips, centerline rumble strips, and/or inverse (traveled way) rumble strips. Shoulder rumble strips are applied only to the shoulder of the road and are intended to help prevent run-off-the-road crashes. Centerline rumble strips apply to changes made along the centerline of the roadway and are intended to prevent head-on collisions between vehicles. Rumble strips in the traveled way are strips that are placed within the lane, perpendicular to the direction of travel. The purpose of these strips is primarily to alert the driver that a decision point is approaching and requires special attention.

The focus of this research was the inverse application of rumble strips, and, throughout this report, *rumble strips* refers to rumble strips in the traveled way (See Figure 1) (*6*, *7*).

Figure 1. Example of Transverse Rumble Strips

Motivation for Initial Research

The impetus for investigating transverse rumble strips was to determine if they were an effective means to warn drivers of an approaching decision point. Previous studies have examined the effect of rumble strips at reducing the mean and/or 85th percentile speeds at multiple locations along the approach to decision points. Measuring the change in speed as a vehicle approaches the intersection may provide a better measure of driver adherence to warning signs, which was one of the primary measures of evaluation (MOE) of this research. An increased drop in speed between locations on the approach may indicate the driver has a greater awareness of the upcoming intersection.

This study included the comparison of large sample sizes of speed measurements, where many of the earlier studies relied on small sample sizes (100 observations of less). Also, multiple stop-controlled intersections were compared using multiple locations of speed measurements. Earlier studies either compared different types of intersections or approaches and/or used only one location to collect speed measurements. This study was more comprehensive with larger sample sizes and multiple study sites. This study also incorporated a control speed location to identify variations in speeds between the before and after data collection periods that were caused by factors other than the rumble strips.

Rumble Strip Use

An examination into the usage of transverse rumble strips was beneficial in determining what sites were most likely to benefit from the installation of rumble strips. A survey of state and local highway agencies and toll road and turnpike authorities was performed (Harwood, 1993) to obtain information on the usage of transverse rumble strips (see Table 1) (*8*).

Table 1. Use of Transverse Rumble Strips

Response	State Highway Agencies	Local Agencies	Toll Roads
Yes	41 (91.1)	7 (46.7)	9 (69.2)
No	4 (8.9)	8 (53.3)	4 (30.8)
Total	45	15	13
Note: The numbers in parentheses are column percentages.			

Source: Harwood, 1993 (*8*)

Rumble strips are typically installed where vehicles are required to either stop or significantly slow down. Rumble strips are intended to draw a driver's full attention to the driving task. Some of the basic reasons to use rumble strips are to warn drivers of the need to stop, slow down, change lanes, or changes in roadway alignment. The most common locations for rumble strip deployments are:

- On approaches to intersections
- On approaches to toll plazas
- On approaches to horizontal curves
- On a lane to be closed
- On the approach to a mainline lane drop
- On approaches to or within work zones

Rumble Strip Cross Sections

There are four common types of rumble strips: milled, rolled, formed, and raised. The four types of rumble strips differ in the manner in which they are installed, their shape and size, and the amount of noise and vibration provided.

Milled rumble strips are prevalent because of the ease of implementation on new or existing asphalt or Portland cement concrete pavements and shoulders. Milled rumble strips are generally installed with a longitudinal width of 7.1 inches (180 mm) and a transverse width of 15.8 inches (400 mm). Tires that pass over milled rumble strips drop roughly 0.5 inches (13 mm) (*2*, *7*).

Rolled rumble strips are generally rounded or V-shaped grooves that have been pressed into hot asphalt pavements when a newly constructed or reconstructed surface coarse is compacted. The grooves are generally 1.3 inches (32 mm) deep and 1.6 inches (40 mm) wide.

The rolled rumble strips are generally constructed using a roller with steel pipes welded to drums (*2*, *7*).

Formed rumble strips resemble the rolled rumble strips. The dimensions are the same, 1.3 inches (32 mm) deep and 1.6 inches (40 mm) wide. Formed rumble strips are either rounded or V-shaped grooves that are pressed into hot asphalt pavements and shoulders during compaction of the constructed or reconstructed surface coarse. The strips are formed by a roller with steel pipes welded to drums, which leave depressions in the hot pavement as they pass over (*2*, *7*).

Raised rumble strips are 2.0 to 12.0 inches (50 to 305 mm) wide rounded or rectangular markers that adhere to new or existing pavements. These types of rumble strips are restricted to use in warmer climates where snow removal is of minimal concern (*2*, *7*).

Rumble Strip Materials

Raised rumble strips can be constructed from many materials, although asphalt rumble strips are the most commonly used type of raised rumble strip (*8*). Rumble strips can also be made from rubber, plastic, exposed aggregates, etc. Raised profile markers (RPMs) have also been used to simulate the rumble effect (*6*).

Effectiveness of Rumble Strips

Several measures of effectiveness (MOE) have been used to evaluate rumble strips. Previous studies have examined MOE related to driver behavior (i.e. the cause-effect relationship between driver behavior and the presence of rumble strips). Typical MOEs used in previous studies include:

- Stop compliance

- Deceleration patterns
- Number of crashes
- Reduction in speed

Previous studies have examined reduction in speed as a measure of effectiveness. The concern with using this measure has been in determining if reductions were meaningful. For example, it has been found that even small differences (e.g. 1 mph) in average speeds were statistically significant when sample sizes were large. However, from a practical standpoint a 1 mph difference in average speed would be rather meaningless. Previous researchers found it necessary to identify a speed differential that would be considered meaningful. Based on many years of research and operational experience and input from other traffic and safety operations experts, previous researchers have often chosen a speed differential of 4-mph or greater to be practically significant or meaningful (*9*).

Rumble strips are used in conjunction with the signs and/or markings to direct attention to an upcoming regulatory or advisory speed limit (*8*). A more readily measured MOE used to evaluate the driver behavior to rumble strips is the change in speed between measurement locations. The change in speed parameter may indicate if drivers adhere to warning signs more often and apply safe approach speeds to intersections after the advent of rumble strips.

Effect of Rumble Strips on Traffic Accident Experience

Studies conducted by various highway agencies have shown that rumble strips can be effective in reducing crashes. The available studies concerning rumble strips include rumble strips placed on stop-controlled approaches to T-intersections and four-way intersections with stop-control on two approaches. All of the accident studies utilized a before-and-after study design.

Study Results

Results from the studies showed that there is a wide range in accident reduction effectiveness. The accident reduction effectiveness ranges from 14 percent to 100 percent, for a variety of safety measures of effectiveness. The measures used in the studies included: total crashes, ran stop-sign crashes, fatal crashes, injury crashes, total accident rates, related accident rates, and right angle crashes. A summary of the studies and their descriptions are shown in Table 2. However, only two of the studies summarized in Table 2 reported a statistically significant (95 percent confidence level) accident reduction from rumble strip installation as indicated by bold face type. The other studies either did not report statistical significance or that the percent reductions were not significant (*8*).

Caveats of Previous Studies

Although the studies reported large reductions in accident effectiveness measures, the studies contained caveats that make drawing conclusions difficult. Six of the ten studies from Table 2 did not report conclusions about the statistical significance of the study results. Of the remaining studies, few incorporated control sites to compare to test sites. Only two of the studies determined traffic volumes in the before and after cases. Several of the studies assumed that the traffic volumes in the before and after study periods were similar, but did not document the assertion. Also, no discussion was present in the literature as to why the sites were selected. No details on the accident history of the sites were presented which could lead to bias in some of the results. If a site had a short term accident history in the before periods, a lower accident experience would be expected in the after study period (*8*).

Table 2. Accident Reduction Effects of Rumble Strips

Study and Date	Location	No. Sites	Site Type	MOE	Percent Change In MOE
Kermit & Hein (1962)	CA	4	Intersection Approaches	Total Crashes	- 59 to -100
Kermit (1968)	CA	1	Intersection Approaches	Ran Stop-sign Crashes	-50
Owens (1967)	MN	2	Intersection Approaches	Total Crashes	-50
Illinois (1970)	IL	5	Intersection Approaches	Total Crashes Ran Stop-sign Crashes	+5 -50
TRRL (1977)	United Kingdom	10	Intersection Approaches Roundabouts Horizontal Curves Small towns	Total Crashes **Related Crashes**	-39 **-50**
Virginia (1981)	VA	9	Intersection Approaches	Total Crashes Fatal Crashes Injury Crashes PDO Crashes Total Accident Rates Related Accident Rates	-37 -93 -37 -25 -44 -89
Carstens (1982)	IA	21	Intersection Approaches	**Total Crashes** Ran Stop-sign Crashes	**-51** -38
Zaidel (1986)	Israel	1	Intersection Approaches	Right-angle crashes	-50 to -67
Moore (1987)	LA	24	Intersection Approaches	Total Crashes Fatal and Injury Crashes Day Crashes Night Crashes	-29 -14 -14 -50
Penn DOT (1991)	PA	8	Intersection Approaches	Total Crashes Ran Stop-sign Crashes	-40 -59

Source: Harwood, 1993 (*8*)

Despite the noted caveats in the accident evaluations, the study results in the literature indicated that rumble strips can reduce traffic crashes at approaches to intersections. The literature was unable to quantify the expected accident reduction effectiveness; however, it did suggest that rumble strips may be effective in reducing accident types that are susceptible to correction by over 50 percent. Also, literature sources suggested that rumble strip installation be considered at locations where rear-end crashes and ran-stop-sign crashes involving an apparent lack of driver attention is present (*8*).

Effect of Rumble Strips on Driver Compliance

Rumble strips have been evaluated as to the effectives of inducing compliance with traffic control devices. The location studies included stop-controlled intersections at T- and four-way intersections. The criteria studied were if drivers made a full stop, made a partial (rolling) stop, or did not stop. The results indicated that drivers made significantly more full stops in the post-treatment period than in the pre-treatment period. The results of the five studies involving stop-sign compliance produced statistically significant improvement and are shown in Table 3 (*8*).

Table 3. Study Result of Stop-Sign Compliance

Study Location	Percentage of Full Stop		Percentage Change
	Pre-Treatment	Post-Treatment	
California	46%	76%	30%
Minnesota	37%	63%	26%
Illinois	91%	95%	4%
Iowa	66%	77%	11%
Israel	91%	95%	4%

Effect of Rumble Strips on Vehicle Speeds

Six studies involving transverse rumble strips were examined. All six used speed reduction as the MOE. The objective of those studies was to determine if transverse rumble strips had an effect on vehicle speed on approaches to intersections, roundabouts, villages, and other roadway junctions. All the studies utilized a before-and-after study design.

Overall, the previous studies indicated that transverse rumble strips result in a small reduction in vehicle speeds. However, reduction in vehicle speeds varied between studies; and speed variance on the junction (e.g. intersections, roundabouts, and villages) approaches increased. This section outlines the study methodology and results from the available studies involving vehicle speeds and transverse rumble strips.

Contra Costa County, California Study

Kermit and Hein (*10*) studied the effects of rumble strips installed at four locations. The locations were at the end of a controlled-access expressway that ended at a T-intersection, an urban T-intersection, a Y-intersection of a county road and a former state highway, and another county road with a four-way intersection. The “rumble strips” used in this study were a series of 25 foot long areas of rough textured aggregate placed on the appropriate lanes at 50 to 100 foot intervals.

The goal of the study was to determine if drivers began to slow down farther from the intersection after treatment of the rumble areas. The speeds at three locations were measured. The three locations were 1000 feet upstream of the intersection, 450 feet upstream of the intersection, and at the subject intersection. The 85th percentile speeds were reported as well as the deceleration rates between points. The results of the study are presented in Table 4 (*10*).

Results of the study showed that despite the increase in approach speed, a significant reduction in vehicle speed occurred after the first three rumble strips were crossed. Deceleration rates were also reported between the points where speed measurements were made. Before the rumble strips were installed, most of the deceleration occurred near the intersection, as shown by the 3.46 ft/sec^2 deceleration rate for the last 450 feet of road. After the rumble strips were installed, deceleration took place over a greater distance and was more gradual. Deceleration rates decreased to 2.70 feet/sec^2 in the last 450 feet of road.

Table 4. Study Results from Contra Costa County Study

Speed Measurement Location	**Measurement**	**Before Rumble Strip Installation**	**After Rumble Strip Installation**
1000 feet Upstream	85th Percentile Speed (mph)	44.0	46.0
	Deceleration Rate (ft/sec/sec)	0.57	1.43
450 feet Upstream	85th Percentile Speed (mph)	41.0	37.0
	Deceleration Rate (ft/sec/sec)	3.46	2.70
Near the Intersection	85th Percentile Speed (mph)	14.8	15.1

Source: Kermit and Hein, 1962 (*10*)

The data collection for the before-and-after study design in Contra Costa County was performed one week before treatment and two months after treatment. The study summarizes the results; however, fails to report statistical analysis procedures or if reductions were statistically significant. Traffic volumes were also not reported for the study.

Transport and Road Research Laboratory (TRRL) Study

The TRRL (*11*) studied the effects of rumble strips on vehicle speeds at ten sites. The rumble strips were installed upstream of such junctions as roundabouts, four-way intersections, T-intersections, horizontal curves, and small towns. The speeds were measured upstream from the junction at 1312 feet (400 meters) and 164 feet (50 meters). The mean speeds were identified at these locations.

The speed measurement analysis between 1312 foot station and the 164 foot station found the effects of the rumble areas were inconsistent. In some instances, the rumble areas caused drivers to use larger deceleration between the two stations, and at other sites a lesser deceleration rate was used. The data for all sites combined only showed a small decrease in vehicle speed between the two stations. The statistical validity of these results was not included in the report (*11*).

Israeli Study

Zaidel et al (*12*) evaluated the use of rumble strips at one stop-controlled intersection approach in Israel. However, no measure was performed to support this claim. Thirty-eight rumble strips were placed over a distance of 883 feet (269 meters) upstream of the intersection. The speeds were measured at eight locations along the approach to the intersection. The mean speeds and standard deviation were reported at each data collection station. The mean speeds were reported to be reduced by 5 to 50 percent after the installation of the rumble strips. The sample data collected from the study is shown in Table 5.

Zaidel et al believed that drivers generally began to slow down sooner and that some drivers slowed down more. Although no direct measurement was used to support this claim. This behavior increases vehicle deceleration rates early in the braking maneuver, but decreases vehicle deceleration rates close to the intersection. The increased deceleration in the earlier part of the braking maneuver was reported to account for the increase in speed variance.

Table 5. Study Results of Israeli Study

Time Period/Measurement	Distance from Intersection (feet)							
	1380	1080	935	835	540	345	150	50
Before Rumble Strips								
Mean Speed (mph)	45.4	44.7	43.9	43.5	40.1	35.7	25.8	15.3
Standard Deviation (mph)	7.3	7.3	7.2	7.2	6.8	6.0	5.0	3.2
After Rumble Strips								
Mean Speed (mph)	43.1	39.1	33.5	27.0	20.4	19.6	15.2	9.1
Standard Deviation (mph)	7.1	7.9	9.5	11.5	8.7	7.2	5.1	3.8
Percent Reduction in mean speed	5.1	12.5	23.7	37.9	49.1	45.0	41.1	40.5
Percent Increase in speed variance	-1.7	9.4	32.8	59.5	28.4	20.8	3.8	21.6

Source: Zaidel, 1986 (*12*)

Minnesota Study

The Minnesota Department of Highways studied the effect of rumble strips at approaches to seven stop-controlled intersections. The rumble strip areas considered consisted of coarse aggregate with a minimum size stone of ¾ inch mixed with and cationic asphalt emulsion. The rumble areas were laid out in differing patterns. Four rumble areas were 25 feet long and spaced 100 feet apart, six rumble areas were 25 feet long and 50 feet apart, and one rumble area was fifty feet long and placed at the intersection (*13*).

Speed data were collected at each site at the following upstream distances: 300 feet, 500 feet, 1000 feet, 1500 feet, and a control station. The amount of speed data collected ranged from

30 passenger vehicles to 101 passenger vehicles. The results are shown in Table 6. An overall reduction in approach speed was found to be statistically significant (95 percent confidence level) at each point of observance. The amount of dispersion; however, increased in some cases after the installation of rumble areas. It was speculated that some drivers slowed down considerably more than others (*13*).

Table 6. Study Results from Minnesota Study

Distance from Intersection (ft)	Average Speed (mph)			Significant?
	Before Installation	After Installation	Difference	
300	31.01	27.99	3.02	Yes
500	36.57	33.59	2.98	Yes
1000	43.70	41.39	2.31	Yes
1500	47.26	44.47	2.79	Yes
Control	52.09	52.58	-0.49	No

*Source: Owens, 1967 (*13*)*

University of Toledo Study

A study performed at the University of Toledo evaluated the effect of rumble strips in reducing speeds on approaches to stop-controlled intersections. Seven approaches were used in the before-and-after study design. The mean speeds were determined at a location 300 feet downstream of the first rumble strip. Of the seven sites, five locations produced statistically significant (95 percent confidence level) reductions in speed. The results of the study are presented in Table 7 (*8*).

Table 7. Study Results from the University of Toledo Study

Location of Rumble Strips	Mean Speed (mph)			Significant?
	Before	After	Reduction	
SR 281, East of SR 108	41.9	35.9	6.0	Yes
SR 281, West of SR 108	47.9	39.9	8.0	Yes
SR 576, North of SR 34	43.9	45.9	-2.0	No
SR 576, South of SR 34	45.9	41.9	4.0	Yes
US 20, East of US 127	51.9	49.9	2.0	Yes
US 20, West of US 127	53.9	51.9	2.0	No
US 20, West of US 108	53.9	49.9	4.0	Yes

Source: Harwood, 1993 (*8*)

University of Minnesota Simulation Study

A driving simulation study performed by the Human Factors Research Laboratory at the University of Minnesota evaluated the alerting affect of rumble strips on the stopping performance of alert drivers. The rumble strips were simulated at stop-controlled intersections. The number of rumble strips varied from no rumble strips to three rumble strips. Two types of rumble strips, wheel track and full coverage rumble strips, were compared. The participants were instructed to drive along a simulated two-lane highway “as they normally would,” and the stopping behavior of the drivers was recorded at each of the stop-controlled intersections. Instances of cross traffic were and were not simulated (*14*).

The virtual driving environment was generated with an SGI Onyx computer. Engine and road noise was generated by the Onyx and fed through a receiver to loudspeakers inside the car. When the front wheels of the car encountered the virtual rumble strips, an auditory cue was sent through the audio system and the steering wheel vibrated. The speed of the car at the time the wheels touched the rumble strip dictated the frequency of the vibration in the driving wheel (*14*).

The results of this study indicated the rumble strips had no effect on the location at which the drivers began to decelerate (took their foot off the accelerator) or on the distance away from the intersection at which they actually stopped. The study did indicate; however, that the presence of rumble strips altered the point at which the driver began to brake. The drivers tended to brake more and earlier when the rumble strips were present as opposed to no rumble strips. The drivers tended to slow down at the same time and stopped at the same time; however, there was more use of the brake earlier in the presence of rumble strips. The results also revealed that drivers used the brake more when full coverage rumble strips are in place than they do when wheel track rumble strips are installed (*14*).

Summary

The previous studies concerning applications of rumble strips on approaches to stop-controlled intersections reported statistically significant reductions in mean and/or 85th percentile speeds. The majority of the speed reductions reported was in the range of 1 to 4 miles per hour (mph). The results were reported to be statistically significant; however, these reductions in approach speed may not be meaningfully different.

Previous studies drew conclusions by comparing different types of sites and in some cases from only one study location. Some of the sites compared were approaches to towns, roundabouts, urban intersections, rural intersections, and horizontal curves. Due to the research being at single sites or multiple types of sites, and the inevitable site-specific characteristics of each location, it is impossible to extrapolate these results to be indicative of transverse rumble strips.

The previous studies reported that there was an increase in speed variation, which may or may not be due to a random variation in vehicle speeds in the before and after conditions. The Contra Costa County, California and the Minnesota study used control locations to account for variations in speeds; however, the TRRL, Israeli, and University of Toledo studies did not report the use a control location. A slight decrease in speed may be the result of factors other than the rumble strips and thus, a control speed trap should be used to observe this variation.

Differences in deceleration rates before and after the installation of rumble strips identify if drivers adhere to warning signs more often and apply safe approach speeds to intersections after the advent of rumble strips. In reviewing the literature, only one previous study used the MOE of deceleration to evaluate the effectiveness of rumble strips as a traffic control device (*10*). This study; however, did not report the statistical measures used to evaluate the data or the number of speeds recorded. Field studies, at sites with similar characteristics and with the proper amount of speed measurements, are needed in evaluating the effectiveness of rumble strips in warning drivers of an upcoming decision point.

The primary objective of safety expenditures on roadways is to improve the safety along the roadway through reductions in accidents and accident severity. The ultimate measure of effectiveness would be an evaluation or analysis of changes in accident experience. Accident-based evaluations are difficult because low accident frequencies require long periods of time to acquire the needed sample sizes. Other complications arise due to bias, inaccuracy, and confounding effects within the accident data base (*15*).

To offset the shortcomings of using accident experience as the sole criterion, non-accident measures are used to provide an intermediate measure. Non-accident measures are considered intermediate because they are meant to be a supplement to and not a substitute for accident-based measures. Some operational non-accident measures that have been identified as surrogates for safety include:

- Spot speeds
- Speed profiles
- Delay
- Travel time
- Percentage of vehicles stopping
- Deceleration profile
- Speed changes
- Queue length

While the proper use of surrogate crash measures can provide intermediate indications as to the effectiveness of implemented safety projects, their direct relationship to crash occurrence has yet to be established (*16*). Surrogate crash measures are recommended for use as an operational review tool and to improve traffic flow and operations during project planning stages. However, it is recommended that acceptance of non-accident measures as surrogate accident measures should be used with caution until such time as quantitative relationships can be established (*15*). The measures of evaluation used in this research project included speed change and spot speeds.

STUDY DESIGN

This section documents the procedures used to collect and analyze traffic data at the selected rural stop-controlled intersections. The first section of this section describes the scope of the study, including a study hypothesis and the general criteria developed for the selection of study sites. The data collection procedures employed to obtain vehicle speed data at each of the study locations are described in the second section. The traffic and speed data was collected with PEEK traffic counters. Setup procedures and deployment configurations of this equipment are described in this section. The installation procedures and materials used are described in the fourth section. The task of reducing the traffic data and the data analysis of the traffic data is described in the final section.

Scope

Previous studies have examined the affects of rumble strips on approaches to various roadway junctions. The scope of this research was focused on rural, stop-controlled intersections. A review of previous research revealed that the application of rumble strips to similar intersections produced a statistically significant reduction in mean and 85th percentile approach speeds. However, the actual reductions were on the magnitude of 1 – 4 miles per hour, which is not practically significant (*9*). The goal of this research is not only to determine if the rumble strips help reduce the approach speed of vehicles, but rather to determine if the rumble strips are effective in warning drivers of an upcoming intersection. The change in drivers approach speed will be analyzed to determine if drivers used a more gradual change in approach speed while approaching the intersection in the post-treatment case as opposed to the pre-treatment case.

Reaction to the rumble strips as an advanced warning treatment would be reflected in the deceleration rates, or change of speed on the approach to the intersection. Larger (but still comfortable) changes in speed, located further upstream, would be an indication of an improvement and that the rumble strips were effective at warning drivers of an approaching intersection. Smaller changes in speed, located further downstream and nearer to the intersection, would indicate an improvement. An overall indication of improvement would be a more gradual and uniform deceleration profile.

Initial reaction to the rumble strips would be reflected in the speeds of vehicles approaching the intersection. As in previous studies, approach speeds were collected and analyzed to determine if drivers utilized a lower approach speed to the intersection. Lower speeds on the approach to the intersection would indicate an improvement.

Previous studies did not differentiate the affect that rumble strips had on unfamiliar or unsuspecting drivers. Another goal of this study was to determine if the rumble strips were more effective on drivers during the night and/or weekend time periods. Drivers may be more unsuspecting of approaching conditions due to unfamiliarity with the roadway, drowsiness, or other inhibiting factors. During these times, rumble strips may be more effective than in day or weekday time periods when there are greater percentages of familiar or suspecting drivers on the roadway.

Study Design

The basic study approach for the research performed here was to collect and to evaluate traffic operations data at given field sites. The experiments were carried out at each site in typical before-and-after fashion. The before treatment case involved collecting traffic operations data while no rumble strips were in place and a Stop-Ahead warning sign was in place. The after treatment case involved collecting data after the rumble strips had been installed. The *ITE Manual of Transportation Engineering Studies* (*17*) recommends before-and-after experiments both for statistical and practical reasons, including:

- Elimination of site-to-site variation;
- Fewer sites are necessary to draw useful conclusions; and
- Results make intuitive sense and are easily understood by engineers and non-technical readers alike.

Site Selection

To satisfy the evaluation scenarios, nine sites were selected and used for field evaluations. These sites consisted of rural stop-controlled intersections, where eight sites had two-way stops and one site was a T-intersection. The locations where data were collected are listed in Table 8.

A number of criteria were used for the selection of sites. The main criterion for site selection was evidence of a hazardous condition that could potentially be remedied through the use of rumble strips. The main criteria for hazardous site identification were reports from TxDOT officials of intersections that had known problems, such as higher-than-state-average accident rates, locations of severe crashes, and/or intersections that have received public complaint. TxDOT also selected these sites based on engineering judgment. These sites had had previous traffic control devices in place, such as warning signs, but the accident rates and the number of complaints had not subsided as a result of these devices. Because selection of sites was based on the perceived availability of sites in the area and the most efficient way to use resources available for the project, the process was not random (*18*). Other selection criteria included:

- Long uninterrupted tangent section on approach
- No evidence of police over-enforcement in the area
- Close proximity to TTI headquarters
- Feasibility and ease of data collection

Table 8. Data Collection Sites

Location	Approach Road	Intersecting Road	Data Collection Direction(s)
Millican	FM 2154	FM 159	Northbound/Southbound
Hearne	FM 2549	FM 359	Northbound/Southbound
Snook	FM 50	FM 60	Northbound/Southbound
Bosque County	FM 3118	SH 22	Northbound
Colorado City	FM 208	SH 20	Northbound/Southbound

The sites selected contained similar features and controls. The features and controls were kept constant so that the speed at which drivers would traverse the sites would not be subject to external factors. The general site selection controls and criteria used in this study are presented in Table 9.

Table 9. Site Selection Controls and Criteria

Control	Criteria
Area Type	Rural
Terrain	No Restriction
Design Classification	Two-Lane on Study Approach
Intersection Control	Stop Ahead on Study Approach
Posted Speed Limit	55 – 70 miles/hour
Traffic Volumes	Low (Less than 3000 vehicles/day)

Data Collection

For the purpose of this research, a before-and-after study design was employed to evaluate the effects of rumble strips. Before-and-after study designs are commonly used in transportation studies to evaluate the impact of transport services and policy on driver reaction, behavior, and safety. In studies of this type, the phenomenon of interest is measured before and after a change in services or policy to assess the impact of the change. For this study, the vehicle approach speeds were measured in the before and after condition and the change was the implementation of rumble strips (*19*).

Determination of Sample Size

With study sites selected, the next task was to collect the geometric data of the sites. The geometric layouts of each site, including final placement of rumble strips, are shown in Appendix A. Next, approach speeds were needed prior to installation of rumble strips. The minimum number of individual speed observations required depends on the variation in speeds and the accuracy of the speed measurements. Equation 1 (*20*) was used to estimate the number of speed observations needed to compute mean and 85th percentile speeds at each site:

$$n = \left(\frac{ts}{\varepsilon}\right)^2 \qquad (1)$$

where

n	=	required sample size;
s	=	standard deviation;
ε	=	user-specified allowable error; and
t	=	coefficient of the standard error of the mean that represents user specified probability level.

The value for standard deviation was estimated from previous studies (*8*, *10 – 13*). The estimation was computed prior to the field studies. Levels of statistical precision (t, ε) were user-specified. For the purposes of this thesis, a 95 percent confidence interval (t = 1.96), and a ε value of 1 mile/hour was chosen. The values for standard deviation from previous studies ranged from 5 to 8 mph. Thus, the value for estimated sample size varied from 125 individual vehicle speeds to 250 individual vehicle speeds. A minimum of 250 individual vehicle speeds was determined to be the required sample size at each study location.

Data Collection Equipment

Tracking of individual vehicle speeds through a given site was accomplished by the use of a series of portable automated vehicle classifiers. Portable automated vehicle classifiers are a commonly used vehicle measurement device by transportation agencies nationwide and allow for a large sample size to be collected. These devices are placed on the roadside and connected to a pair of sensors (pneumatic tubes in this case) that are affixed to the pavement surface. The device recorded information for each axle that traverses over the sensors. The device was then able to compute desired information about each vehicle.

Speeds of individual vehicles were tracked by the automated vehicle classifiers by placing a number of devices in succession at specific locations throughout the study site. The classifiers and pneumatic hoses were placed at three locations: a control location, at the warning sign, and near the intersection. Time clocks were synchronized for all devices. Individual vehicles were later tracked during the data reduction phase by tracking time stamps and classifications among successive counters.

Another option for the data collection equipment was Light Detecting and Ranging (LIDAR) devices. LIDAR devices measure speed and range of a moving object by sending out hundreds of invisible infrared laser light pulses per second. The laser beams are reflected off the objected and directed back to the device. Internal algorithms are then used to derive the speed of the moving object from a successive number of range calculations.

Due to the low traffic volume that was expected at each of the study locations; the automated vehicle classifiers were used. The classifiers were able to minimize the amount of person-hours required at the sites to collect a sufficient sample size and also were durable enough to remain in the field during the study periods. A LIDAR device was used to ensure that the set up of the speed tubes was done correctly and that accurate speeds were recorded by the speed tubes.

The accuracy of speed tubes as well as other portable speed measurement devices (including LIDAR) has been proven to be accurate in determining the speed of traveling vehicles. In a study by the Texas Transportation Institute (TTI), the accuracy and precision of five portable speed measurement systems were evaluated in a controlled field evaluation. The researchers found that there was little difference (less than 1.5 mph difference) in the speed measurement systems. It was also stated that all devices were accurate and that speed measurement equipment should be selected to suit the characteristics of a given data collection situation (*21*). A comparison of the advantages and disadvantages of automated vehicle classifiers versus LIDAR is shown in Table 10 (*21*).

Table 10. Advantages and Disadvantages of LIDAR versus Automated Vehicle Classifiers.

	LIDAR	Automated Vehicle Classifiers
Advantages	• Accurate, precise, and reliable • Small and lightweight • Simple to use and requires very little training • Greater level of worker safety • Data collector has supervision over measurements, improving reliability • Vehicles may easily be tracked through a site • Very little data reduction	• Accurate, precise, but somewhat less reliable • Large sample sizes are obtained with less effort • Few person-hours are necessary for data collection • Speeds are measured at a precise location for each vehicle • Vehicle/traffic characteristics other than speed may be measured
Disadvantages	• Cosine bias if equipment is offset from vehicle path, such as at curves • Many person-hours needed for large sample size • Difficult to measure speed at a precise location on the roadway • Potential data bias if data collector is visible to drivers • Potential data bias if high percentage of radar/laser detector use by the motoring public	• Equipment failures occasionally occur • Lower level of worker safety • Equipment may be challenging to use • Traffic control required to place/remove equipment • Equipment vandalism • Anomalous vehicles are difficult to determine due to lack of supervision • Potential data bias if sensors are visible to drivers

Peek ADR 2000 traffic counters were used, operating in Raw Data mode. All data was collected using the counters and downloaded into a format that was manageable by Microsoft Excel. The geometric data (lane widths and distances) were measured using a measuring wheel.

Placement of Counters

As previously mentioned, there were three locations at which the traffic data counters were placed. The control location was placed on the approach at a point where the driver could not see the intersection or warning (Stop-Ahead) sign. The control location was used to compare changes in vehicle speeds in the before and after conditions. The second counter, referred to as the warning sign location, was placed at the Stop-Ahead sign. The final counter, referred to as the intersection location, was placed 450 to 500 feet upstream of the warning sign and 100 to 700 feet from the intersection (see Figure 2).

These locations were chosen so as to evaluate the driver reaction to the rumble strips. The MOE used to evaluate the driver reaction is the change in speed between speed trap locations. Change in speed approaching the stop sign is an appropriate MOE as it is desirable to reduce erratic vehicular decelerations and invoke a more comfortable deceleration profile (*15*, *22*). An indication of improvement would be illustrated by higher changes in speed (but still comfortable) further upstream and lower changes in speed further downstream.

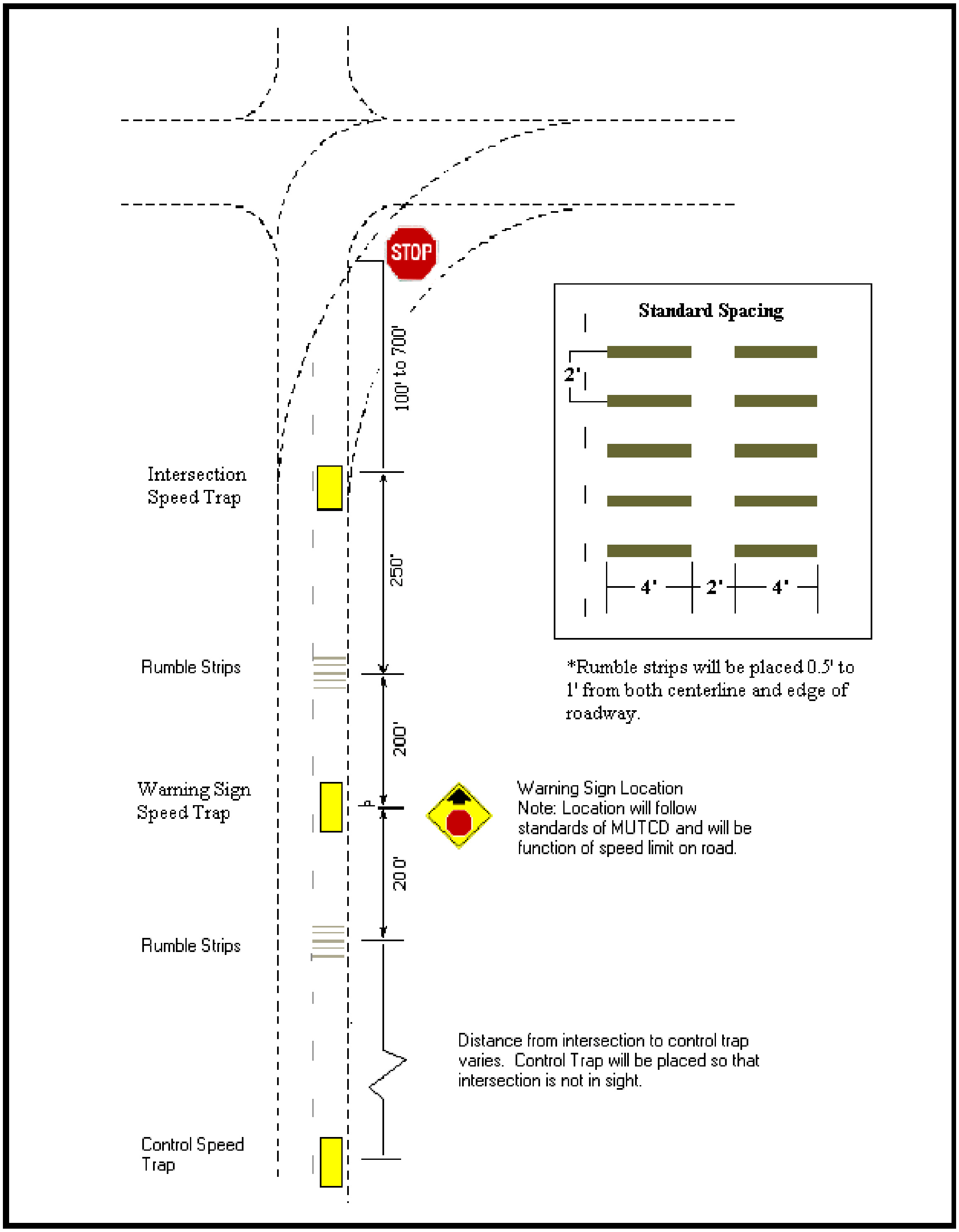

Figure 2. Standard Site Layout

The traffic counters were installed as shown in Figure 2. The Two Tube Class and Speed mode was used to collect the data. After configuring the data files as specified in the *Peek ADR 2000 Manual* (*23*), the pneumatic hoses were placed within the traveled way. The pneumatic hoses were placed 16 feet apart, which was assumed by the traffic counter. A typical setup of the traffic counter and pneumatic hoses is shown in Figure 3.

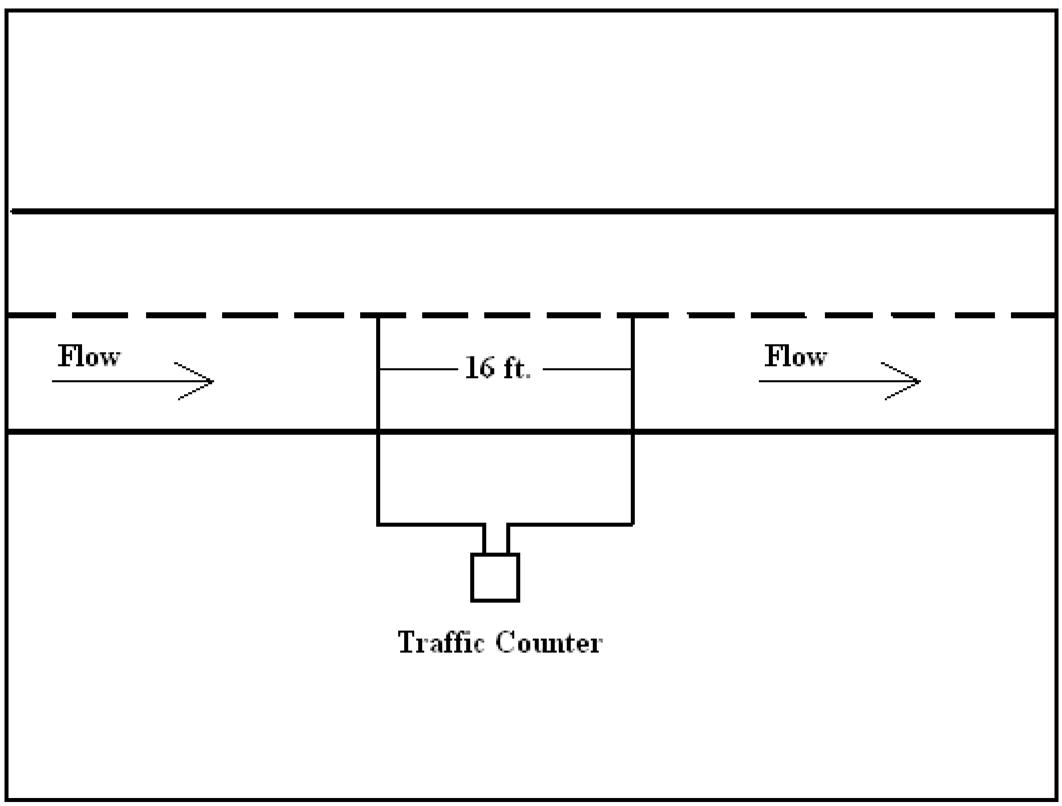

Figure 3. Typical Traffic Counter and Pneumatic Hose Configuration

Duration of Study

A typical data collection period proceeded in the following manner: the field crew arrived at the site at approximately 10:00 A.M. to setup and begin observations by 11:00 A.M. A drive-through of the site was performed to locate the subject intersection, the warning sign, and a location for the control speed trap. The location of the control speed trap depended upon the requirement that drivers could see neither intersection nor the warning sign. Once the location of the control speed trap was located, the traffic counters and pneumatic hoses were placed as shown in Figure 3.

Data were collected during both weekday and weekend periods. The data were analyzed to determine if there was any discernable change in the effectiveness associated with the rumble strips on weekend drivers as opposed to weekday drivers. Weekday periods were defined as Monday through Friday and weekend periods were defined as Saturday through Sunday. Data was also collected during daytime and nighttime periods to determine if the effectiveness of the rumble strips changed throughout the day. The daytime and nighttime periods were defined from the sunrise and sunset times reported in *The Old Farmer's Almanac* (*24*). Generally, daytime was defined as sunrise to sunset and nighttime was defined as sunset to sunrise. Periods in which sunlight was directly in driver's eye was removed; however, this was minimal due to sites running in the North and South directions. The dates of the data collection periods for each site are shown in Table 11.

Table 11. Data Collection Periods

Location	Before Data Collection		After Data Collection	
	Starting Date	Ending Date	Starting Date	Ending Date
Millican	8/15/2003	8/18/2003	11/18/2003	11/20/2003
Hearne	8/22/2003	8/25/2003	2/20/2004	2/23/2004
Snook	9/5/2003	9/10/2003	12/12/2003	12/16/2003
Bosque County	9/23/2003	9/24/2003	11/21/2003	11/24/2003
Colorado City	5/12/2003	5/14/2003	6/25/2003	6/26/2003

Installation of Rumble Strips

After collecting sufficient before speed data, the rumble strips were installed. In all of the test locations, a common brand of rumble strips was used. The Rumbler rumble strip from Swarco Industries, Incorporated, was used exclusively at all test locations. Swarco Industries produces three types of strips: reflective yellow, reflective white and black (*25*). For the purpose of this study, the reflective white rumble strip was used.

Rumble Strip Characteristics

Each Rumbler rumble strip consists of a four foot-wide piece of white rubber with three raised ridges. The three ridges acted to provide the rumble effect and also to provide the audible warning. The reflective white rumble strip, which was used in this study, has a potential to have more warning capabilities because of the added visual effect (*25*). A cross-sectional view of the Rumbler rumble strip is shown in Figure 4 (*6*).

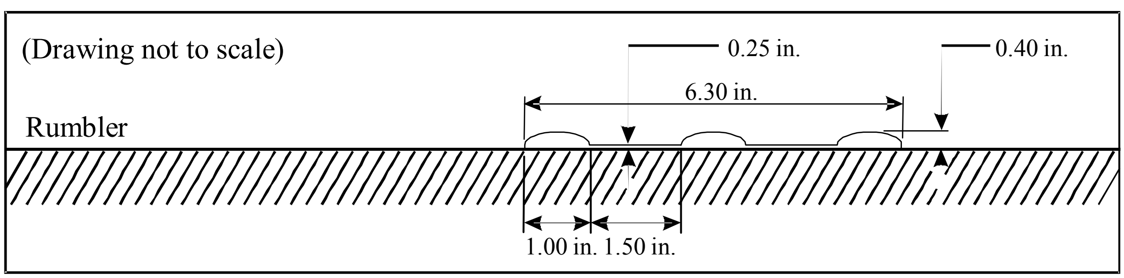

Figure 4. Cross Section of Rumbler

Deployment Configuration

Two sets of Rumbler rumble strips were installed on the approach to the stop-controlled intersection. The sets were spaced 500 feet apart, with the downstream set being 250 feet downstream of the warning sign and the upstream set being 250 feet upstream of the warning sign. Each set contained ten rumble strips, spaced two feet center to center. These strips are four feet long, which leaves space for a gap in the traveled way for motorcycles. A minimum of a two foot gap was included in the center of the lane and a six inch space was left between the edge of the strips and both the edge-line and centerline. A diagram of a typical rumble strip deployment for a set of rumble strips is shown in Figure 5.

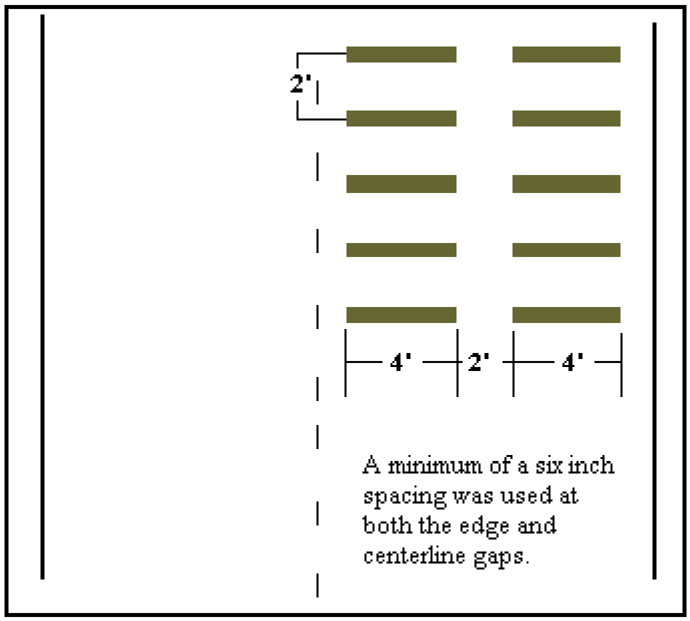

Figure 5. Standard Rumble Strip Layout

Installation of Rumble Strips

For proper installation, the pavement had to be clean, dry, and warmer than 50° F. The pavement was dry, and its temperature just before the installations was above 70° F in all cases. Once the pavement was clean, it was marked using a marking line and road chalk for proper placement and layout of the rumble strips. Adhesive, which was supplied by Swarco, was then applied to the pavement with a paint roller and allowed to set for approximately three minutes. After allowing the adhesive to set, seal tape was installed on the areas where the rumble strips would be located. An additional coat of adhesive was applied to the seal tape and allowed three minutes to set. The strip was placed on the seal tape and tampered manually and allowed about ten minutes to adhere to the surface before traffic was allowed to traverse over them. A typical installation is shown in Figures 6 and 7.

Figure 6. Installation of Rumble Strips

Figure 7. Upstream View of Installed Rumble Strips

Rumble Strip Installation Cost

A factor that must be considered in the decision to implement the rumble strips was the cost associated with the installation process. The following section outline the costs associated with installing the rumble strips. The overall cost was estimated from two main areas: the initial equipment cost, including materials, and the cost for the time required to install the rumble strips.

The installation procedures of the rumble strips were outlined in a previous section. The material costs were estimated from the installation costs experienced during the duration of this research project. The materials needed to install the rumble strips used in this research project included:

- Adhesive (5 gallons);
- Seal tape (20 strips or 80 feet);
- P-K Nails (approximately 60 nails); and
- Rumble strips (20 strips or 80 feet).

From prior installation experience, it was assumed that a minimum of four workers would be required for the installation of the rumble strips. Two workers were needed for the actual installation and two workers were needed for traffic control. The value of $20 per person-hour was used in the analysis. A wage rate of $20 per hour was conservative for most maintenance personnel. For example, TxDOT maintenance personnel generally earn $8.50 - $12.50 per hour plus benefits (*26*). An installation time of 2 hours was assumed for the analysis.

The cost of materials and labor were estimated to be $250 and $250, respectively. The total cost associated with the installation of the rumble strips was estimated to be $500. A cost estimated for the materials and labor is shown in Table 12.

Table 12. Estimated Cost of Rumble Strip Installation

Item	Unit	Cost per Unit	Total Cost
Adhesive	5 Gallons	LUMP	$150.00
Seal Tape	20 Strips (80 Feet)	LUMP	$40.00
P-K Nails	1 Box (100 nails per box)	LUMP	$20.00
Rumble Strips	20 Strips (80 Feet)	LUMP	$410.00
Maintenance Workers	4 Workers at 2 hours each	$20 per person-hour	$160.00
		Total Estimated Cost	**$780.00**

The estimated cost raised rumble strips was $500 - $1000 dollars (*7*). The cost of other types of rumble strips, which include milled, rolled, and formed, could not be found in pertinent literature. However, all types are listed as low-cost (less than $2000) safety treatments.

The rumble strip installations occurred in May and September of 2003. The raised rumble strips, which were used in this case, stayed in place for the duration of the study (6 – 8 months). Although there were observations of cracking and damage to the rumble strips, they were in place as of April 2004.

DATA ANALYSIS AND RESULTS

This section documents the field data collection and analytical procedures for the experiments performed in this project, including data screening, data formatting, and statistical analysis. The before data were collected a month prior to installing the rumble strips and the after data were generally collected a minimum of a month after the installation of rumble strips. Refer to Table 11 for the exact dates of data collection for each site. This section also presents the results of the analyses. The findings of the statistical analyses allowed for conjectures to be made as to the practicality of the findings and relative impacts on safety.

Data Reduction

Data collection files from the traffic counters were downloaded and imported into a Microsoft Excel format for the data reduction process. The number of initial observations ranged from 980 vehicles to 5400 vehicles. The following items were collected from the counters: date, time of day, number of vehicles per hour, vehicle classification, and vehicle speed. Individual vehicle speeds and classifications were then analyzed to ensure that only free-flowing, passenger cars were included in the database. Any non-passenger car and any vehicle less than fifteen-seconds after the previous vehicle were deleted from the data file. The percentage of passenger vehicles at each site ranged from 60 to 70 percent of the data set. The percentage of passenger vehicles that were in platoons was less than 10 percent for all the sites. Free-flow, as suggested by the *Highway Capacity Manual* (HCM), is indicated by a headway greater than or equal to five seconds (*27*). However, the more conservative headway of fifteen seconds was used to ensure no impact from platoons.

Once in spreadsheet format, timestamps were compared at successive counters in an attempt to "track" vehicles through the study approach. The expected travel times were calculated based on speed and distance between the counters and also assuming a uniform deceleration, or in a few cases, acceleration. The expected travel times were used to estimate a time of arrival at each successive counter. By comparing the estimated time of arrival with the timestamp from the counter, the majority of the vehicles could be uniquely identified as they passed each of the three speed collection points. After tracking the vehicles, the speed change between each speed collection point was determined for each vehicle traveling through the site. Some of the vehicles were not able to be tracked through the site; however, the percentage of the site data that could not be tracked was less than five percent for each site.

Data files for each site, which contained only free-flow, passenger cars, were then analyzed. The data file included 50 to 60 percent of the original data set and the number of observations ranged from 500 to 2800. A summary of the data is shown in Appendix B. This summary included the following information for each rumble strip location:

- Number of speed observations
- 85th percentile speeds
- Standard deviation of speeds
- Mean speeds
- Minimum speeds
- Maximum speeds
- Variance of speeds

Data Analysis

Upon completion of the data collection and formatting procedures, the data were analyzed to determine statistically significant correlations between the rumble strips and changes in traffic operational characteristics. To analyze the relationships between the variables, appropriate statistical tests were selected for each evaluation. The following subsections describe the variables and statistical tests employed in the analyses. Due to the site-to-site differences, data from each site were analyzed separately. A graphical analysis was also performed to provide a visual indication of any relationships that might exist between the before and after treatment conditions. All statistical tests were performed at a 95 percent confidence level ($\alpha = 0.05$). The histograms and data analyses were completed using Statistical Package for Social Sciences (SPSS).

Test for Normality

The initial step in the data analysis was to determine if the data were normally distributed. To test for normal distribution in the data set, the change in speed between the control speed trap and the intersection speed trap was plotted in a histogram for each data set. A normal distribution would be indicated if the data had minimal skewness and followed the bell-shaped distribution that is associated with normally distributed data.

Data Analysis Variables

The principal objective of this research project was to assess the effectiveness of rumble strips on driver behavior under various field conditions. Therefore, a detailed experiment was devised for each site based on the geometric characteristics. The following sections list descriptions of the independent, covariate, and dependent variables.

The warning device treatment was the primary independent variable in the data analysis for each site. The null treatment was always the existing sign(s) that were in place. The existing warning treatments were the Stop-Ahead signs (ASTM Type III). The alternative treatments were the placement of rumble strips in addition to the existing warning sign. The null treatment was considered the before case (prior to the rumble strip installation) and the alternative treatment was considered the after case (with the rumble strips installed). Additional independent variables that were included in the analysis were as follows:

- Ambient lighting condition (Day or Night Period);
- Data collection periods (Weekday or Weekend);
- Vehicle type (passenger vehicles with headways greater than 15 seconds); and
- Weather condition (data were only collected under clear/partly cloudy weather conditions).

For the data analyses, the upstream control point speed was used as a covariate. Covariates are random variables that are treated as concomitants or as other influential variables that affect the response (*28*). It is reasonable to assume that the magnitude of drivers' response to signs, geometric conditions, or intersections varied according to the speed at which they generally chose to drive (i.e., their uninhibited free-flow speed) (*29*). For example, drivers who travel faster on tangent sections will likely travel faster through curves. It was assumed that when approaching a stop-controlled intersection, faster drivers will be forced to slow down more than slower drivers.

To provide an explicit measure of uninhibited free-flowing driver behavior, initial spot speed measurements were taken on a tangent section upstream of the project site. Upstream speed measurements served as "control" data for the analysis. Upstream control point speed was included as a covariate in the analysis to account for the impact of individual drivers' uninhibited free-flow speed on speeds at the study site.

The stop-controlled intersection studies utilized similar measures of evaluation. Multiple literature sources have considered speed-related measures (i.e., speeds, decelerations, and speed variance) for vehicles approaching an intersection as appropriate for stop-controlled intersection studies. The traffic operational measures for each of the evaluations performed at stop-controlled intersection that were used as dependent variables were speed changes between data collection points and speeds approaching intersection (warning sign and intersection speeds.

Speed Data Analysis

To examine the effectiveness of the rumble strips in warning drivers of upcoming decision points, the change in speed was compared in the before and after condition. There were three locations at which speed measurements were collected at all sites for both time periods: (1) free flowing (control point), (2) warning sign, and (3) intersection. The change in speed parameter was calculated between the warning sign and intersection speed traps for each approach.

To determine if the transverse rumble strips caused a significant reduction in speed changes, a statistical procedure known as the multiple factor analysis of variance (ANOVA) was used. The multifactor ANOVA allows for testing of differences between mean values of multiple populations as a function of independent variables (i.e. before study or after study; day or night light conditions; and weekday or weekend study periods) and the interactions between the independent variables (*28*). The confidence level that was used was 95 percent. Thus, if the p-value was less than 0.05 (5 percent), then the null hypothesis can be rejected. The null and alternative hypotheses that were tested for analysis were:

- Null Hypothesis (H_0): The changes in speed or approach speeds were not significantly different for the time periods.
- Alternative Hypothesis (H_a): The changes in speed or approach speeds were significantly different for the time periods.

A model was developed for the multifactor ANOVA analyses from the independent and covariate variables that were discussed previously. The first model (see Equation 2) tested before and after conditions based on light conditions. The specific comparisons made using Equation 2 were Day (Before) versus Day (After) and Night (Before) versus Night (After). The second model (see Equation 3) tested before and after conditions based on data collection days. The specific comparisons made using Equation 3 were Weekday (Before) versus Weekday (After) and Weekend (Before) versus Weekend (After). These tests were also done to determine if the rumble strips were more effective during times that drivers might be less attentive or less familiar with the roadway. The following equations were used for the comparisons of all MOEs:

$$\begin{aligned} \text{MOE} &= \beta_0 + \beta_1(\text{Study}) + \beta_2(\text{Light}) + \beta_3(\text{Control Speed}) + \\ &\beta_4(\text{Study} \times \text{Light}) + \beta_5(\text{Light} \times \text{Control Speed}) + \\ &\beta_6(\text{Study} \times \text{Control Speed}) + \beta_7(\text{Study} \times \text{Light} \times \text{Control Speed}) \end{aligned} \tag{2}$$

$$\begin{aligned} \text{MOE} &= \beta_0 + \beta_1(\text{Study}) + \beta_2(\text{Period}) + \beta_3(\text{Control Speed}) + \\ &\beta_4(\text{Study} \times \text{Period}) + \beta_5(\text{Period} \times \text{Control Speed}) + \\ &\beta_6(\text{Study} \times \text{Control Speed}) + \beta_7(\text{Study} \times \text{Period} \times \text{Control Speed}) \end{aligned} \tag{3}$$

where

MOE = The measure of evaluation (speed change or approach speed);

Study = Study period condition (before or after study condition);

Light = Ambient light condition (day or night);

Period = Data collection period (weekday or weekend); and

Control Speed = Speed at free flow counter.

The control point speed was entered into the analysis as a covariate. Adding the control point speed as a covariate provides a way to account for vehicles having different speeds prior to the driver viewing the intersection. The models that were used to compare the before and after conditions can be summarized by the following equation (see Equation 4) where the MOE is proportionate to the control speed plus a treatment effect (intercept, α).

$$\text{MOE} = \alpha_i + \beta(\text{Control Speed}) \tag{4}$$

By comparing only one control speed in the ANOVA models, an assumption was made that the relationship (i.e. slope values) for control speed are constant regardless of the control speed. To account for different slopes, two control speeds were chosen to evaluate the models. The control speeds were chosen based on the mean and 85th percentile speeds for each site. If significant differences in approach speeds or speed change occurred at one or both control speeds, those differences would be observed by choosing two different control speeds.

The beta (β) values in the equation represented the regression coefficient estimates, which help predict the speed changes and approach speeds. The estimates were examined as to their significance in the model. All the coefficients were found to be significant while performing the multifactor ANOVA. The significant differences between before and after studies were denoted by the Study variable and β_1 in Equations 2 and 3. The significant differences between daytime and nighttime periods were denoted by the Light variable and β_2 in Equation 2. The significant differences between weekday and weekend periods were denoted by the Period variable and β_2 in Equation 3.

The β_3 value in Equations 2 and 3 corresponded to the regression coefficient estimate for the control speed. As mentioned previously, the control speed was used as a covariate to account for the different speeds at which drivers entered the study location in the before and after study condition. The additional beta values (β_4, β_5, β_6, and β_7) corresponded to the interactions between the study, light, control speed, and/or period conditions.

Before study periods were denoted by -1 and after study periods were denoted by 1 for the linear contrast models in the SPSS analysis. There were a series on linear contrasts performed for the data sets. In the case where before daytime data were compared to after daytime data, a value of 1 was coded in for daytime periods and a value of 0 was coded in for nighttime periods. This allowed for a Day (Before) versus Day (After) comparisons. The nighttime, weekday, and weekend comparisons were coded similarly for the respective linear contrasts.

Graphical Analysis

The graphical analysis consisted of construction speed-plots of the mean speed at the three designated data collection locations: control (free flow), warning sign, and intersection. The objective of the graphical analysis was to visually compare the pre-treatment approach behavior with the post-treatment behavior.

Results

All sites included data collected during daytime and nighttime periods. However, weekend data were not collected at all of the sites. Since no weekend data were collected at these sites, a weekday versus weekend comparison was not made for these locations. The sites where weekend data were collected included Snook (FM 50 NB), Snook (FM 50 SB), Hearne (FM 2542 NB), and Hearne (FM 2549 SB).

The findings presented here have been organized based on the site location. Within each site location is a summary of the site characteristics, data analysis results, and speed profile. The data for each of the sites was determined to be normally distributed. The histograms for each site are presented in Appendix C. The 85th percentile speeds, which were calculated in the summary statistics, were also reported here to show any meaningful reductions.

Bosque County

The Bosque County study site was located at the intersection of FM 3118 and SH 22 near Waco, Texas. The site is a T-intersection that is near a recreational area, which tends to attract many unfamiliar drivers. TXDOT indicated that there were multiple reports of cars driving through the intersection without stopping. The posted speed limit along the approaches was 70 mph.

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Tables 13, 14, and 15, respectively. A graphical representation of the speed profiles for the overall before and after studies is shown in Figure 8.

Table 13. Bosque County (FM 3118) Change in Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1859	55	12.246	12.181	-0.065	0.714
		70	17.388	17.802	0.414	0.355
Night	261	55	12.839	12.084	-0.755	0.105
		70	16.084	17.422	1.338	0.201

* Statistically significant at 95% level of confidence.

Table 14. Bosque County (FM 3118) Intersection Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1859	55	39.852	39.425	-0.427*	0.044
		70	46.873	45.791	-1.082*	0.044
Night	261	55	39.884	40.250	0.366	0.512
		70	44.117	46.489	2.372	0.059

* Statistically significant at 95% level of confidence.

Table 15. Bosque County (FM 3118) Warning Sign Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1859	55	52.098	51.606	-0.492*	0.004
		70	64.261	63.593	-0.668	0.126
Night	261	55	52.723	52.334	-0.389	0.392
		70	60.201	63.911	3.710*	0.000

* Statistically significant at 95% level of confidence.

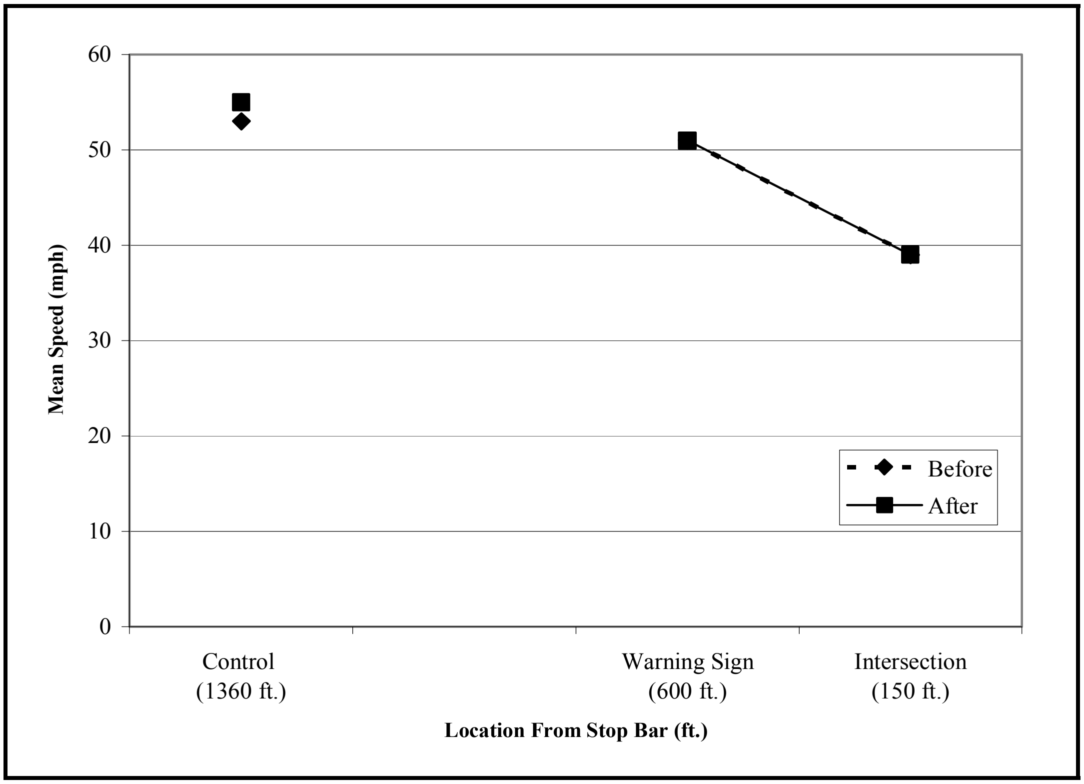

Figure 8. Bosque County (FM 3118) Speed Profile

Snook

The Snook study site was located at the intersection of FM 50 and FM 60. The site is a two-way stop intersection and is unobstructed. The intersection is; however, the first stop in ten miles in both directions and is subject to unexpectedness for the driver. The posted speed limit along the approaches was 70 mph.

Southbound Approach

Data from the southbound approach on FM 50 near the Snook site had to be separated into two cases, vehicles entering the highway from a side road (turning vehicles) and through vehicles (highway vehicles). This was due to a bi-modal distribution in the control speeds (see Figure 9). This distribution was due to the control speed trap being located near a side road.

The side road was located 420 feet upstream of the control speed trap. Vehicles turning onto FM 50 from the side road would traverse over the control speed trap; however, the speed would be lower than that of a vehicle traveling straight through the site. To analyze the data, the site was split into two groups. A speed of 45 mph was used to separate the groups. The average speeds for the turning vehicles and straight through vehicles were 33 mph and 68 mph, respectively. The standard deviations for the turning vehicles and the straight through vehicles were 4.0 mph and 8.0 mph, respectively. By taking a range of three standard deviations away from the mean in each case yielded a delineating speed of 45 mph.

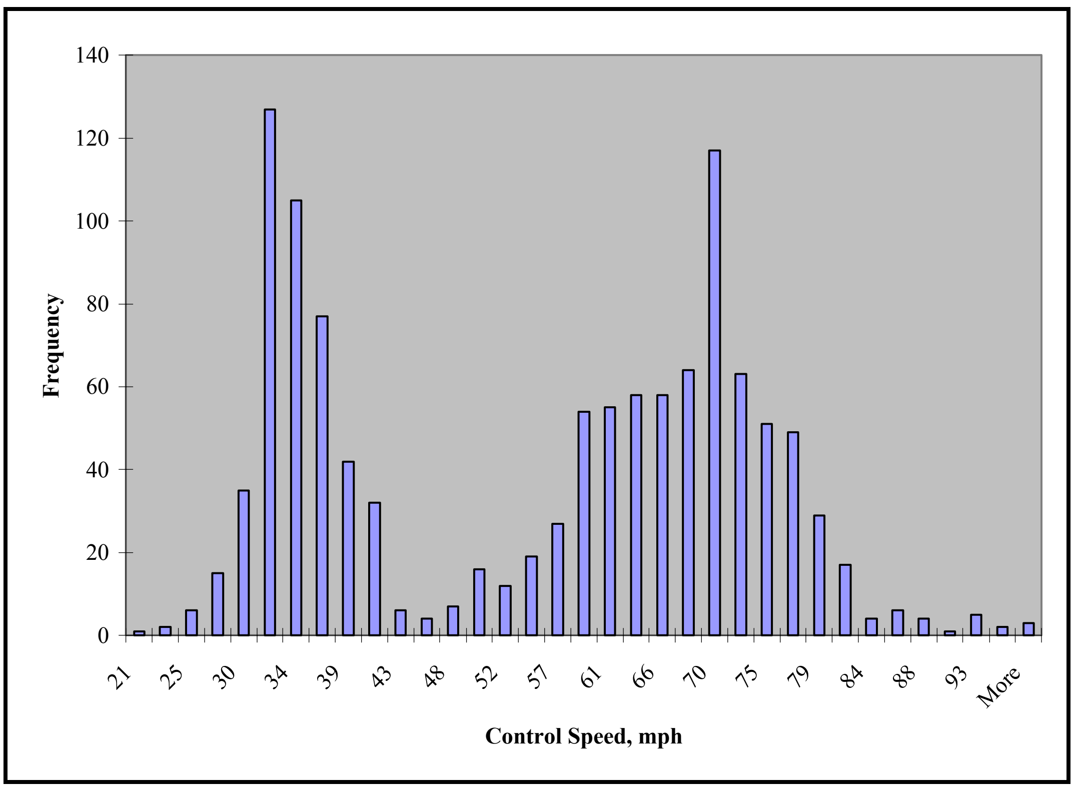

Figure 9. Bi-Modal Distribution of the Southbound Approach at Snook (FM 50)

Turning Vehicles

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Tables 16, 17, and 18, respectively. A graphical representation of the speed profiles for the overall before and after studies is shown in Figure 10.

Table 16. Snook (FM 50 SB Turning Vehicles) Change in Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	361	35	10.704	10.358	-0.346	0.653
		40	11.509	9.480	-2.030	0.139
Night	57	35	12.113	4.636	-7.477*	0.000
		40	14.693	6.003	-8.690*	0.005
Weekday	203	35	11.426	10.501	-0.925	0.390
		40	12.882	10.400	-2.482*	0.137
Weekend	215	35	10.463	8.329	-2.134*	0.045
		40	11.327	5.538	-5.789*	0.007

* Statistically significant at 95% level of confidence.

Table 17. Snook (FM 50 SB Turning Vehicles) Intersection Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	361	35	46.846	47.950	1.104	0.217
		40	49.890	49.120	-0.771	0.628
Night	57	35	43.282	47.970	4.688*	0.046
		40	46.136	46.332	1.196	0.737
Weekday	203	35	46.128	46.129	0.001	1.000
		40	46.581	50.061	-2.509	0.192
Weekend	215	35	49.063	46.555	-3.480*	0.005
		40	49.411	53.052	3.641	0.141

* Statistically significant at 95% level of confidence.

Table 18. Snook (FM 50 SB Turning Vehicles) Warning Sign Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	361	35	57.550	58.308	0.758	0.387
		40	61.400	58.599	-2.801	0.073
Night	57	35	55.395	52.606	-2.789	0.226
		40	59.829	52.335	-7.494*	0.033
Weekday	203	35	57.554	56.629	-0.925	0.451
		40	61.945	56.954	-4.991*	0.009
Weekend	215	35	57.044	58.390	1.346	0.267
		40	60.737	58.590	-2.198	0.380

* Statistically significant at 95% level of confidence.

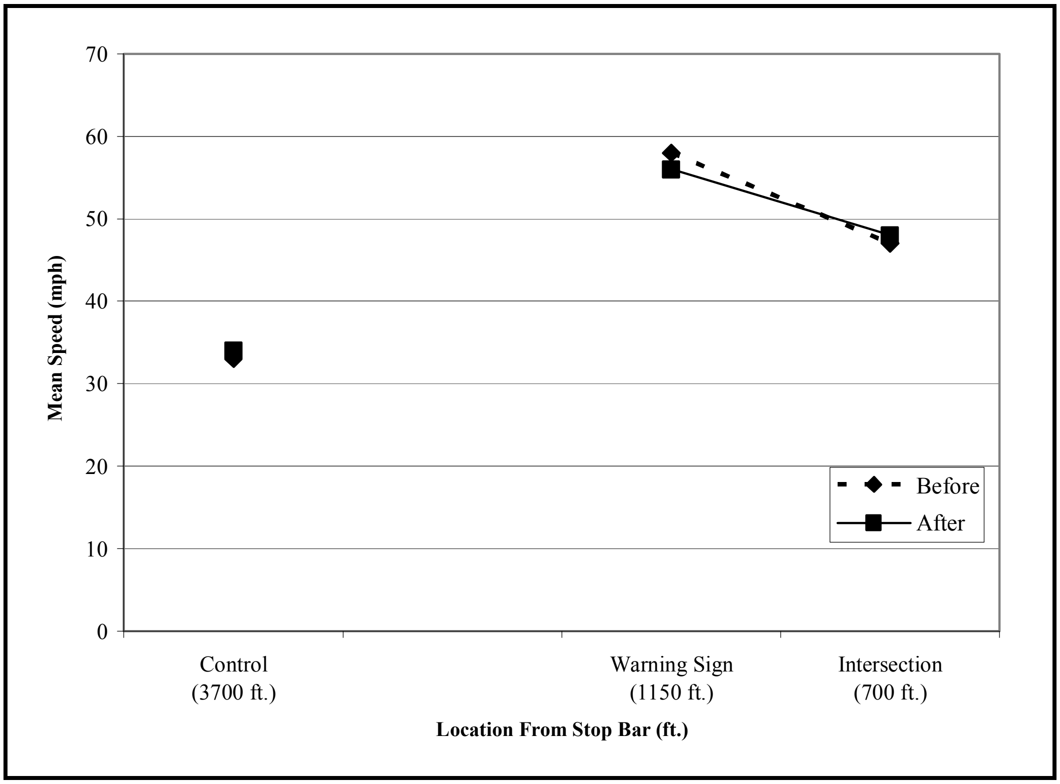

Figure 10. Snook (FM 50 SB Turning Vehicles) Speed Profile

Highway Vehicles

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Tables 19, 20, and 21, respectively. A graphical representation of the speed profiles for the overall before and after studies is shown in Figure 11.

Table 19. Snook (FM 50 SB Highway) Change in Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	570	65	10.928	11.827	0.899	0.060
		80	14.014	14.916	0.902	0.298
Night	107	65	9.662	10.262	0.600	0.604
		80	10.613	12.309	1.697	0.432
Weekday	269	65	11.356	12.472	1.115	0.116
		80	15.285	14.763	-0.522	0.711
Weekend	408	65	10.323	10.968	0.644	0.259
		80	12.357	14.818	2.460*	0.013

* Statistically significant at 95% level of confidence.

Table 20. Snook (FM 50 SB Highway) Intersection Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	570	65	45.040	46.087	1.047	0.078
		80	51.921	51.785	-0.136	0.899
Night	107	65	42.591	45.189	2.598	0.071
		80	50.286	50.165	-0.120	0.964
Weekday	269	65	44.612	45.258	0.646	0.468
		80	51.894	50.460	-1.434	0.418
Weekend	408	65	44.548	46.385	1.837*	0.010
		80	51.609	51.906	0.297	0.811

* Statistically significant at 95% level of confidence.

Table 21. Snook (FM 50 SB Highway) Warning Sign Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	570	65	55.969	57.914	1.945*	0.000
		80	65.935	66.700	0.766	0.420
Night	107	65	52.253	55.451	3.198*	0.012
		80	60.898	62.475	1.576	0.505
Weekday	269	65	55.968	57.730	1.761*	0.026
		80	67.179	65.223	-1.956	0.214
Weekend	408	65	54.871	57.352	2.481*	0.000
		80	63.966	66.723	2.757*	0.013

* Statistically significant at 95% level of confidence.

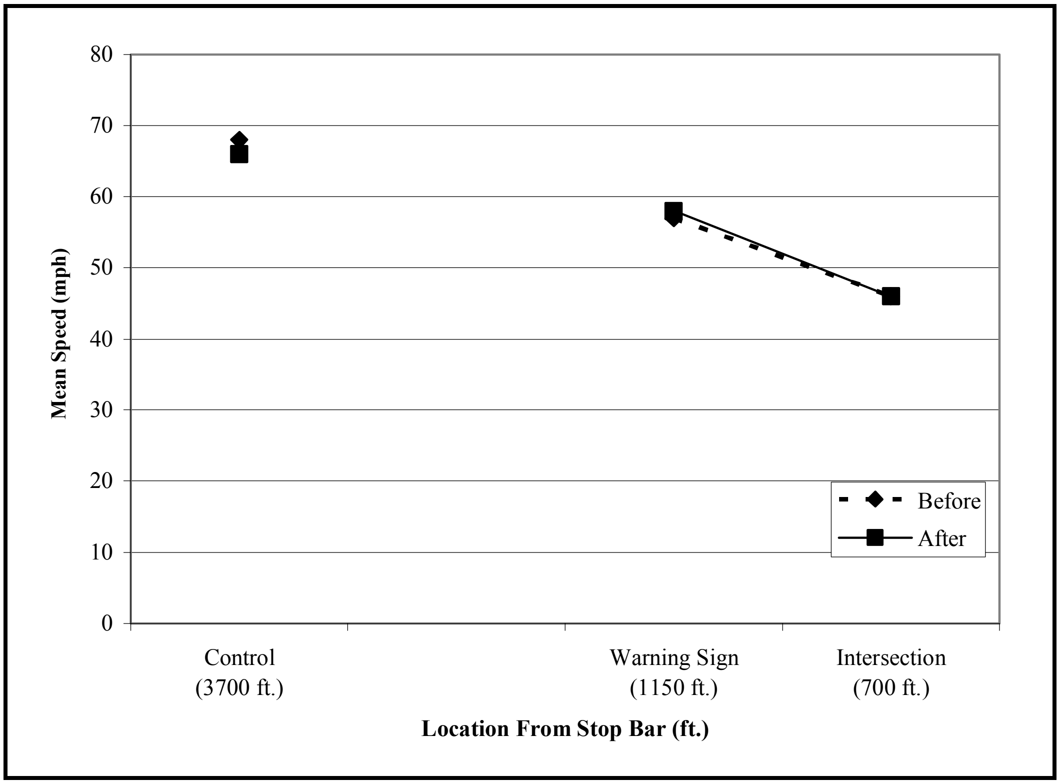

Figure 11. Snook (FM 50 SB Highway) Speed Profile

Northbound Approach

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Tables 22, 23, and 24, respectively. A graphical representation of the speed profiles for the overall before and after studies is shown in Figure 12.

Table 22. Snook (FM 50 NB) Change in Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2455	65	7.012	7.588	0.576*	0.000
		80	9.371	9.752	0.381	0.060
Night	401	65	7.953	7.180	-0.773	0.060
		80	10.125	9.946	-0.180	0.749
Weekday	1237	65	7.685	7.394	-0.291	0.161
		80	9.922	9.734	-0.188	0.524
Weekend	1619	65	6.785	7.679	0.894*	0.000
		80	9.040	9.782	0.742*	0.003

* Statistically significant at 95% level of confidence.

Table 23. Snook (FM 50 NB) Intersection Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2455	65	53.022	49.454	-3.568*	0.000
		80	61.018	57.032	-3.986*	0.000
Night	401	65	50.016	47.971	-2.045*	0.004
		80	55.551	54.581	-0.969	0.317
Weekday	1237	65	52.610	49.396	-3.214*	0.000
		80	60.174	57.209	-2.966*	0.000
Weekend	1619	65	52.344	49.300	-3.043*	0.000
		80	60.727	56.547	-4.180*	0.000

* Statistically significant at 95% level of confidence.

Table 24. Snook (FM 50 NB) Warning Sign Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	2455	65	60.034	57.042	-2.992*	0.000
		80	70.839	66.784	-3.606*	0.000
Night	401	65	57.969	55.151	-2.818*	0.000
		80	65.676	64.527	-1.149	0.235
Weekday	1237	65	60.269	56.790	-3.506*	0.000
		80	70.097	66.943	-3.153*	0.000
Weekend	1619	65	56.129	56.979	-2.149*	0.000
		80	69.768	66.329	-3.439*	0.000

* Statistically significant at 95% level of confidence.

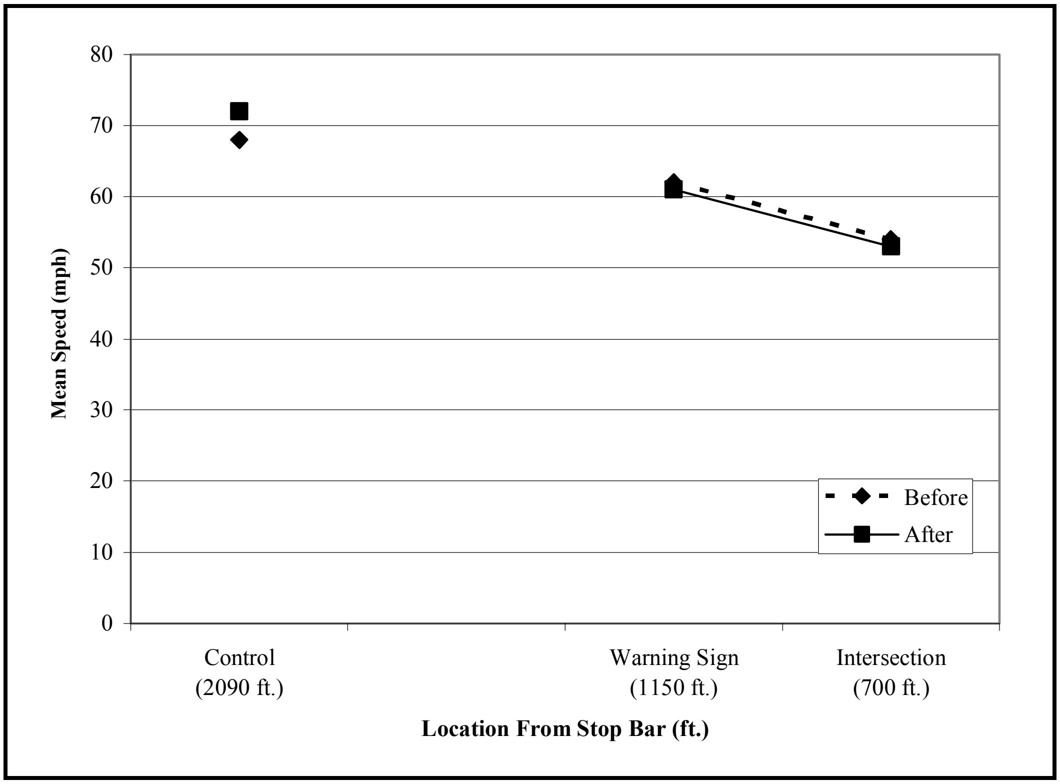

Figure 12. Snook (FM 50 NB) Speed Profile

Colorado City

The Colorado City study site was located at the intersection of FM 208 and SH 22. The site is a four-way stop-controlled intersection. The intersection is obstructed due to alignment conditions and follows a long tangent that could lead to unexpected conditions for the drivers. The posted speed limit along the approaches was 70 mph.

Southbound Approach

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Tables 25, 26, and 27, respectively. A graphical representation of the speed profiles for the overall before and after studies is shown in Figure 13.

Table 25. Colorado City (FM 208 SB) Change in Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	691	50	10.423	9.534	-0.888	0.072
		65	13.942	13.250	-0.692	0.248
Night	170	50	10.412	10.660	0.248	0.762
		65	13.810	12.212	-1.598	0.194

* Statistically significant at 95% level of confidence.

Table 26. Colorado City (FM 208 SB) Intersection Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	691	50	39.955	31.523	-4.432*	0.000
		65	39.381	35.245	-4.136*	0.000
Night	170	50	33.769	30.406	-3.363*	0.001
		65	36.885	34.377	-2.507	0.091

* Statistically significant at 95% level of confidence.

Table 27. Colorado City (FM 208 SB) Warning Sign Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	691	50	46.378	41.058	-5.230*	0.000
		65	53.323	48.495	-4.827*	0.000
Night	170	50	44.182	41.067	-3.115*	0.007
		65	50.695	46.590	-4.105	0.019

* Statistically significant at 95% level of confidence.

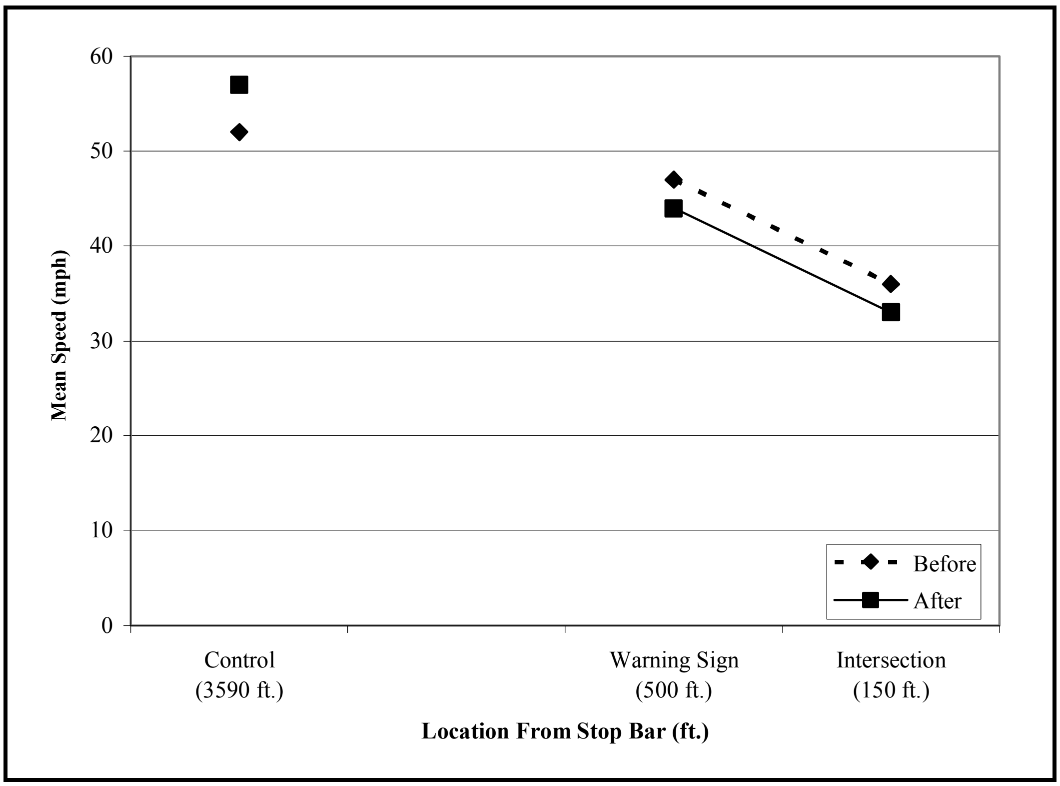

Figure 13. Colorado City (FM 208 SB) Speed Profile

Northbound Approach

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Tables 28, 29, and 30, respectively. A graphical representation of the speed profiles for the overall before and after studies is shown in Figure 14.

Table 28. Colorado City (FM 208 NB) Change in Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	407	50	8.964	6.781	-2.183*	0.000
		65	10.959	9.017	-1.942*	0.011
Night	109	50	9.014	6.791	-2.223*	0.014
		65	12.153	8.616	-3.537*	0.023

* Statistically significant at 95% level of confidence.

Table 29. Colorado City (FM 208 NB) Intersection Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	407	50	33.819	35.152	1.333*	0.035
		65	37.474	39.304	1.830*	0.049
Night	109	50	32.735	33.575	0.841	0.440
		65	35.075	39.763	4.688*	0.013

* Statistically significant at 95% level of confidence.

Table 30. Colorado City (FM 208 NB) Warning Sign Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	407	50	42.783	41.933	-0.849	0.145
		65	48.433	48.321	-0.112	0.897
Night	109	50	41.749	40.366	-1.382*	0.168
		65	47.229	48.379	1.151	0.506

* Statistically significant at 95% level of confidence.

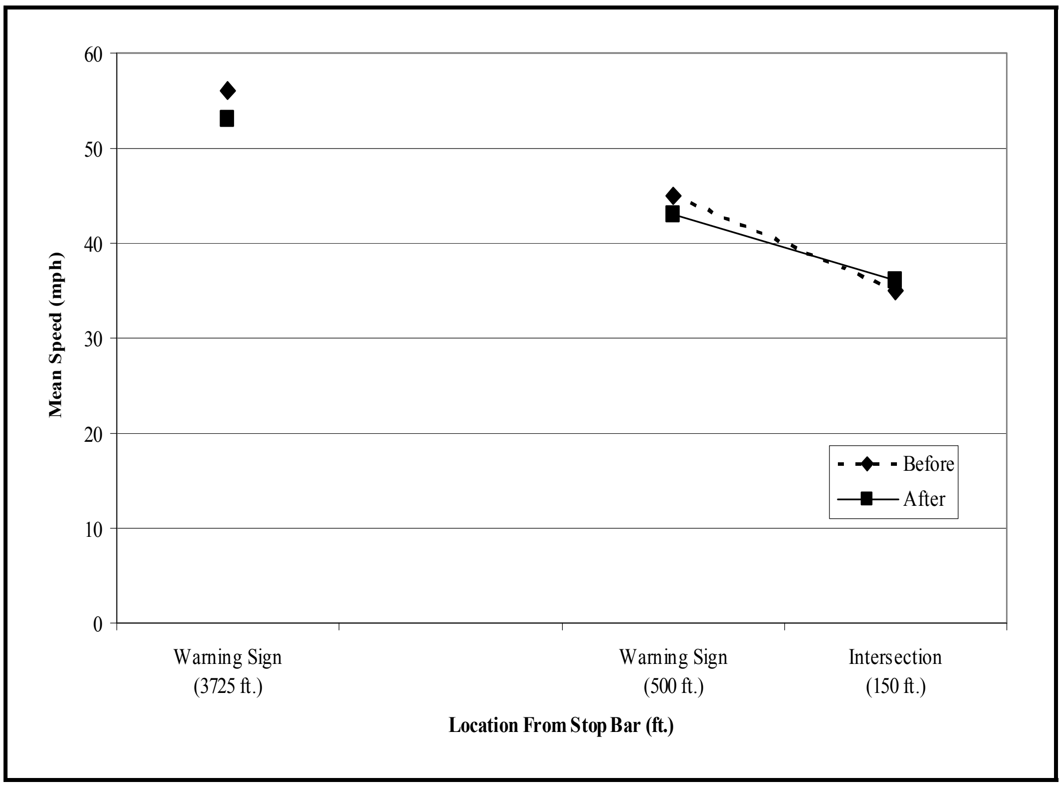

Figure 14. Colorado City (FM 208 NB) Speed Profile

Millican

The Millican study site was located at the intersection of FM 2154 and FM 159. The site is a four-way stop intersection that is used by drivers to bypass SH 6, especially in the southbound direction. The intersection was obstructed to due overgrown vegetation near the intersection as well as sight distance obstructions. The intersection was the first stop for ten miles in the southbound direction, which could be and unexpected intersection to some drivers. One disadvantage to this study site was that a business was located on the west side of the subject roadway (FM 2154). The driveway was a very low-volume drive and was assumed to have a very minimal effect on the results. The posted speed limit along the approaches was 70 mph.

<u>Southbound Approach</u>

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Tables 31, 32, and 33, respectively. A graphical representation of the speed profiles for the overall before and after studies is shown in Figure 15.

Table 31. Millican (FM 2154 SB) Change in Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	794	65	10.190	8.895	-1.294*	0.003
		75	14.573	13.540	-1.033*	0.029
Night	128	65	8.280	7.502	-0.778	0.401
		75	12.055	12.055	0.365	0.762

* Statistically significant at 95% level of confidence.

Table 32. Millican (FM 2154 SB) Intersection Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	794	65	41.723	42.638	0.915	0.093
		75	47.591	49.052	1.460*	0.015
Night	128	65	42.762	46.952	4.190*	0.000
		75	51.077	52.715	1.638	0.286

* Statistically significant at 95% level of confidence.

Table 33. Millican (FM 2154 SB) Warning Sign Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	794	65	51.912	51.533	-0.379	0.482
		75	62.164	62.591	0.427	0.474
Night	128	65	51.041	54.454	3.413*	0.003
		75	63.132	65.135	2.003	0.187

* Statistically significant at 95% level of confidence.

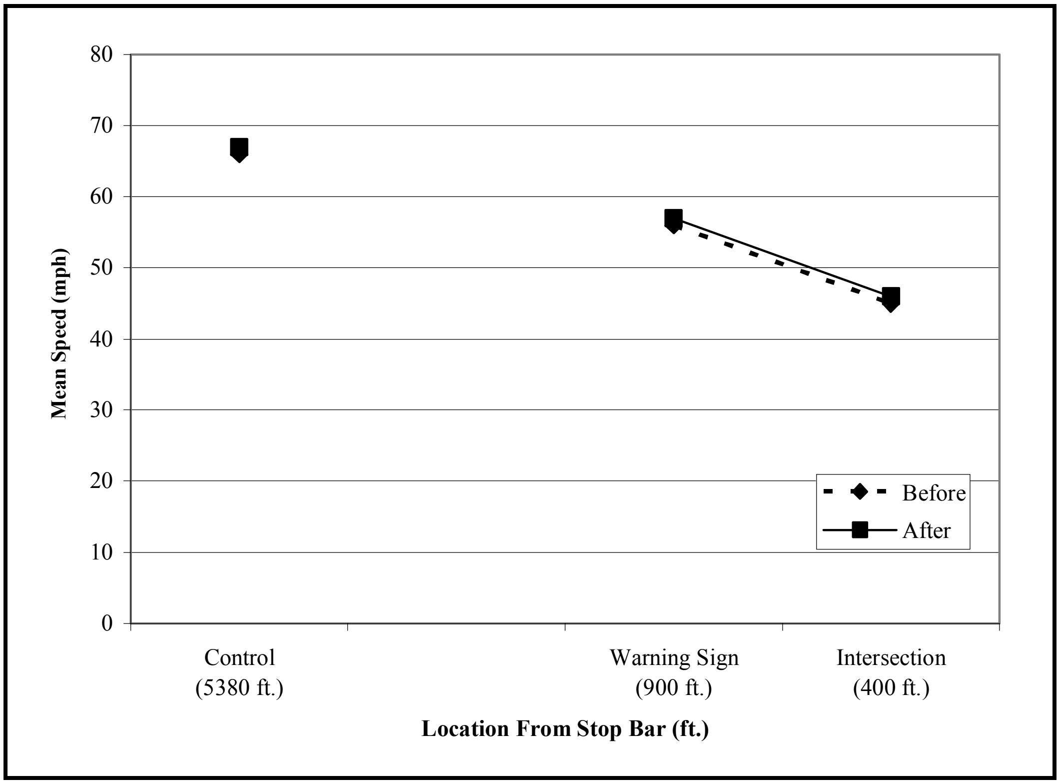

Figure 15. Millican (FM 2154 SB) Speed Profile

Northbound Approach

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Tables 34, 35, and 36, respectively. A graphical representation of the speed profiles for the overall before and after studies is shown in Figure 16.

Table 34. Millican (FM 2154 NB) Change in Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1294	60	11.808	10.144	-1.664*	0.001
		75	15.595	16.793	1.198	0.056
Night	378	60	10.126	8.973	-1.153	0.218
		75	13.656	17.750	4.093*	0.004

* Statistically significant at 95% level of confidence.

Table 35. Millican (FM 2154 NB) Intersection Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1294	60	37.757	39.308	1.551*	0.001
		75	41.018	39.896	-1.122*	0.049
Night	378	60	39.487	41.280	1.793*	0.036
		75	44.128	39.629	-4.499*	0.000

* Statistically significant at 95% level of confidence.

Table 36. Millican (FM 2154 NB) Warning Sign Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	1294	60	49.565	49.452	-0.113	0.807
		75	56.613	56.689	0.075	0.897
Night	378	60	49.613	50.253	0.641	0.469
		75	57.784	57.379	-0.406	0.756

* Statistically significant at 95% level of confidence.

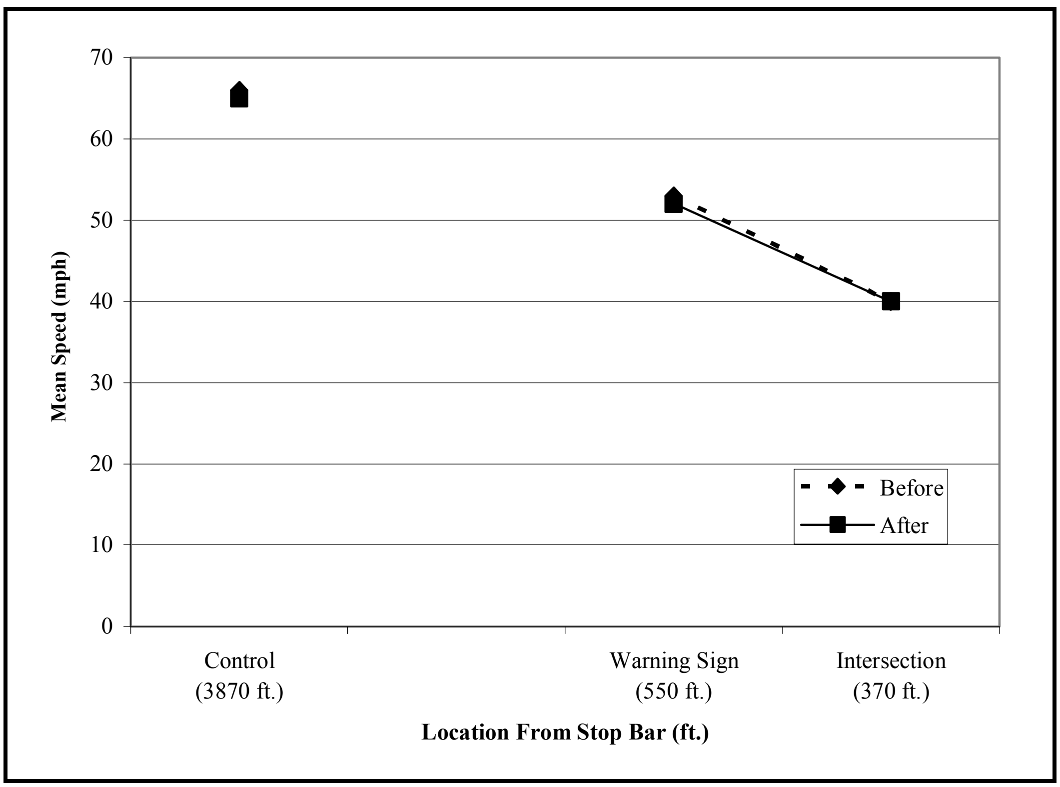

Figure 16. Millican (FM 2154 NB) Speed Profile

Hearne

The Hearne study site was located at the intersection of FM 2549 and FM 391. The site is a two-way stop and an obstructed intersection due to the alignment and the vegetation along the approach to the intersection. There is also very few cues that an intersection is approaching. There is only standard TXDOT signage along the approach to the intersection. The posted speed limit along both approaches was 70 mph.

<u>Northbound Approach</u>

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Tables 37, 38, and 39, respectively. A graphical representation of the speed profiles for the overall before and after studies is shown in Figure 17.

Table 37. Hearne (FM 2549 NB) Change in Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	821	60	8.433	8.493	0.061	0.820
		75	11.696	11.981	0.286	0.494
Night	172	60	9.220	9.578	0.358	0.497
		75	12.598	13.753	1.155	0.241
Weekday	327	60	8.675	8.961	0.285	0.523
		75	12.358	12.444	0.086	0.909
Weekend	666	60	8.483	8.659	0.176	0.534
		75	11.404	12.225	0.821	0.073

* Statistically significant at 95% level of confidence.

Table 38. Hearne (FM 2549 NB) Intersection Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	821	60	48.858	48.733	0.148	0.709
		75	54.454	54.298	-0.156	0.802
Night	172	60	47.432	47.420	-0.012	0.988
		75	54.006	52.230	-1.775	0.226
Weekday	327	60	48.661	47.728	-0.934	0.159
		75	54.676	54.570	-0.107	0.923
Weekend	666	60	48.239	48.650	0.411	0.327
		75	54.245	53.825	-0.420	0.537

* Statistically significant at 95% level of confidence.

Table 39. Hearne (FM 2549 NB) Warning Sign Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	821	60	57.018	57.226	0.208	0.576
		75	66.150	66.280	0.130	0.824
Night	172	60	56.651	56.998	0.346	0.639
		75	66.604	65.984	-0.620	0.653
Weekday	327	60	57.336	56.688	-0.648	0.296
		75	67.035	67.014	-0.021	0.984
Weekend	666	60	56.722	57.309	0.587	0.135
		75	65.649	66.050	0.401	0.529

* Statistically significant at 95% level of confidence.

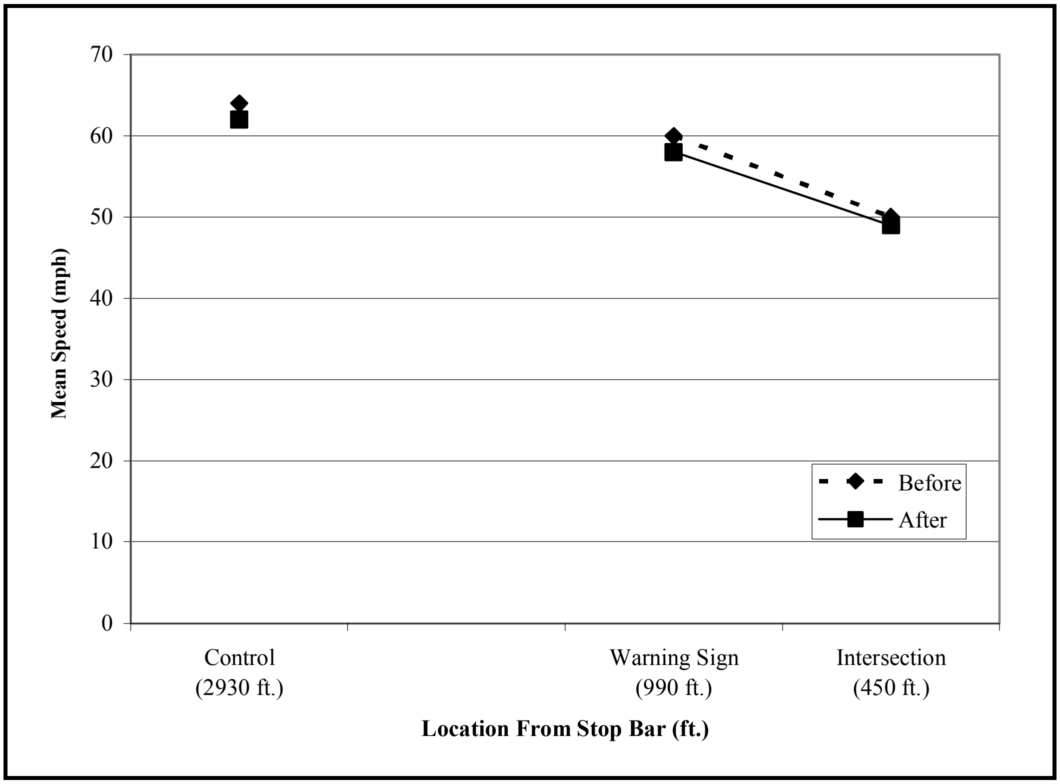

Figure 17. Hearne (FM 2549 NB) Speed Profile

Southbound Approach

The results for the change in speed, intersection spot speed, and warning sign spot speed comparisons are presented in Tables 40, 41, and 42, respectively. A graphical representation of the speed profiles for the overall before and after studies is shown in Figure 18.

Table 40. Hearne (FM 2549 SB) Change in Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Speed Change from Warning to Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	690	60	7.169	7.512	0.343	0.251
		75	9.233	10.278	1.045*	0.045
Night	122	60	6.839	6.698	-0.141	0.844
		75	9.444	9.068	-0.376	0.759
Weekday	234	60	6.769	7.207	0.438	0.440
		75	9.145	10.170	1.025	0.263
Weekend	578	60	7.272	7.426	0.155	0.630
		75	9.346	10.079	0.733	0.199

* Statistically significant at 95% level of confidence.

Table 41. Hearne (FM 2549 SB) Intersection Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Intersection Speed Trap (mph)			
			Before	After	Δ	Significance
Day	690	60	50.406	47.511	-2.896*	0.000
		75	55.504	52.943	-2.561*	0.004
Night	122	60	48.929	47.548	-1.381	0.260
		75	56.992	54.786	-2.207	0.291
Weekday	234	60	50.716	46.114	-4.603*	0.000
		75	56.817	53.833	-2.984	0.057
Weekend	578	60	49.952	47.864	-2.088*	0.000
		75	55.091	53.181	-1.910	0.050

* Statistically significant at 95% level of confidence.

Table 42. Hearne (FM 2549 SB) Warning Sign Spot Speed Results

Light Condition/Period	Overall Sample Size	Control Speed (mph)	Warning Sign Speed Trap (mph)			
			Before	After	Δ	Significance
Day	690	60	57.575	55.023	-2.552*	0.000
		75	64.737	63.221	-1.516	0.108
Night	122	60	55.768	54.246	-1.522	0.242
		75	66.436	63.853	-2.583	0.244
Weekday	234	60	57.486	53.321	-4.164*	0.000
		75	65.961	64.003	-1.958	0.240
Weekend	578	60	57.223	55.290	-1.933*	0.001
		75	64.437	63.260	-1.177	0.256

* Statistically significant at 95% level of confidence.

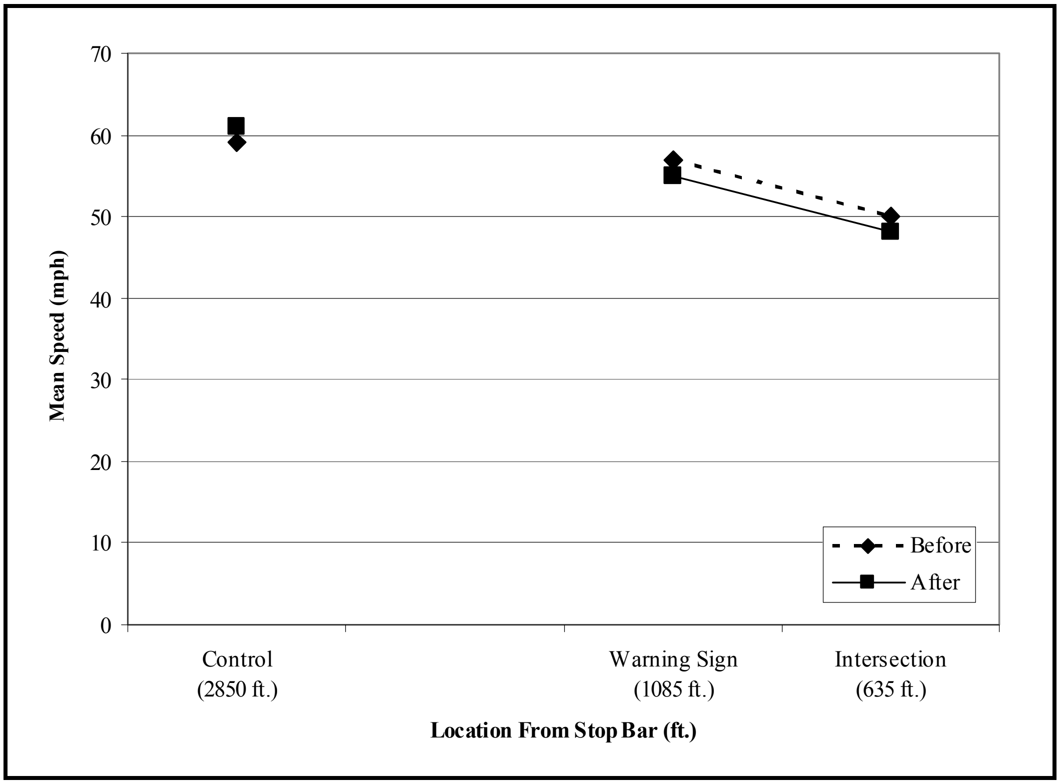

Figure 18. Hearne (FM 2549 SB) Speed Profile

Comparison of 85th Percentile Speeds

The 85th percentile speeds for each of the sites were compared in the before and after condition. The 85th percentile speeds were examined to determine if there were any effects on drivers traveling at speeds higher-than-average or effects on speeders. The speeds were examined to determine if there were any meaningful reductions (greater or equal to a reduction of 4 mph) in 85th percentile speed. There were instances of the warning sign spot speed and the intersection spot speed decreasing by 1 – 2 mph; however, there were no instances of reductions greater than or equal to 4 mph. The 85th percentile speed results are presented in Table 43.

Table 43. Comparison of 85th Percentile Speeds

Site	85th Percentile Speeds (mph)					
	Control		Warning Sign		Intersection	
	Before	After	Before	After	Before	After
Bosque County	60	61	57	58	45	44
Snook SB (Turning Vehicles)	37	39	63	66	52	55
Snook SB (Highway Vehicles)	75	74	66	65	53	53
Snook NB	75	79	69	69	61	60
Colorado City SB	59	65	53	51	41	38
Colorado City NB	63	61	50	48	40	41
Millican SB	72	73	63	64	50	52
Millican NB	73	73	60	60	46	46
Hearne NB	74	71	67	65	56	55
Hearne SB	69	72	65	66	57	55

Summary

Overall, the installation of rumble strips generally produced small, but statistically significant ($p \leq 0.05$), changes in traffic speeds. There were some negative driver behavioral impacts (i.e. speed increases) that occurred after the installation of rumble strips. The findings are summarized below (see Table 44) by site location. The table summarizes that data presented by reporting the primary findings from each site and if the impacts of the rumble strips were perceived to be beneficial. Primary findings included speed changes, reductions in approach speeds, and patterns that existed for the data.

Table 44. Primary Findings

Site	Primary Finding	Beneficial Impact?
Bosque County (FM 3118)	• Approach speeds reduced slightly (less than 1 mph) in most cases • Approach speeds evaluated at Night yielded an increase in speed • No significant effect on speed change parameter	No
Snook (FM 50 SB Turning)	• Nighttime and weekend data yielded significant differences (2 – 8 mph) in speed change parameter • Inconsistent effects on approach speeds	Marginal
Snook (FM 50 SB Highway)	• Speed change parameter increased slightly (0.6 – 1 mph) • Slight (1 – 2 mph) increases in approach speeds	No
Snook (FM 50 NB)	• Inconsistent effect on speed change parameter • Small (less than 1 mph) speed changes found to be significant differences • Approach speeds reduced in all cases • Most speed reductions were reported to be significantly different at a 2 – 3 mph change	Marginal
Colorado City (FM 208 SB)	• No significant differences in speed change parameter • Approach speeds were significantly reduced • Approach speeds reduced from 2 – 5 mph	Yes
Colorado City (FM 208 NB)	• Speed change parameter significantly reduced • Speed change differences were reduced by 2 – 3 mph • Intersection spot speeds increased • Warning sign spot speeds decreased slightly	Marginal
Millican (FM 2154 SB)	• Slight decrease in speed change parameters • Approach speeds increased	No
Millican (FM 2154 NB)	• Inconsistent effects on both speed change and approach speeds • Small (1 mph) changes in both speed change and approach speed parameters	No
Hearne (FM 2549 NB)	• No significant differences in speed change or approach speed parameters • Approach speeds were reduced slightly (less than 1 mph)	No
Hearne (FM 2549 SB)	• Inconsistent effect on speed change parameter • Approach speeds were reduced • Approach speeds had significant reductions at 2 – 4 mph	Marginal

CONCLUSIONS AND RECOMMENDATIONS

This research used field measured vehicle speeds to investigate the impact of rumble strips on driver behavior on approaches to rural stop-controlled intersections. A summary of the research results is presented in this section as well as the conclusions and recommendations developed in this research.

The objective of this research was to determine if the presence of rumble strips affected driver behavior and resulted in a more uniform deceleration pattern. A more uniform deceleration pattern would indicate that drivers had been more adequately aware of upcoming decision points and better suited to make decisions. The results of previous research have produced varied results. Previous research has reported a statistically significant reduction in speed; however, the reduction in speed has been of the magnitude of 2 to 5 mph, which may not be practically significant.

To accomplish this objective, nine approaches to rural stop-controlled intersections were used for evaluations. It was hypothesized that the rumble strips would prompt a change in traffic speeds. Speed data were collected and analyzed to evaluate the effectiveness of rumble strips on driver behavior and traffic operations.

Conclusions

The conclusions from this research can be summarized as follows:

- For the most of the sites analyzed, the installation of rumble strips did not significantly affect the speed change between the warning sign speed trap and intersection speed trap. There were a number of small (less than 1 mph) reductions in the speed change parameters throughout the sites; however, none of these reductions were statistically significant. There were three sites (Colorado City NB, Millican NB and Millican SB) where significant speed change reductions of greater than 1 mph were observed. However, the overall trend was small reductions in speed change between the warning sign and intersection speed collection points.

- A number of sites indicated statistically significant changes in approach speeds between before and after study conditions. However, these changes were of the magnitude of 2 – 3 mph and based on literature reviewed (9), a reduction of 4 mph is required to be practically significant. Thus, the rumble strips were not successful at reducing approach speeds.
- The data were analyzed to observe any discernable patterns pertaining to light condition. The pattern that was hypothesized prior to the data analysis was that the rumble strips would have a greater effect (i.e. reduced spot speeds and/or greater speed change) during nighttime periods as opposed to daytime periods when drivers may have lower attentiveness. No discernable pattern existed in the data analyzed in which nighttime speed reductions were significantly different and daytime speed reductions were not significantly different.
- The data were analyzed to observe any discernable patterns pertaining to data collection period. The pattern that was hypothesized prior to the data analysis was that the rumble strips would have a greater effect (i.e. reduced spot speeds and/or greater speed change) on weekend periods as opposed to weekday periods when there may be more drivers unfamiliar with the area. No discernable pattern existed in the data analyzed in which weekend speed reductions were significantly different and weekday speed reductions were not significantly different.
- In some instances, approach speeds increased a statistically significant amount. This behavior did not support an improvement in traffic operations as a result of the installation of rumble strips.

- Data were analyzed to determine if the rumble strips were more effective when drivers entered the study location at higher control speeds. There was no discernable pattern that existed to allow a conclusion that the rumble strips were more effective when drivers entered the study location at a higher control speed.
- The 85th percentile speeds were reported to determine if there were any patterns of reductions in higher speeds. There were no meaningful reductions (equal to or greater than 4 mph) in the 85th percentile speeds at any of the three speed trap locations for any of the sites. Most speed differences were 2 – 3 mph.
- Although the data does not support an overall reduction in speeds, previous literature reports reductions in accidents. Due to the minimal cost associated with installing rumble strips and the high value of life, $2.7 million, (*30*), rumble strips should still be considered as a traffic control device at stop-controlled intersections until further analysis of long term crash rates at these intersections can be examined (see recommendations below).

Recommendations and Areas for Further Research

Based on the results and conclusions of this research, the following recommendations were made:

- The primary goal of the study was to determine if drivers applied a more uniform deceleration profile after the installation of rumble strips. An additional measure of evaluation to help determine the effectiveness on rumble strips on deceleration may be to measure the location where vehicles begin to decelerate.
- The use of LIDAR equipment may help to generate more accurate speed profiles. LIDAR technology is able to track vehicles through the study approach more accurately and does not depend on the uniform deceleration between speed trap locations.

- This study measured the effectiveness of rumble strips on free-flow passenger vehicles only. Similar experiments involving non-passenger vehicles (trucks) would be useful in determining the effect of rumble strips on different classes of vehicles.
- A more direct measure as to the effectiveness of the rumble strips may be to perform a long term study dealing with accidents, accident rates, or stop-sign compliance at the sites.
- A benefit-cost analysis on in-lane rumble strips would be helpful in determining a proper course of action when deciding to install them or not. The benefit-cost analysis could incorporate the results from a long-term accident study involving in-lane rumble strips.

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APPENDIX A

GEOMETRIC SITE LAYOUTS

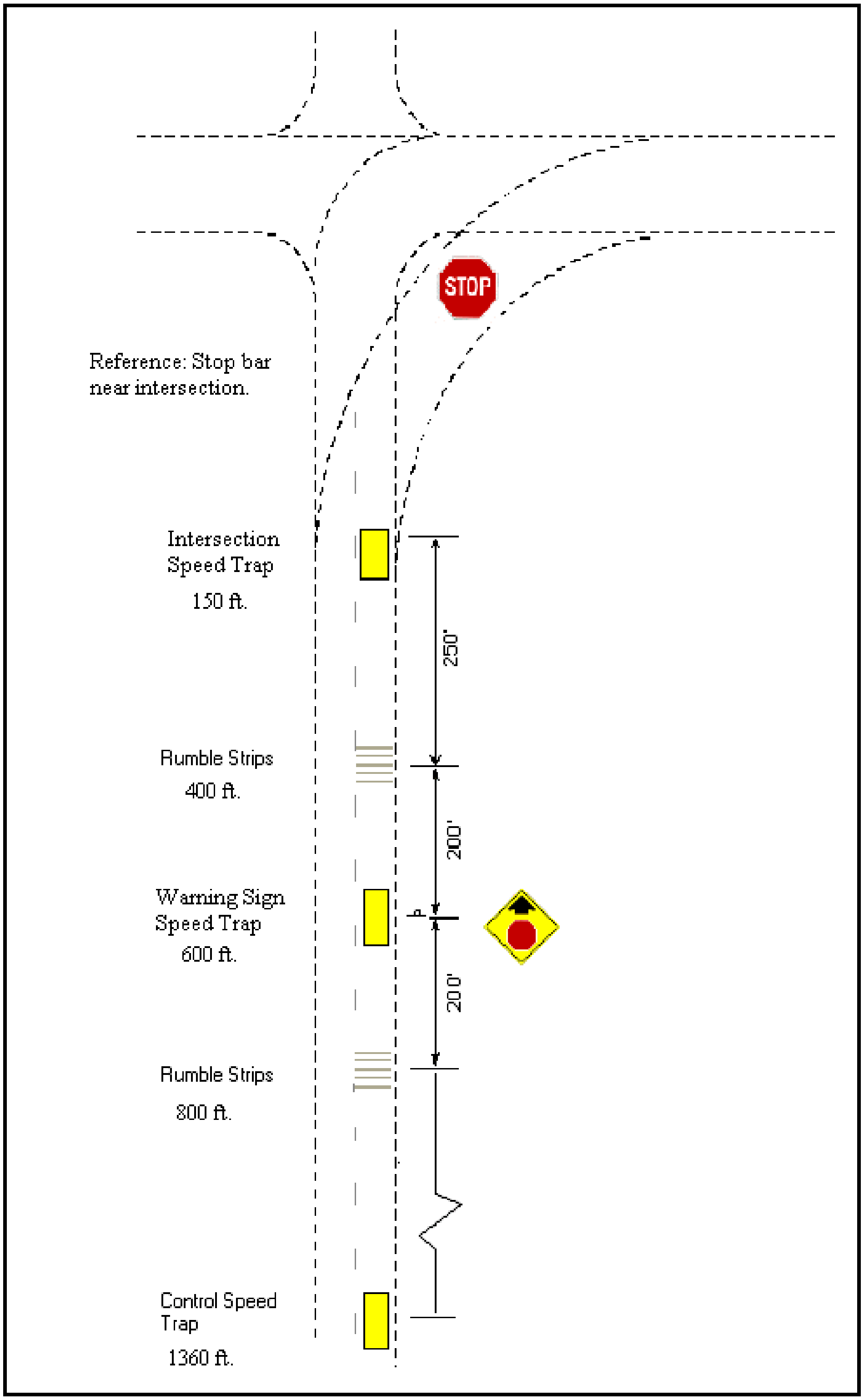

Figure A- 1. Bosque County (FM 3118) Site Layout

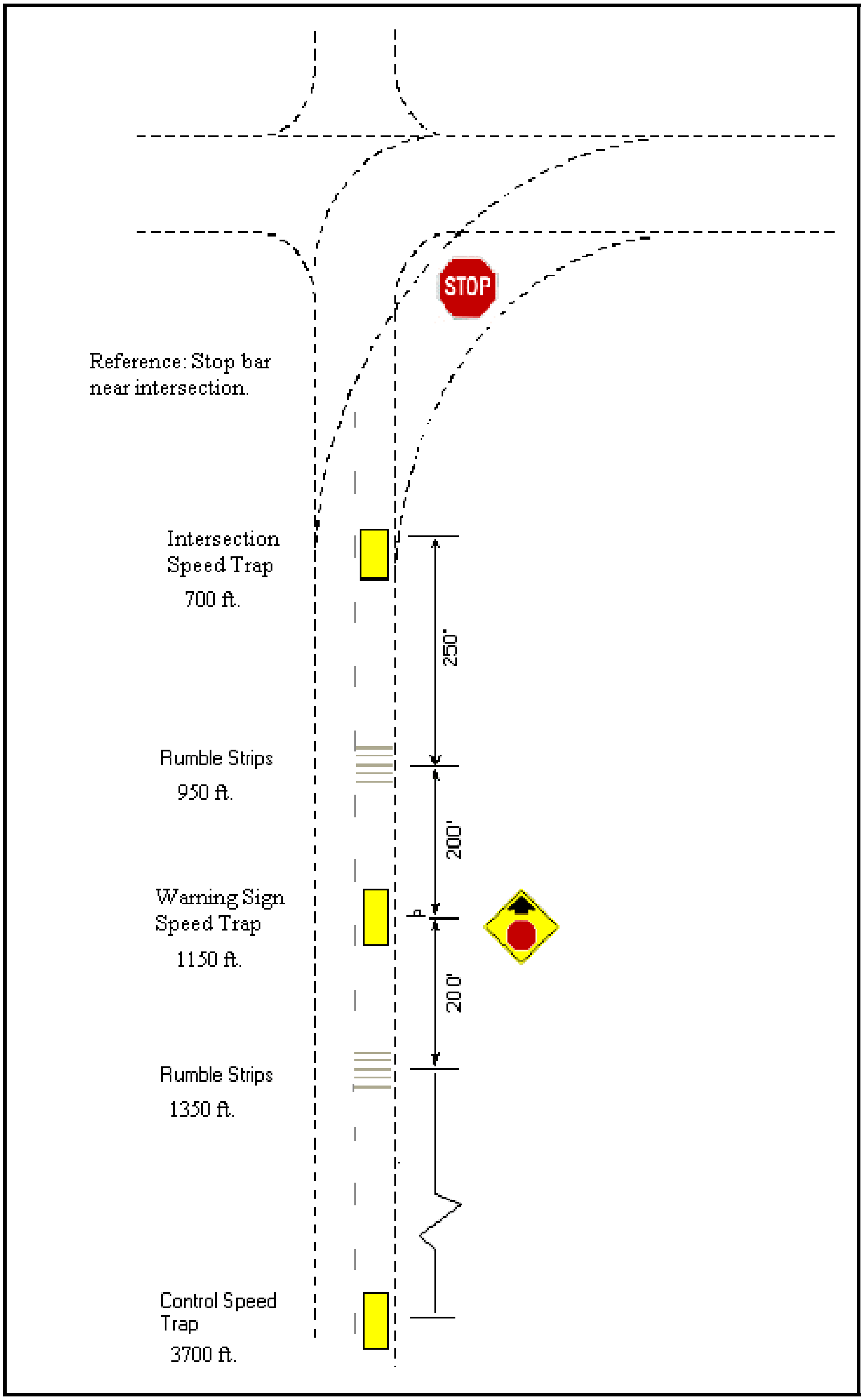

Figure A- 2. Snook (FM 50 SB Highway Vehicles) Site Layout

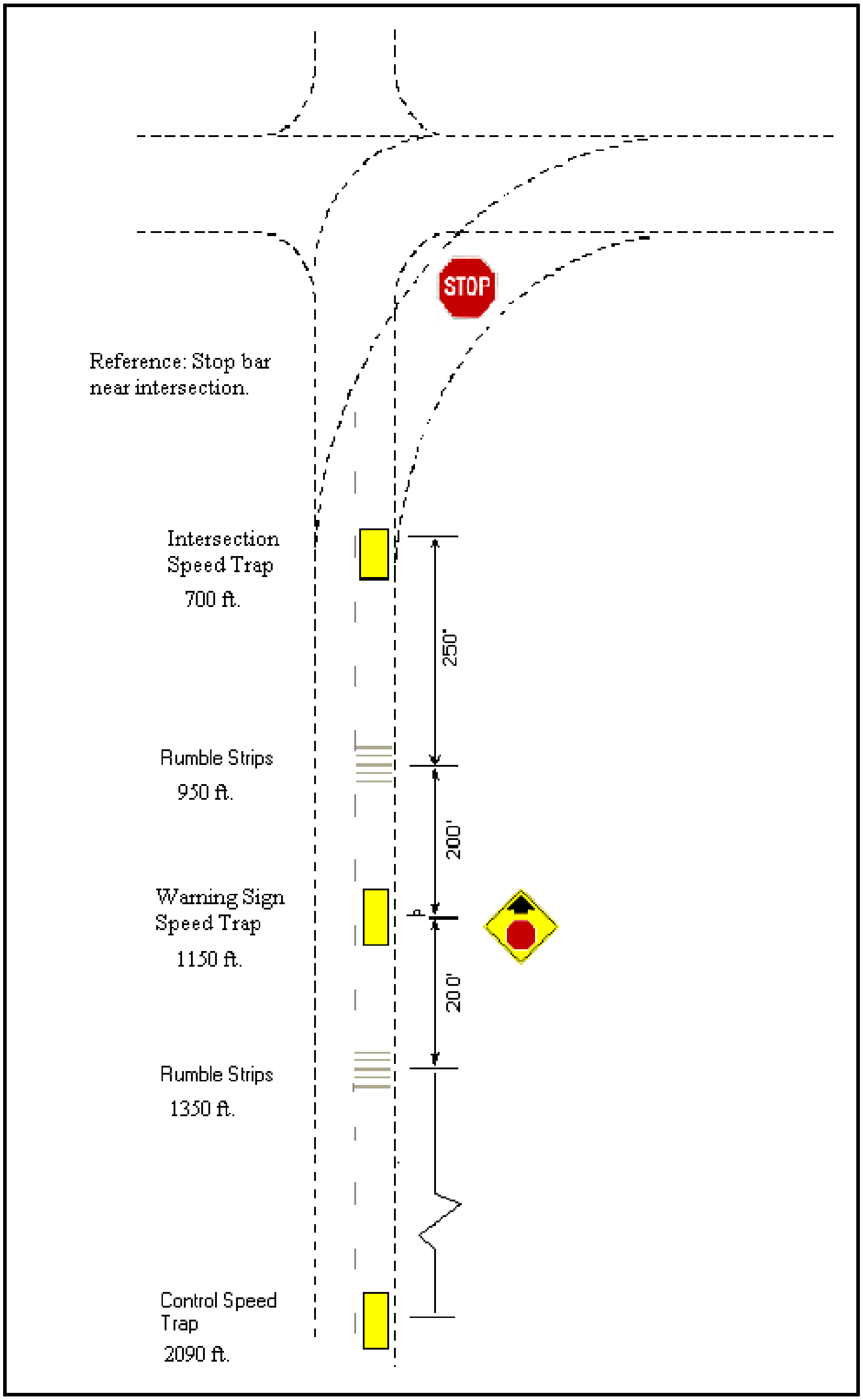

Figure A- 3. Snook (FM 50 NB) Site Layout

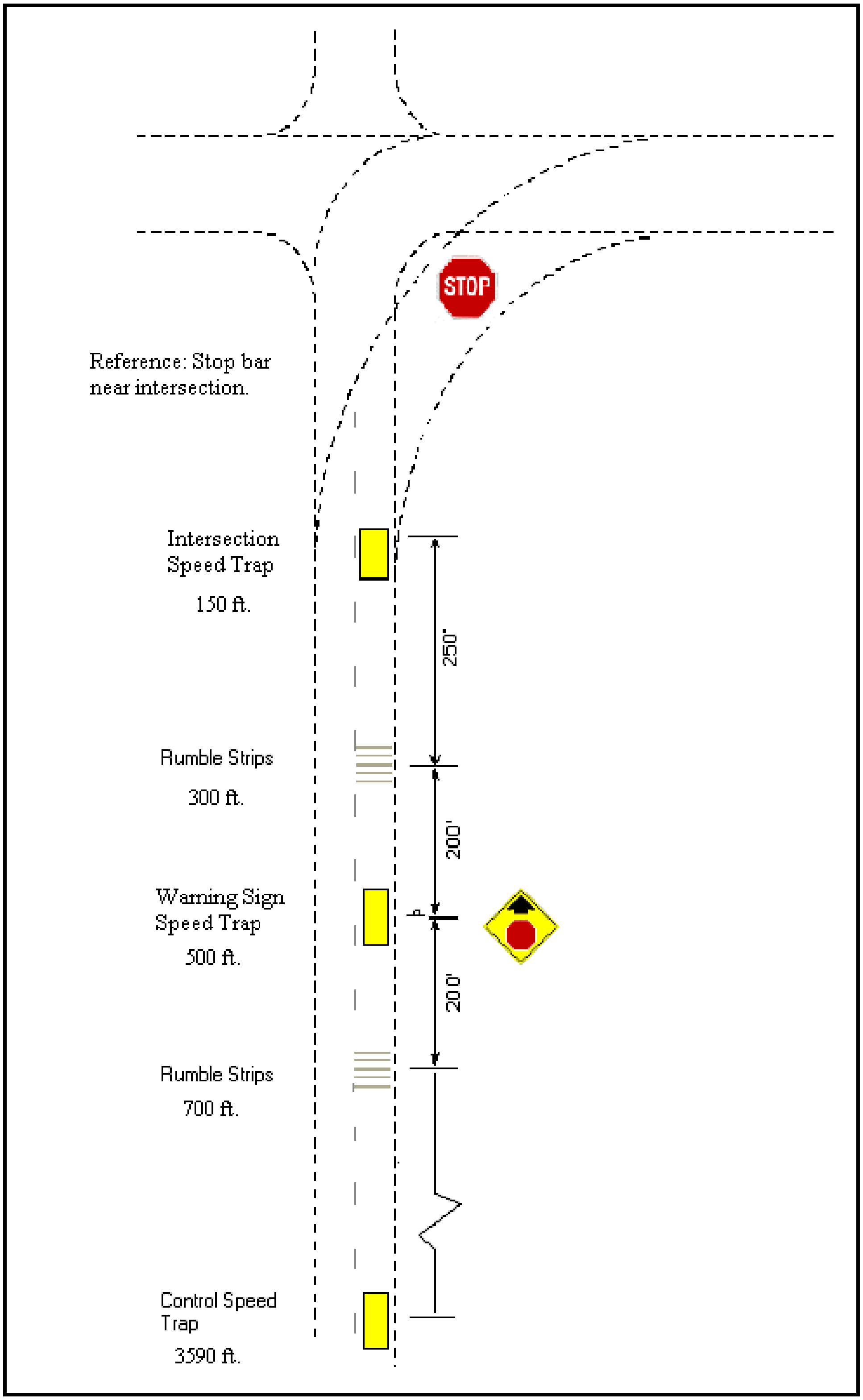

Figure A- 4. Colorado City (FM 208 SB) Site Layout

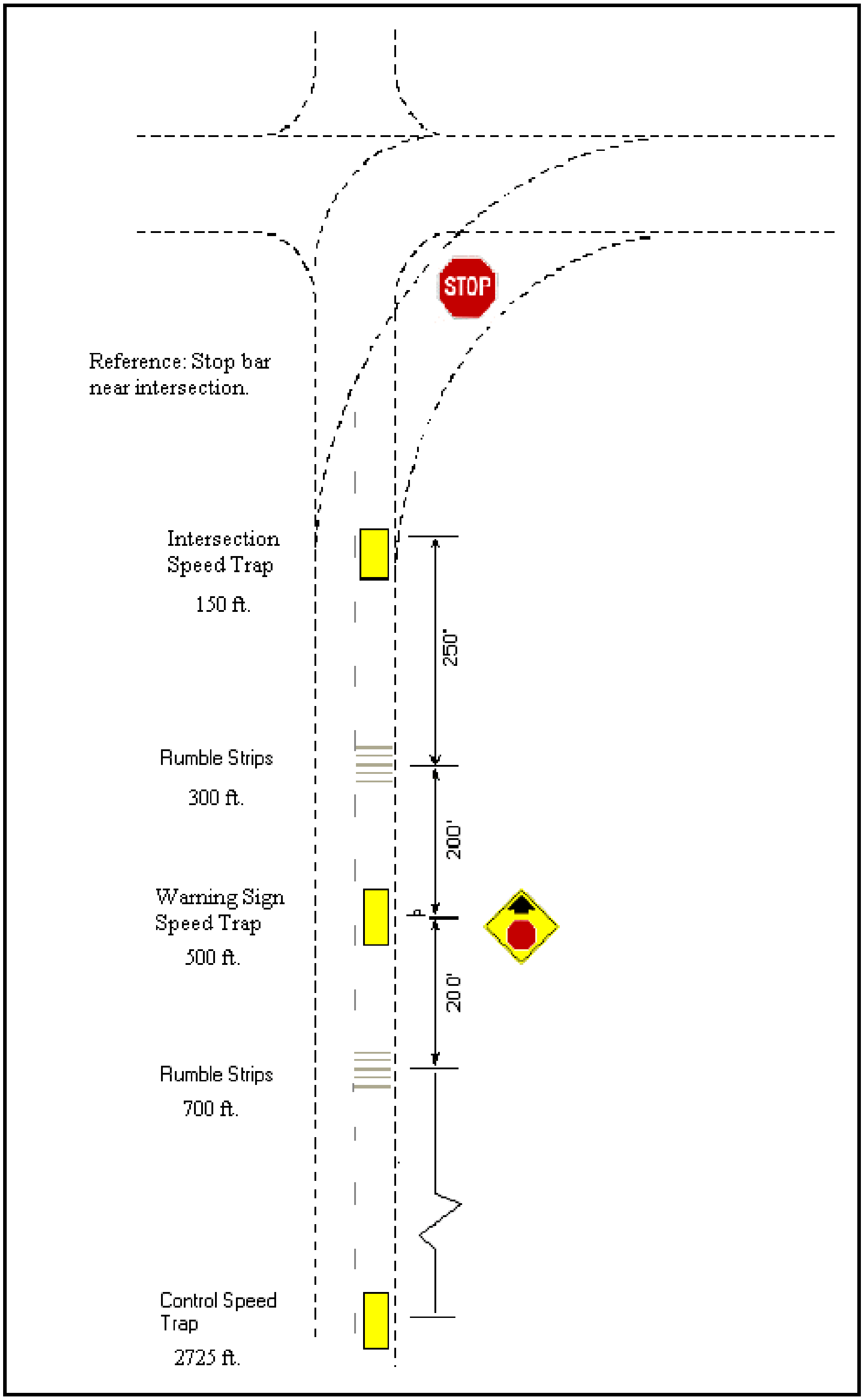

Figure A- 5. Colorado City (FM 208 NB) Site Layout

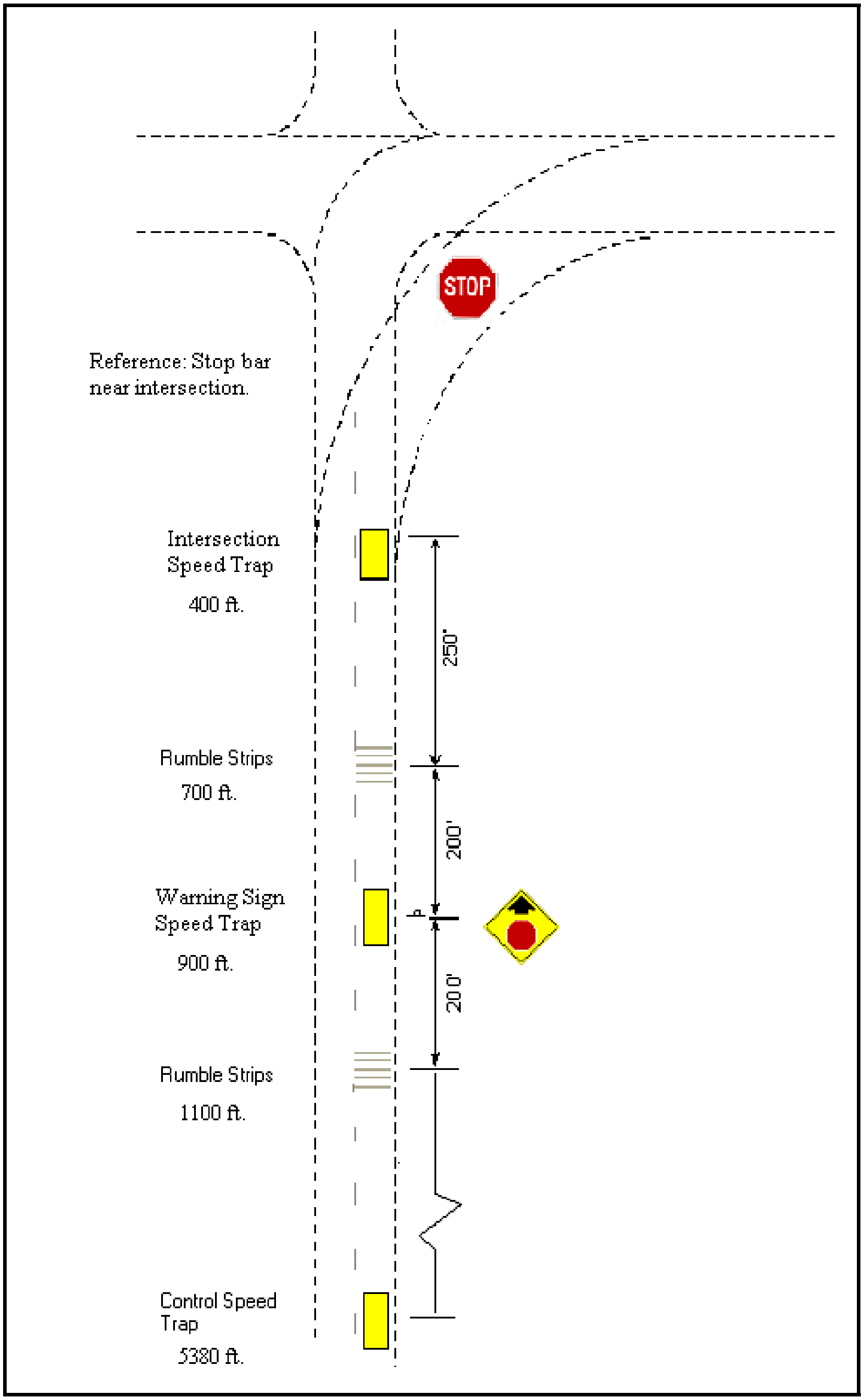

Figure A- 6. Millican (FM 2154 SB) Site Layout

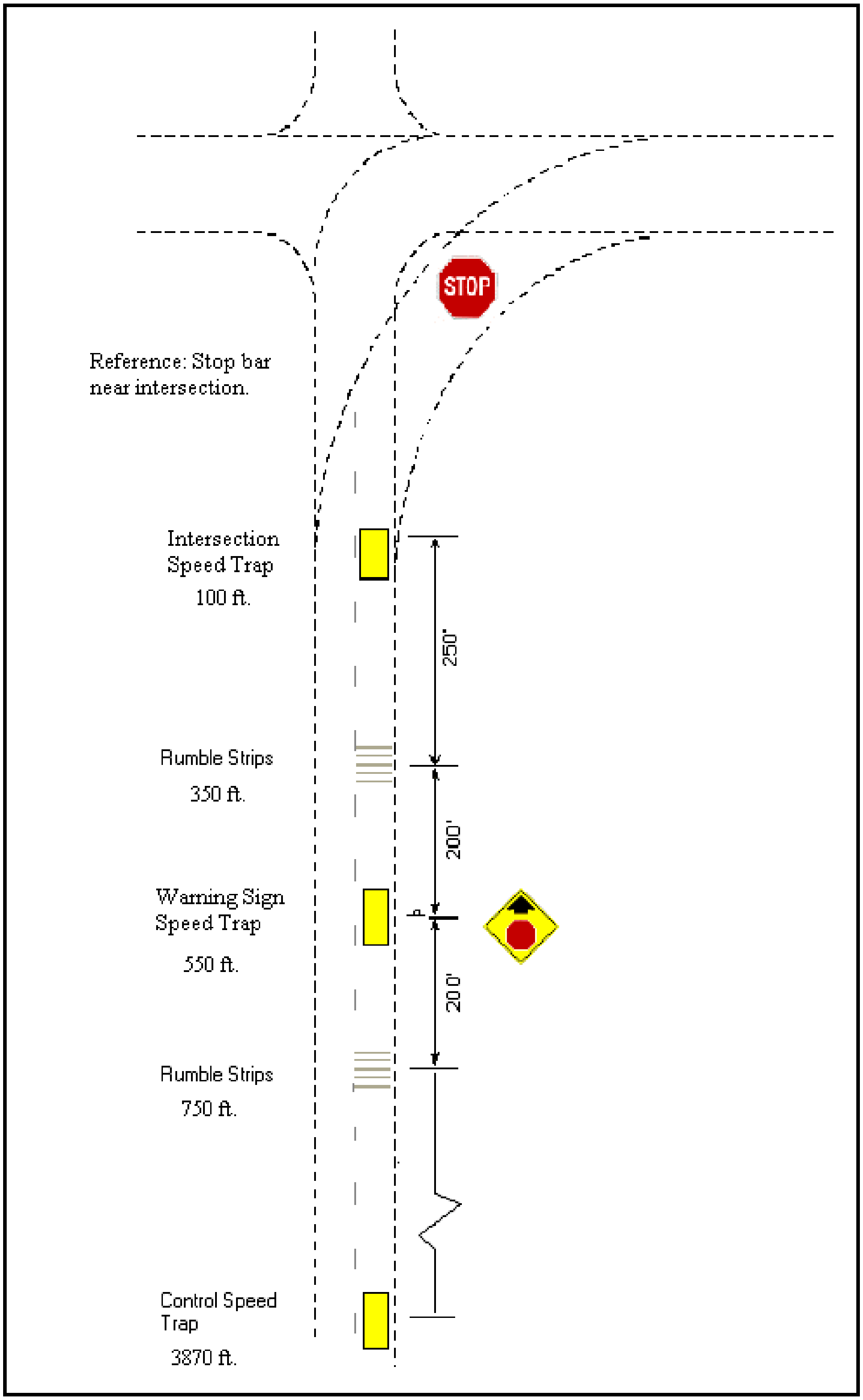

Figure A- 7. Millican (FM 2154 NB) Site Layout

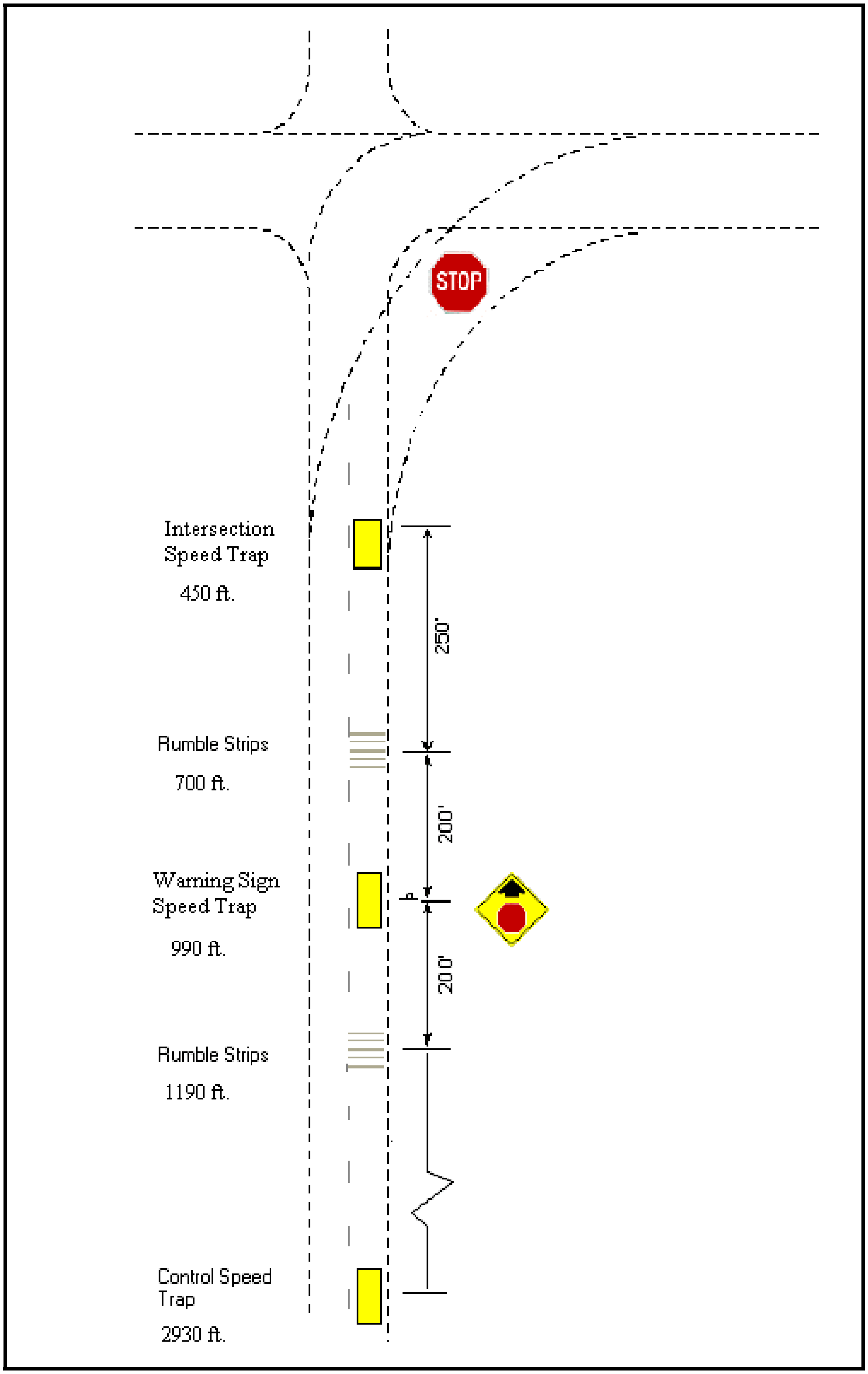

Figure A- 8. Hearne (FM 2549 NB) Site Layout

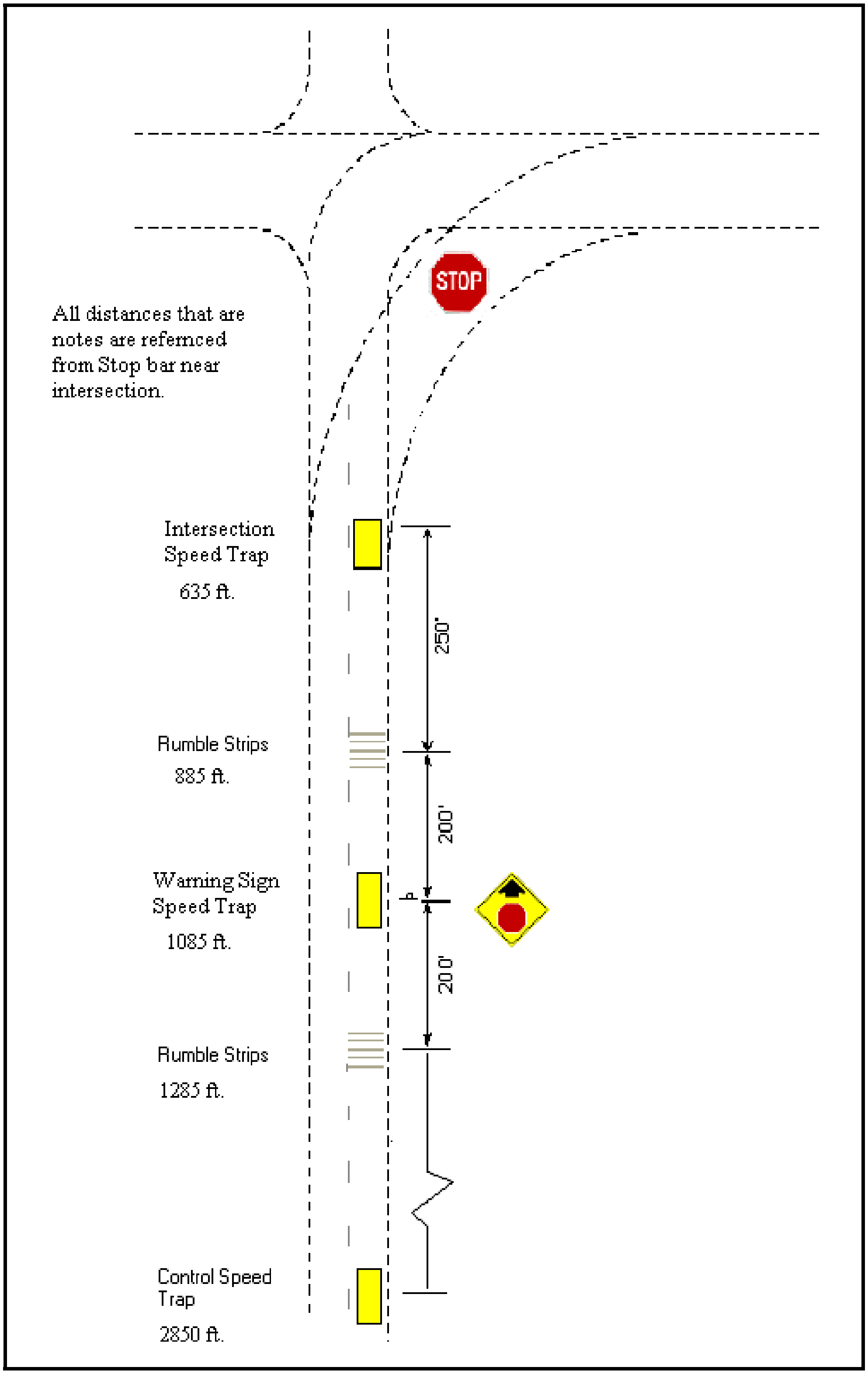

Figure A- 9. Hearne (FM 2549 SB) Site Layout

APPENDIX B

SITE SUMMARY STATISTICS

Table B- 1. Bosque County (FM 3118) Summary Statistics

Statistic	Control Location		Warning Location		Intersection Location	
	Before	After	Before	After	Before	After
Sample Size	643	1476	643	1476	643	1476
Mean Speed (mph)	53	54	51	51	39	39
Median Speed (mph)	53	55	51	51	39	39
Std. Deviation (mph)	7.2	6.8	6.4	6.4	5.3	5.0
Variance (mph)	52.4	46.6	41.1	40.6	27.9	24.6
Minimum Speed (mph)	8	25	31	27	19	20
Maximum Speed (mph)	76	76	74	73	54	54
85^{th} Percentile Speed (mph)	60	61	57	58	45	44

Table B- 2. Snook (FM 50 SB Turning Vehicles) Summary Statistics

Statistic	Control Location		Warning Location		Intersection Location	
	Before	After	Before	After	Before	After
Sample Size	318	101	318	101	318	101
Mean Speed (mph)	33	34	55	58	45	48
Median Speed (mph)	33	34	56	59	46	48
Std. Deviation (mph)	3.8	4.1	7.1	8.2	7.4	6.9
Variance (mph)	14.1	17.1	49.9	67.7	54.4	46.9
Minimum Speed (mph)	21	22	29	32	19	20
Maximum Speed (mph)	46	45	76	77	63	61
85^{th} Percentile Speed (mph)	37	39	63	66	52	55

Table B- 3. Snook (FM 50 SB Highway Vehicles) Summary Statistics

Statistic	Control Location		Warning Location		Intersection Location	
	Before	After	Before	After	Before	After
Sample Size	437	239	437	239	437	239
Mean Speed (mph)	68	66	57	58	45	46
Median Speed (mph)	68	67	57	58	47	46
Std. Deviation (mph)	8.4	8.7	8.3	7.7	7.9	7.1
Variance (mph)	71.3	76.3	68.1	59.6	63.3	50.9
Minimum Speed (mph)	46	47	32	41	19	19
Maximum Speed (mph)	97	97	80	80	67	67
85th Percentile Speed (mph)	75	74	66	65	53	53

Table B- 4. Snook (FM 50 NB) Summary Statistics

Statistic	Control Location		Warning Location		Intersection Location	
	Before	After	Before	After	Before	After
Sample Size	1689	1167	1689	1167	1689	1167
Mean Speed (mph)	68	72	62	61	54.3	53
Median Speed (mph)	69	72	62	61	55	52
Std. Deviation (mph)	6.9	7.7	7.1	7.1	6.4	6.5
Variance (mph)	48.1	58.6	50.0	50.9	41.4	41.9
Minimum Speed (mph)	46	34	36	39	35	36
Maximum Speed (mph)	92	109	85	89	75	75
85^{th} Percentile Speed (mph)	75	79	69	69	61	60

Table B- 5. Colorado City (FM 208 SB) Summary Statistics

Statistic	Control Location		Warning Location		Intersection Location	
	Before	After	Before	After	Before	After
Sample Size	710	151	710	151	710	151
Mean Speed (mph)	52	56.46	47	44	36	33
Median Speed (mph)	53	56	47	44	36	33
Std. Deviation (mph)	7.1	8.6	6.5	6.3	5.1	4.8
Variance (mph)	50.1	73.2	42.5	39.2	25.5	23.1
Minimum Speed (mph)	30	25	25	30	23	20
Maximum Speed (mph)	78	83	69	61	52	46
85^{th} Percentile Speed (mph)	59	65	53	51	41	38

Table B- 6. Colorado City (FM 208 NB) Summary Statistics

Statistic	Control Location		Warning Location		Intersection Location	
	Before	After	Before	After	Before	After
Sample Size	327	189	327	189	327	189
Mean Speed (mph)	56	53	45	43	35	36
Median Speed (mph)	55	53	45	43	35	36
Std. Deviation (mph)	7.1	7.3	5.5	5.4	5.5	5.2
Variance (mph)	50.9	52.6	30.3	29.4	29.7	27.2
Minimum Speed (mph)	30	33	26	25	15	18
Maximum Speed (mph)	73	75	63	57	51	52
85^{th} Percentile Speed (mph)	63	61	50	48	40	41

Table B- 7. Millican (FM 2154 SB) Summary Statistics

Statistic	Control Location		Warning Location		Intersection Location	
	Before	After	Before	After	Before	After
Sample Size	365	557	365	557	365	557
Mean Speed (mph)	66	67	56	57	45	46
Median Speed (mph)	67	67	56	57	45	46
Std. Deviation (mph)	6.5	6.3	6.9	6.7	6.0	5.6
Variance (mph)	41.7	40.0	47.2	45.2	35.4	31.4
Minimum Speed (mph)	41	36	37	33	22	31
Maximum Speed (mph)	87	87	86	77	69	66
85th Percentile Speed (mph)	72	73	63	64	50	52

Table B- 8. Millican (FM 2154 NB) Summary Statistics

Statistic	Control Location		Warning Location		Intersection Location	
	Before	After	Before	After	Before	After
Sample Size	1146	526	1146	526	1146	526
Mean Speed (mph)	66	65	52	52	39.6	40
Median Speed (mph)	67	66	52	52	40	40
Std. Deviation (mph)	7.4	7.4	7.1	7.2	6.2	6.3
Variance (mph)	55.1	54.5	49.9	52.4	38.2	39.9
Minimum Speed (mph)	39	33	23	29	19	15
Maximum Speed (mph)	105	87	77	72	66	62
85^{th} Percentile Speed (mph)	73	73	60	60	46	46

Table B- 9. Hearne (FM 2549 NB) Summary Statistics

Statistic	Control Location		Warning Location		Intersection Location	
	Before	After	Before	After	Before	After
Sample Size	642	351	642	351	642	351
Mean Speed (mph)	64	62	59.6	58	50	49
Median Speed (mph)	64	62	60	58	50	50
Std. Deviation (mph)	9.4	9.2	7.6	7.3	6.4	6.1
Variance (mph)	89.2	84.1	57.1	52.6	40.5	36.6
Minimum Speed (mph)	29	25	37	36	32	31
Maximum Speed (mph)	101	87	90	88	75	63
85^{th} Percentile Speed (mph)	74	71	67	65	56	55

Table B- 10. Hearne (FM 2549 SB) Summary Statistics

Statistic	Control Location		Warning Location		Intersection Location	
	Before	After	Before	After	Before	After
Sample Size	587	225	587	225	587	225
Mean Speed (mph)	59	61	57	55	50	48
Median Speed (mph)	61	61	57	56	50	48
Std. Deviation (mph)	10.5	10.1	8.0	9.4	7.1	7.3
Variance (mph)	110.0	102.7	63.3	88.2	49.9	52.9
Minimum Speed (mph)	18	24	31	16	29	30
Maximum Speed (mph)	87	81	93	78	74	66
85^{th} Percentile Speed (mph)	69	72	65	66	57	55

APPENDIX C

SITE HISTOGRAMS

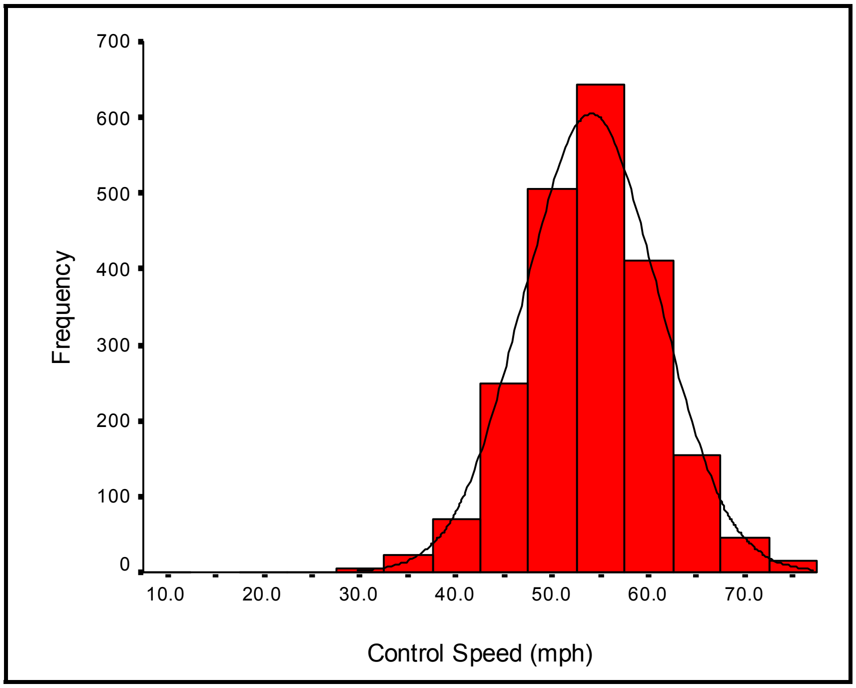

Figure C- 1. Bosque County (FM 3118) Histogram

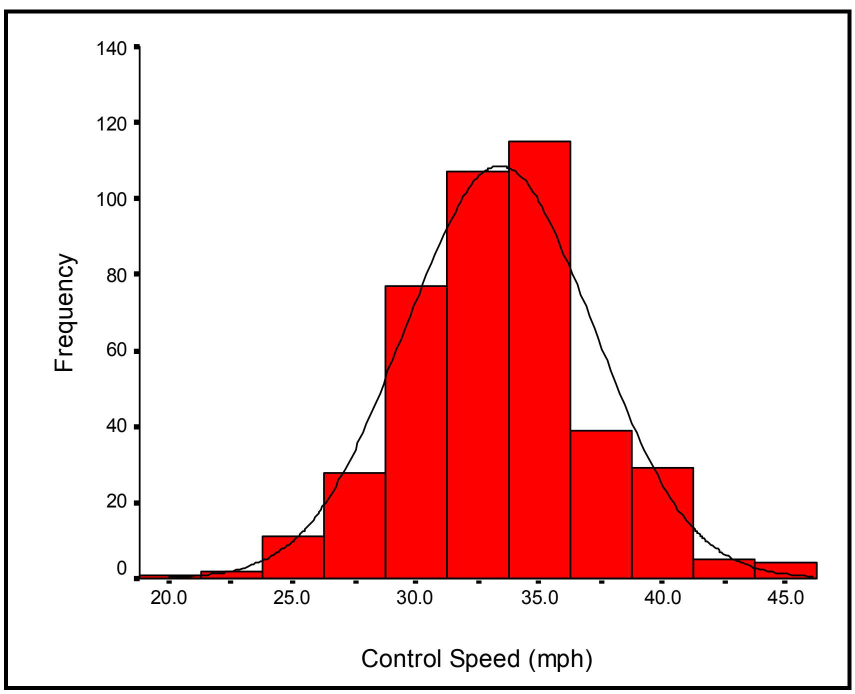

Figure C- 2. Snook (FM 50 SB Turning Vehicles) Histogram

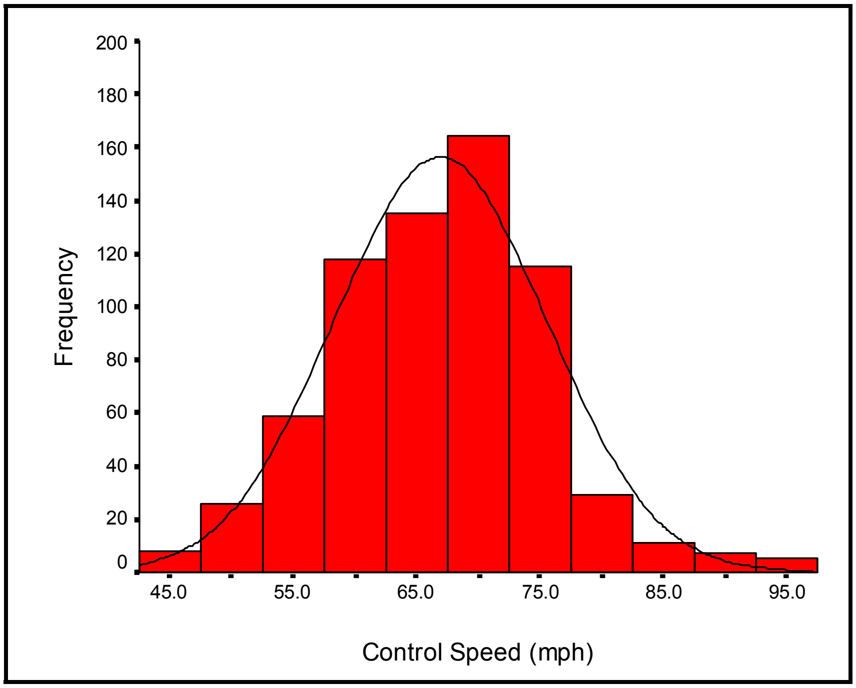

Figure C- 3. Snook (FM 50 SB Highway Vehicles) Histogram

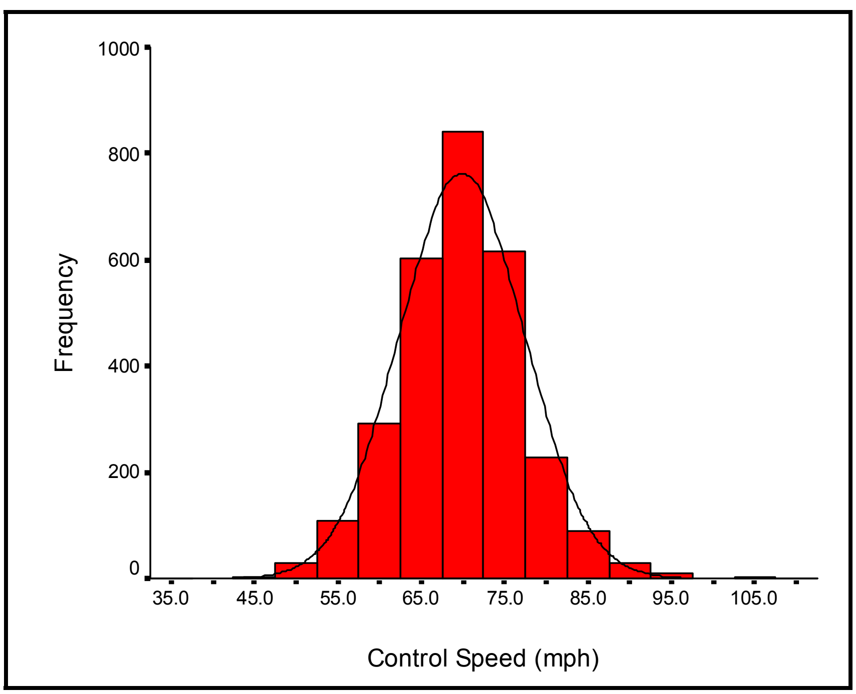

Figure C- 4. Snook (FM 50 NB) Histogram

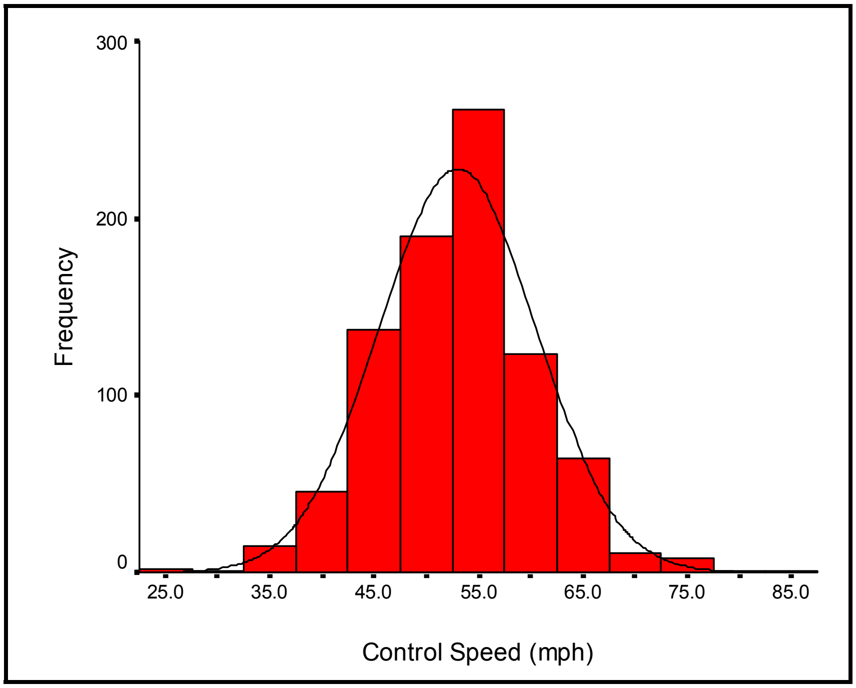

Figure C- 5. Colorado City (FM 208 SB) Histogram

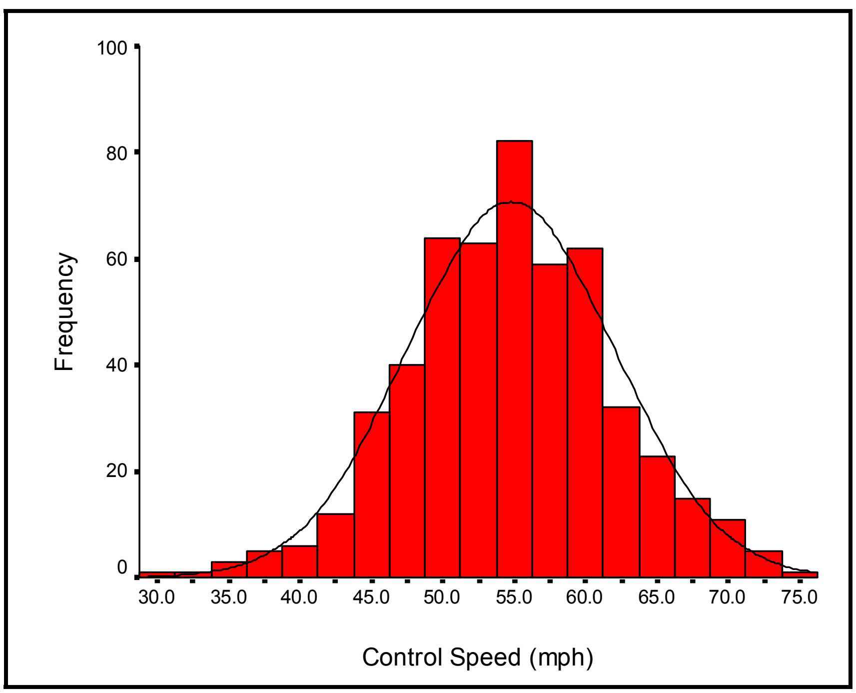

Figure C- 6. Colorado City (FM 208 NB) Histogram

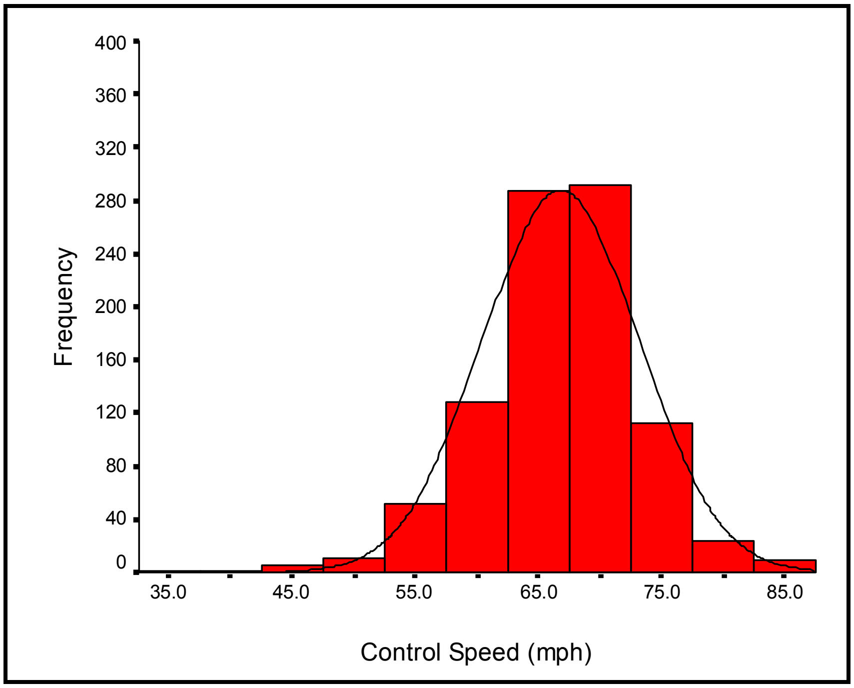

Figure C- 7. Millican (FM 2154 SB) Histogram

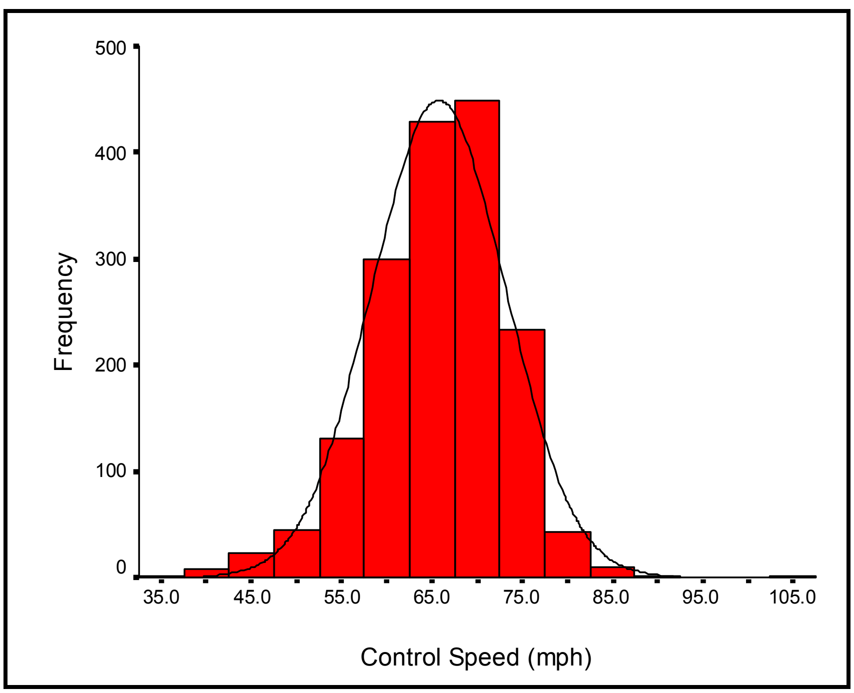

Figure C- 8. Millican (FM 2154 NB) Histogram

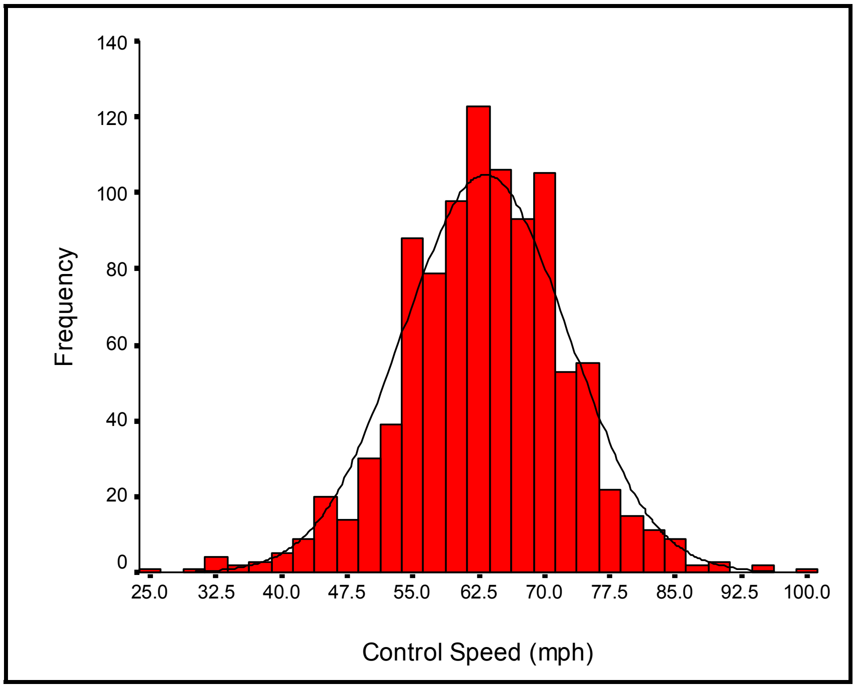

Figure C- 9. Hearne (FM 2549 NB) Histogram

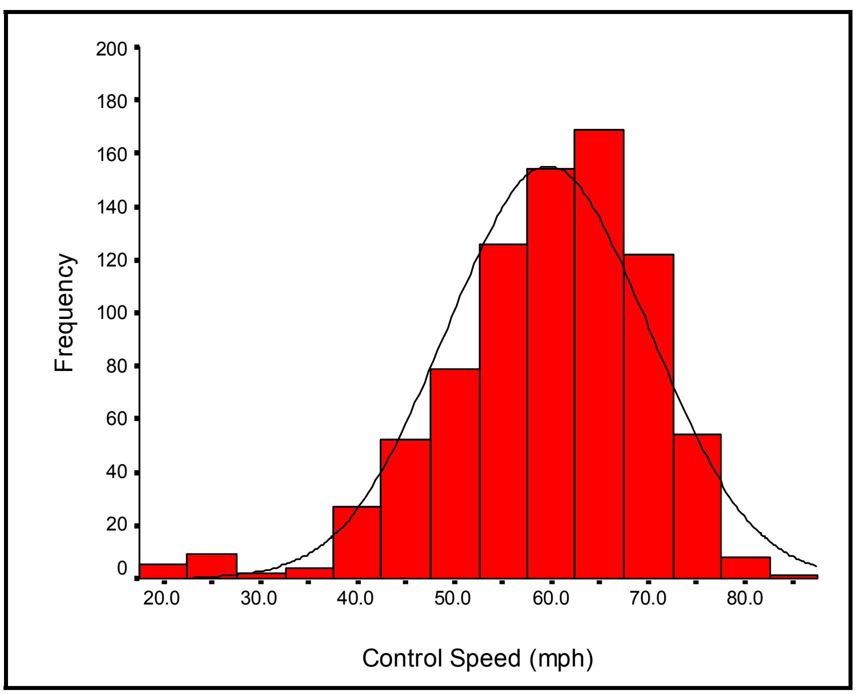

Figure C- 10. Hearne (FM 2549 SB) Histogram

VITA

Tyrell D. Thompson was born and raised in Newark, Ohio. After graduating from Licking Valley High School in 1998, he attended Ohio University where he received his Bachelor of Science degree in civil engineering in November 2002. Ty's activities included Theta Tau National Engineering Fraternity, Tau Beta Pi Ohio Delta Chapter, American Society of Civil Engineers, and Golden Key National Honor Society. Ty also participated in two design contests, The Big Beam Design Contest and the WERC Design Contest.

As an undergraduate, Ty completed six internships with the Licking County Engineer's Office in Newark, Ohio and two quarters of cooperative education experience with BBC&M Engineering in Dublin, Ohio. While at the Licking County Engineer's Office, Ty performed duties involving surveying, engineering design, traffic studies, and project cost estimation. Many of the projects he worked on were related to the redesign and reconditioning of several county and township roadways. With BBC&M Engineering, he worked on many projects involving highway and heavy construction. Many of his duties involved surveying, construction inspection, material testing, and subsurface investigations.

After graduating from Ohio University, Ty pursued a Master of Science degree in civil engineering at Texas A&M University. While at Texas A&M University, he was employed by the Texas Transportation Institute. He received his Master of Science degree in civil engineering in August of 2004.

Ty's areas of interest include geometric highway design, transportation planning, corridor planning, transit planning and design, and transportation economics. Questions or comments regarding this thesis can be sent to 221 Fairway Drive, Pataskala, Ohio 43062.