This is to certify that the dissertation entitled

EVALUATION OF VARIABLE SPEED LIMITS IN WORK ZONES

presented by

Disapat Lavansiri

has been accepted towards fulfillment of the requirements for the

Ph.D. degree in Civil Engineering

William C. Taylor
Major Professor's Signature

12 AUG 2003

Date

PLACE IN RETURN BOX to remove this checkout from your record.
TO AVOID FINES return on or before date due.
MAY BE RECALLED with earlier due date if requested.

DATE DUE	DATE DUE	DATE DUE
APR 0[illegible] 2006		
0516/06		

EVALUATION OF VARIABLE SPEED LIMITS IN WORK ZONES

By

Disapat Lavansiri

A DISSERTATION

Submitted to
Michigan State University
in partial fulfillment of the requirements
for the degree of

DOCTOR OF PHILOSOPHY

Department of Civil and Environmental Engineering

2003

ABSTRACT

EVALUATION OF VARIABLE SPEED LIMITS IN WORK ZONES

By

Disapat Lavansiri

The use of variable speed limits (VSL) permits the posted speeds to be determined based on current conditions and to vary by time and location within work zones. This research evaluated the effectiveness of the VSL system under various work zone conditions based on data collected during a field test in work zones in Michigan. The measures of effectiveness used in this evaluation included changes in average speed, travel time through the work zone, 85th percentile speed, speed variance, and percentage of higher speed vehicles. MOE data "before," "during," and "after" the VSL operation were compared.

The results indicated that the VSL system worked well at locations in the work zone where there were no ramps in the vicinity. Relatively large increases in the displayed speeds (8-10 mph) at these locations resulted in small increases in the average speeds (1-2 mph), which in turn resulted in the reductions in the travel times through the work zone. The percentage of higher speed vehicles at most of the locations either stayed the same or became lower "during" the VSL deployments, which indicates an improvement in speed limit compliance. However, at most trailers the 85th percentile speeds did not change in the same direction as the changes in the displayed speeds as hypothesized. The impact of the system on speed variance was inconsistent.

Although the changes in the average speed and the travel time following the deployment of VSL were small, they were in the right direction. The VSL did respond to the day-to-day and trailer-to-trailer average speed variations, and thus the credibility of the posted speed limit was improved.

ACKNOWLEDGEMENTS

I would like to thank my advisor, Dr. William Taylor, for his invaluable advice and support throughout my graduate student years at Michigan State University and for giving me an opportunity to work on the variable speed limit project.

I would also like to thank Dr. Richard Lyles, my committee member, for giving me an opportunity to work on the variable speed limit project and for his support and direction throughout this project.

I would like to give thanks to Dr. James Hannan and Dr. Ghassan Abu-lebdeh, my committee members, for their professional suggestions.

I would like to acknowledge the Federal Highway Administration and the Michigan Department of Transportation for providing a financial support for this research.

Last but not least, I would like to show my gratitude to my parents, Direk and Supatra Lavansiri, who have always given me unconditional support and encouragement.

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

Chapter 1

INTRODUCTION

1.1 Description of the problem

In work zones, static speed limits are sometimes not credible for the motorists because they cannot reflect up-to-date roadway conditions, traffic flow conditions, and construction activities. For example, there are many long work zones marked with low speed limits where no construction activity occurs until miles after the start of the work zone. The use of variable speed limits (VSL) permits the posted speeds to be determined based on current conditions and to vary within the site, which may result in higher speed limit compliance and lower speed variance. Consequently, VSL may reduce congestion and improve safety in work zones. However, the use of VSL in work zones has not been thoroughly studied. In this study, the implementation of VSL in work zones was tested to determine their effectiveness under various conditions.

1.2 Objective and scope of the research

A VSL system designed to improve traffic flow and safety in work zones was evaluated in this research. The scope of the research includes:

a. identification of measures of effectiveness (MOEs) to quantify the impact of the VSL system; and

b. evaluation of the impacts of the VSL system on these MOEs under various work zone conditions.

1.3 Research approach

This research is based on data collected during a field test of variable speed limits in work zones in Michigan. This project was sponsored by the Federal Highway Administration (FHWA) and the Michigan Department of Transportation (MDOT). The VSL system was tested under various traffic conditions, a variety of work activities, and different types of traffic separations. The hourly traffic conditions ranged from relatively low volume to congested conditions. The work activities and traffic separations ranged from minor work (concrete patching) with exposed workers separated from adjacent traffic only by barrels to intense work (total reconstruction) with workers separated from adjacent traffic by a median. The four work zones used in this study were part of the one large work zone, which was located on I-96 from US-127 to Wacousta Road as shown in figure 1.1 (Images in this dissertation are presented in color.). This part of I-96 skirts the southern and western edges of Lansing, Michigan. Different speed limit setting algorithms were developed for each work zone. The MOE data were collected "before", "during", and "after" the VSL deployment (although not in all three time periods in each zone). The data "before" and "after" each VSL deployment were used as a base case. For the base case, the speed limit was posted at a constant 50 mph. The MOEs in the "before," "during," and "after" conditions are compared and discussed in the following chapters.

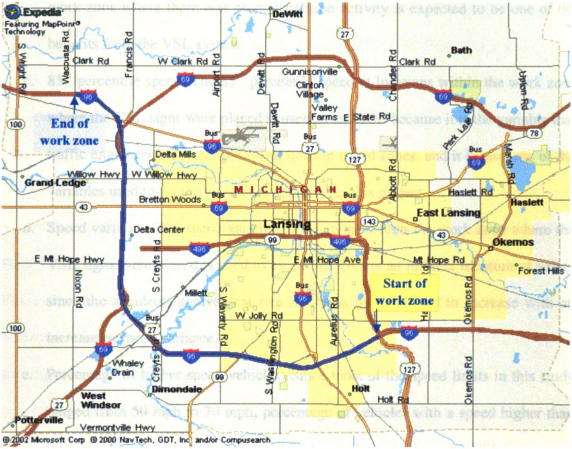


Figure 1.1. I-96 work zone site

1.4 Measures of effectiveness

The variables measured or calculated to determine the effectiveness of the VSL system are:

a. Average speed: The average speed at locations within the work zone where the VSL signs were placed is used as one MOE. Changes in the average speed at these locations are one measure of a change in the motorists' behavior.

b. Travel time through the work zone: The travel time through the part of the work zone where the VSL system was located is also used as an MOE. This travel time is estimated from the average speeds. A decrease in travel time in the part of the work zone where there was no construction activity is expected to be one of the benefits from the VSL system.

c. 85th percentile speed: The 85th percentile speed at locations within the work zone where the VSL signs were placed is used as an MOE because it is the variable that traffic engineers use to set the speed limit in speed zones, and it is also one of the variables used to set the variable speed limit in this project.

d. Speed variance: The speed variance at locations within the work zone where the VSL signs were placed is used as an MOE. This is an indirect measure of safety since the accident involvement rate has been hypothesized to increase with an increase in speed variance.

e. Percentage of higher speed vehicles: Since most of the speed limits in this study ranged from 50 mph to 70 mph, percentage of vehicles with a speed higher than 60 mph and 70 mph at locations within the work zone where the VSL signs were placed are used as an MOE. The percentage of higher speed vehicles is used as a surrogate measure of speed limit compliance.

Chapter 2

LITERATURE REVIEW

The literature on speed characteristics and accident relationship will be reviewed. Then, the mechanism for setting and enforcing speed limits in work zones, particularly in VSL-controlled work zones, will be reviewed. Finally, previous applications of VSL will be discussed.

2.1 Speed-accident relationship

Many studies have been conducted on the relationship between speed and accident involvement. The most widely referenced study was conducted by David Solomon in 1964. Solomon (1964) documented the speed and characteristics on a sample of vehicles and drivers involved in accidents on two- and four-lane main rural highways in 11 states. This study was based on the accident records of nearly 10,000 drivers, speed observations, and interviews with 290,000 drivers. Solomon found a U-shaped relationship between crash involvement rates and travel speeds with the lowest crash involvement rate at a speed slightly above the average speed. He indicated that "the greater the variation in speed of any vehicle from the average speed of all traffic, the greater its chance of being involved in an accident" and that "the severity of accidents increased as speed increased, especially at speeds exceeding 60 mph." However, critics of Solomon's study question the dependence on police accident reports for the pre-crash speeds of the accident-involved vehicles, since these can be unreliable.

West and Dunn (1971) conducted a study on accidents, speed deviation, and speed limits on Indiana Highway 37. This study was based on the average speeds from magnetic loop detectors and the estimated speeds of accident-involved vehicles from professional accident investigators. The accuracy of the speed estimate in Solomon's study was addressed by recording the pre-crash speeds of the accident-involved vehicles at the time of the crash. The results showed that the involvement rate was higher for the vehicles deviating on the slow side than for the vehicles deviating on the fast side. However, after the accidents involving turning vehicles were deleted, the involvement rate was approximately the same for high and low speed deviations and the involvement rate was lowest when the vehicles traveled close to the average speed. The U-shaped relationship (figure 2.1) became flatter than Solomon's because the elevated accident involvement rates for the slower vehicles were reduced. Harkey, Robertson, and Davis (1990) also found the U-shaped relationship between crash involvement rate and deviation from the average speed with the lowest involvement rate at 7 mph above the mean speed or at about the 90th percentile of the travel speeds observed. This study was based on two-lane and multi-lane highways in North Carolina and Colorado. The accidents considered in this study were limited to weekday, non-alcohol, and non-intersection involved.

A more recent study by Aljanahi, Rhodes and Metcalfe (1999) investigated the relationship between traffic speed characteristics and personal injury accidents under free flow conditions. This study was based on accident records in Tyne and Wear County of the United Kingdom, and in Bahrain. Only non-intersection accidents not involving pedestrians were considered. Aljanahi et al. indicated that in Bahrain, there is statistically significant evidence of an association between mean speed and accident rate, while in Tyne and Wear the statistical relationship is weaker and points to a stronger relationship between accident rate and the variability of traffic speed.

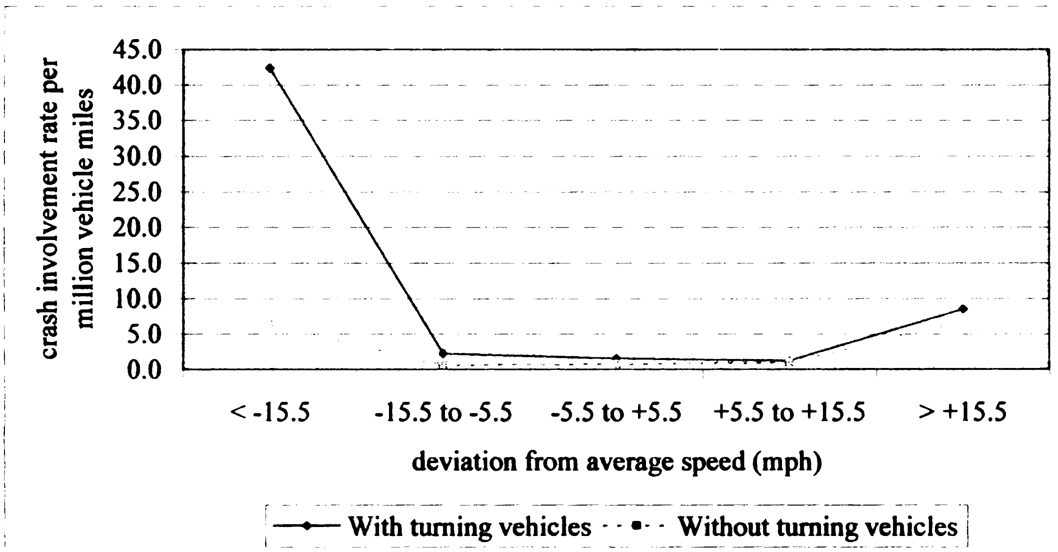


Figure 2.1. Accident involvement rates with and without turning vehicles (West and Dunn, 1971)

All of these studies were conducted on non-limited access highways. A study similar to Solomon's was done on interstate freeways in 20 states by Cirillo (1968). Cirillo indicated that as the speed of a vehicle deviates from the mean speed of traffic, either above or below the mean speed, the chance of the vehicle being involved in an accident increases. The lowest accident involvement rate occurred at 12 mph above the mean speed. The comparison of the accident involvement rate by deviation from mean speed between Solomon's and Cirillo's is shown in figure 2.2.

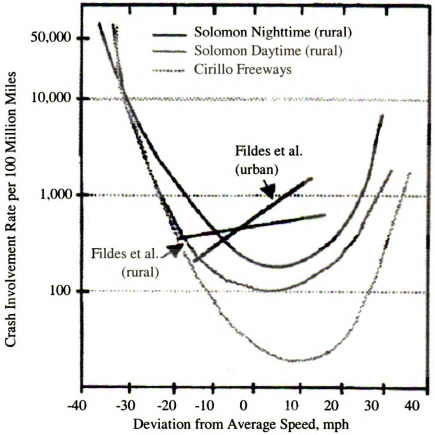


Figure 2.2. Accident involvement rates by variation from mean speeds (Committee for Guidance on Setting and Enforcing Speed Limits, 1998)

Garber and Gadiraju (1989) performed a study on "factors affecting speed variance and its influence on accidents" on 36 locations of interstate freeways, arterial highways, and collector roads in Virginia from 1983 through 1986. Traffic data were collected by a traffic recorder, while accident data were obtained from the Virginia Department of Transportation and Virginia Department of Motor Vehicles. Garber and Gadiraju concluded that "accident rates increase with increasing speed variance for all classes of roads" and that "the accident rate on a highway does not necessarily increase with an increase in average speed." They also suggested that "speed variance will approach minimum values if the posted speed limit is between 5 and 10 mph lower than the design speed." Lave (1985) investigated the relationship between speed and the fatality rate based on the accident records in 1981 and 1982 on interstates, arterials and collectors in all of the states, except Alaska and Hawaii. The results indicated that there is no statistically discernable relationship between the fatality rate and average speed, though there is a strong positive relationship between fatality rate and speed variance.

There are also a few studies where conflicting results were found. Fildes, Rumbold, and Leening (1991) examined crash involvement rates as a function of speed on urban arterials and two-lane rural roads in Australia. The results indicated that the accident involvement rate has a positive linear relationship with travel speed instead of the U-shaped relationship found in previous studies (figure 2.2). The accident involvement rates were lowest at speeds below the average speed and highest at speeds above the average speed. The problems with this study were that the results were based on a small sample size and self-reported crash involvement and speed. Another Australian study by Kloeden, McLean, and Moore (1997) partly supported the result from Fildes et al. Kloeden et al. found a positive relationship between the probability of involvement in a casualty crash and speeds above, but not below the average speed. The study focused on weekday, daylight accidents, excluding alcohol-related crashes in the Adelaide metropolitan area. The Committee for Guidance on Setting and Enforcing Speed Limits (1998) indicated that the absence of a significant association between speed and crash involvement at speeds below the average traffic speed may well be the result of the study design that excluded all but injury crashes, since crashes at lower speeds tend to be less severe.

Although the results from all of the studies reviewed are not completely consistent, most studies found that there is a U-shaped relationship between crash involvement rates and travel speeds with the lowest crash involvement rate at speeds slightly above the average speed and that the accident involvement rate increases with an increase in speed variance, but does not necessarily increase with an increase in average speed.

Because of the short duration of each VSL deployment in this study, it was not possible to conduct a safety analysis.

2.2 Work zone speed limits setting and enforcement

2.2.1 Work zone speed limits setting

A major problem in setting work zone speed limits is the lack of uniform guidelines for determining the appropriate speed limit in any situation. The Manual on Uniform Traffic Control Devices (MUTCD, 2001) only presents a general guideline for determining speed limits. The MUTCD states that "when a speed limit is to be posted, it should be the 85^{th} percentile speed of free flowing traffic, rounded up to the nearest 10 km/h (5 mph) increment. Other factors that may be considered when establishing speed limits are the following: A. road characteristics, shoulder condition, grade, alignment, and sight distance; B. the pace speed; C. roadside development and environment; D. parking practices and pedestrian activity; and E. reported crash experience for at least a 12-month period. "

In an attempt to develop work zone guidelines, Graham-Migletz Enterprise, Inc. (GME, 1996) conducted a study for the National Cooperative Highway Research Program (NCHRP) on "A Procedure for determining work zone speed limits." The research approach included a survey of state highway agencies to determine the existing work zone speed limit policies, and an analysis of speed and accident data from 68 work zone sites in seven states: California, Florida, Georgia, Iowa, Missouri, Montana, and New York. The existing highway agency work zone speed limit policies and guidelines were investigated by sending questionnaires to all 52 state highway agencies in the United States. The results indicated that there were three general policies used by state highway agencies: (1) eighteen states avoid speed limit reductions whenever possible (Speed limits are set based on specific factors when they are necessary.); (2) five states use blanket speed limit reductions at all work zone sites; and (3) twenty-nine states establish the need for a work zone speed limit based on specific factors. Among the seven states where the analysis of speed and accident data were conducted, California, Florida, and Iowa avoid speed limit reductions whenever possible, Georgia and Montana use blanket speed limit reductions, and Missouri and New York establish the need for a work zone speed limit based on specific factors. In the past, Michigan used a combination of these approaches, with a 45-mph regulatory speed limit in work zones with lane closures, and a flexible policy on speed limits where work was on or outside of the shoulder or in work zones without lane closures.

The results from the speed data analysis conducted in the GME study indicated that motorists reduced their speed in work zones, even in work zones with no speed limit reduction. The average speeds in work zones with no speed limit reduction were approximately 5 mph lower than they were upstream of the same work zone. The speed limit compliance was greatest in work zones where the speed limit was not reduced, and decreased when the speed limit was reduced more than 10 mph. The results from the speed and accident data analysis showed that a speed limit reduction of 10 mph resulted in the smallest increase in speed variance within the work zone relative to upstream of the work zone and the smallest increase in the accident rate in the construction period relative to pre-construction period. GME concluded that:

- "Work zone speed limit reductions should be avoided whenever possible, particularly in work zones where all work activities are located on the shoulder or roadside areas and when no work activities are underway.
- A 10-mph reduction below the normal speed limit is desirable when work takes place on or near the travel way, particularly on rural freeways, or when personnel are required to work for extended periods in an unprotected position within 10 feet of the edge of the traveled way.
- Work zone speed limit reductions larger than 10 mph are undesirable and should be avoided except where required by restricted geometric or other work zone features that can not be modified."

GME recommended a four-step work zone speed limit procedure: (1) determine the existing speed limit; (2) determine the work zone condition that applies; (3) determine which factors for the applicable work zone condition apply; and (4) select the work zone speed limit. The work zone speed limit procedure flowchart is shown in figure 2.3.

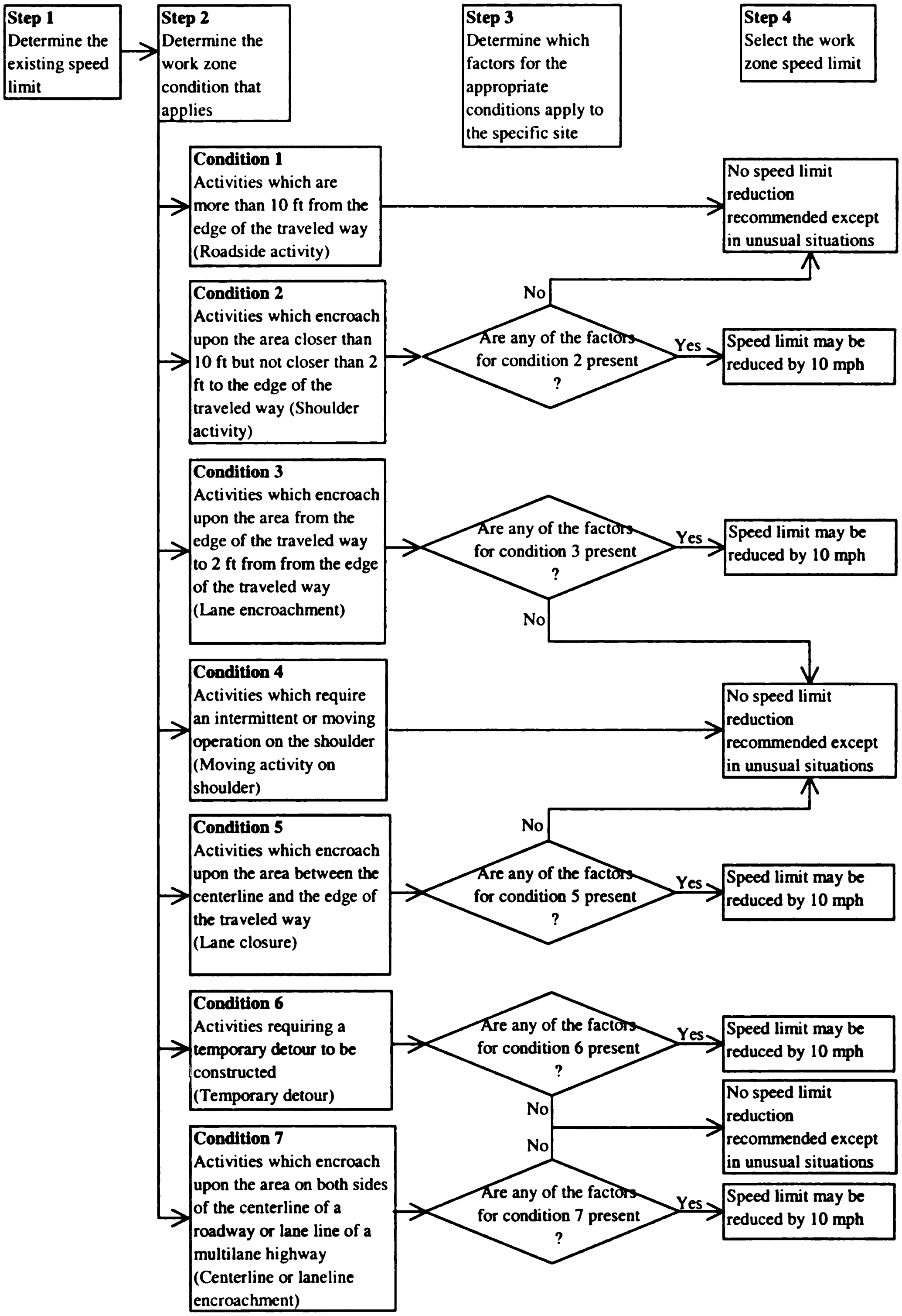


Figure 2.3. Work zone speed limit procedure flowchart (GME, 1996)

Migletz et al. (1999) conducted a validation study of their 1996 work zone speed limit procedure in 30 work zones in the same seven states. This study focused on work zones where speed limits were either not reduced or where the speed limit was reduced by 10 mph. The mean speeds, 85^{th} percentile speeds, and speed variances in work zones that implemented state highway agency policies were compared with work zones that implemented the GME work zone speed limit procedure. The average reductions in mean speed and 85^{th} percentile speed from upstream to within the work zone in work zones where the speed limit was based on the GME procedure were closer to the posted speed limit reduction than work zones where the speed limit was based on highway agency policies. Speed variance was higher in work zones than upstream of those same work zones regardless of which procedure was used. In work zones where the speed limit was based on highway agency policies, the speed variances increased by 61 and 34 percent for speed limit reductions of 0 and 10 mph respectively, while in work zones where the speed limit was based on the GME procedure, the speed variances only increased by 16 and 10 percent for speed limit reductions of 0 and 10 mph respectively. The substantial difference in speed variances between the work zones where the speed limit was based on highway agency policies and the work zones where the speed limit was based on the GME procedure was assumed to result from the more consistent speed-limit-setting procedure using the work zone activities and locations. Migletz et al. concluded that "the application of the work zone speed limit procedure leads to more uniform speed and, therefore, should result in safer and more efficient traffic operations." However, it is not clear why there would be a difference in the speed variance between locations where the speed limit change was zero based solely on the procedure used to determine that no change in the speed limit was required.

2.2.2 Work zone speed limit enforcement

Richards, Wunderlich, and Dudek (1985) evaluated several work zone speed control techniques, including flagging, law enforcement, changeable message signs, effective lane width reduction, rumble strips, and conventional regulatory and advisory speed signing. The results indicated that flagging and law enforcement were effective methods for controlling speeds in work zones. The best flagging treatment reduced speeds an average of 19 percent, while the best law enforcement treatment reduced speeds an average of 18 percent.

There were three types of law enforcement used in this study: a stationary patrol car, a circulating patrol car, and a police traffic controller. The police traffic controller is a uniformed officer standing on the side of road next to a speed sign and manually motioning traffic to slow down. Among these three types of law enforcement, the stationary patrol car and the police traffic controller were equally effective, while the circulating patrol car was less effective. Although the police traffic controller was effective, the authors concluded that it was not appropriate for a freeway due to the safety concerns. The stationary patrol car performed slightly better with the light and radar on.

Ullman (1991) verified this finding, but he also found that a radar signal without the presence of visible law enforcement personnel had only a small effect on average speeds within and approaching work zones. However, he determined that a radar signal had a slightly greater effect on vehicles approaching work zones at a speed greater than

65 mph, and on trucks because these two groups of vehicles tend to be equipped with a radar detector.

The results from a study by Richard et al. (1985) confirmed that enforcement is an important factor in work zone speed limit control. A study of the effect of enforcement strategy on traffic speeds by Hool et al. (1983) confirmed some of the findings mentioned before. Hool et al. reported that the marked stationary patrol vehicle was the most effective speed control tactic and that the unmarked patrol vehicle, even when issuing citations, had little effect on the speed.

The studies mentioned above concerned the enforcement of the speed limit in work zones in general; the enforcement of variable speed limits will be described next. One of the most successful VSL systems is located on the London orbital, M25. The variable speed limits are mandatory and are enforced by photo radar. Harbord and Jones (1996) indicated that if the motorists violate the speed limits, they will receive a ticket in the mail with a photograph of their vehicle, which includes details of the time, date, location, the vehicle speed, and the posted speed at the time of violation. Nuttall (1995) reported that this enforcement resulted in a very high speed limit compliance rate, 98 percent, during the first three months of operation in 1995. After two years of operation, Harbord (1998) indicated that there was no evidence that the level of compliance had declined. However, he reported that a small number of drivers increase their speed slightly between VSL sign gantries if the gantries are located significantly more than 1 km apart.

No study was found on the enforcement of variable speed limits in the United States, but there is a study on judicial issues related to the enforcement of variable speed limits by Hines (2002). This study examined the impact of judicial decisions and judicial enforcement on the likely success of enforcing a variable speed limit program. Hines concluded that, "where there is a delegation of authority to an administrative agency with appropriate limitations, and the agency acts within those limitations, speed limits that are established may be enforced without fear that they will be subject to challenge." She also stated that legal issues that will arise from the enforcement of variable speed limits should be no different from the legal issues that have been considered by courts in adjudicating alleged violations of prima facie speed limits and other fixed maximum speed limits.

2.3 Previous application of VSL

The previous applications of VSL are discussed below in terms of the factors used to set the speed limits.

2.3.1 Weather

- Arizona: The Fuzzy Variable Speed Limit Device (FVSLD) was installed on the I-40 corridor in rural northern Arizona. Placer (2001) indicated that the objective of the FVSLD project was to develop a reliable system to determine a safe speed for the current road and weather conditions and communicate this speed to drivers. The speed limit was based on a fuzzy logic algorithm that approximates the human reasoning process. According to Placer, this project was divided into 3 phases. In Phase I, the fuzzy concept was validated and a software system that displayed prudent highway speeds based on real-time weather and road surface conditions was developed. Phase II was concerned with hardware and software upgrades and equipment and sensor installations at the test site. Phase III included data collection regarding the road surface and weather information and confirmation of the status of enforcement and liability for Arizona. No results were published on this study.

- Utah: Perrin et al. (2000) reported on the use of the Adverse Visibility Information System Evaluation (ADVISE) system on I-215 to reduce variability in speeds between vehicles during reduced visibility events. The variable message signs (VMS) are used to advise drivers of the appropriate speed for the current condition based on the visibility information from visibility sensors, as shown in table 2.1. Perrin et al. indicated that the ADVISE system decreased the standard deviation of the speed by 22 percent and increased the overall mean speed by 15 percent on the average among all of the visibility ranges. Perrin et al. indicated that "this was accomplished by advising the overly cautious drivers that the safe speed was faster than they initially thought."

Table 2.1. Highway visibility range criteria for VMS in Utah (Perrin et al., 2000)

Highway visibility range (meters)	VMS message
> 250	No message
200 to 250	"Fog Ahead" alternating with "Poor Visibility"
150 to 200	"Max Speed 50" alternating with "Poor Visibility"
100 to 150	"Max Speed 40" alternating with "Poor Visibility"
60 to 100	"Max Speed 30" alternating with "Poor Visibility"
< 60	"Max Speed 25" alternating with "Poor Visibility"

- Washington: A VSL system was installed on I-90 across Snoqualmie Pass. The system consists of 13 light-emitting diode (LED) changeable message signs over 40 miles, but only 17 miles of the road are operated with a VSL during the winter months. Robinson (2000) indicated that the objectives of the system are to improve safety and to increase the availability of road condition and weather information to motorists crossing the Snoqualmie Pass. The regulatory speed limits are set based on roadway conditions as shown in table 2.2. The decision to reduce the speed limit is based on feedback from multiple weather stations, snowplow operators, and the State Patrol. A "Traction tire" (in table 2.2) is defined as a studded tire. A "traction tire" may also be a tire that meets tests identified by the Rubber Manufacturers Association (RMA) defining the tire as suitable for use in severe snow conditions. Ulfarsson et al. (2002) analyzed the effect of the VSL system on the relationship between mean speeds and speed deviations. The relationships were examined both at a VSL site and at a site close by. Ulfarsson et al. reported that the effect of VSL was to significantly reduce mean speed and slightly increase the speed standard deviation, but the magnitudes of the reduction in the mean speed and the increase in the speed standard deviation were not reported. The results also suggested that drivers show compensatory behavior, drivers accelerated faster when exiting the VSL zone when the speed limit was reduced than when it was not. Ulfarsson et al. indicated that this compensatory behavior could increase accident frequency downstream of the work zone, negating the safety benefits of lower mean speeds.

Table 2.2. Speed-limit-setting algorithm for Washington State (Robinson, 2000)

Roadway conditions	Speed limit (mph)
Normal	65
Traction tires advised	55
Traction tires required	45
Chains required	35

- Australia: Twelve VSL signs were installed over 7 miles of the F6 Toll Way South of Sydney. Robinson stated that the objective of this system was to reduce the number of rear-end collisions in fog. The displayed speeds, which are based on the visibility distance and the speed of the preceding vehicle, are advisory. No results were published on this study.
- Finland: A VSL system was installed on E18 in Southern Finland. The system consists of 67 VSL signs, 13 changeable message signs (CMS), and two unmanned weather stations. Robinson stated that the objective of this system was to improve safety without decreasing driver motivation to obey speed limits. The regulatory speed limits are based on roadway conditions as shown in table 2.3. Rama and Luoma (1997) reported that "81 percent of the drivers said the posted speed limit was appropriate and 95 percent of the drivers stated that the variable speed limits were useful." Rama (1998) also indicated that in winter a change of the posted speed limit from 100 km/h to 80 km/h decreased the mean speed of cars traveling in free-flow traffic by 3.4 km/h, in addition to the average mean speed reduction of 6.3 km/h caused by adverse weather and road surface conditions, and that the reduction of the speed limit was accompanied by a decrease in the speed variance. However, the values of mean speeds and speed variances before and after the speed limit reduction were not reported.

Table 2.3. Speed-limit-setting algorithm for Finland (Robinson, 2000)

Roadway conditions	Speed limit (km/h)
Good	120
Moderate	100
Poor	80

- Netherlands (Breda): A VSL system was installed on A-16 near Breda to elicit safer driving behavior during fog. The system consists of VSL signs spaced approximately 0.5 miles apart over 7.4 miles of road, 20 visibility sensors, and automatic incident detection. The posted speeds are based on the visibility from sensors, as shown in table 2.4. The posted speeds are also based on incidents. If an incident is detected, the first and second signs upstream from the incident will display 50 and 70 km/h respectively. Robinson stated that this system resulted in a reduction in mean speed during fog conditions of about 8 to 10 km/h. However, it is not clear whether the observed reduction is relative to the condition without VSL or the condition without fog.

Table 2.4. Speed-limit-setting algorithm for Breda-Netherlands (Robinson, 2000)

Visibility (feet)	Speed limit (km/h)
> 140	100
140 to 70	80
< 70	60

2.3.2 Grade

- Colorado: Janson (1999) evaluated a Downhill Truck Speed Warning System (DTSWS) in the Eisenhower Tunnel on I-70. In order to reduce runaway truck accidents, the DTSWS advises vehicle-specific safe operating speeds for long downgrades for trucks with greater than 40,000 lbs. gross vehicle weight. The DTSWS consists of a weigh in motion (WIM) sensor, changeable message signs (CMS), and inductive loop detectors. The displayed advisory speed for each truck is calculated based on weight, speed, and axle configuration. The advised speeds and the mean truck speeds with the system on and off are shown in table 2.5.

Table 2.5. DTSWS advised speed and mean truck speeds with the system on and off (Janson, 1999)

Weight range (lbs.)	Advised speed (mph)	With system on		With system off	
		Mean speed (mph)	# of trucks	Mean speed (mph)	# of trucks
40,000 to 48,600	30	40.1	15	48.4	27
48,600 to 51,200	25	30.5	2	43.5	3
51,200 to 55,500	20	37.6	4	34.9	3
55,500 to 63,500	15	32.8	7	41.5	5
63,500 to 80,900	10	30.0	24	34.4	25
>80,900	5	16.9	1	25.6	1

Janson indicated that on the average the mean truck speed was reduced by 7.6 mph from 41.1 mph to 33.5 mph. However, he found that 2.4 mph of the 7.6 mph change in speed was the result of an increased numbers of heavier trucks in the time period when data were collected with the sign activated. He also indicated that truck drivers surveyed responded very positively to the system and its potential to improve safety. Based on the result of this study, Janson revised the advised speeds. The revised advised speeds are shown in table 2.6.

Table 2.6. Revised DTSWS advised speed (Janson, 1999)

Weight range (lbs.)	Advised speed (mph)
40,000 to 48,500	35
48,500 to 55,000	25
55,000 to 80,000	15
>80,000	10

- Oregon: The Oregon Department of Transportation installed a Downhill Speed Information System (DSIS) on I-84 between Pendleton and La Grande to advise truck drivers of the safe speed for traveling down Emigrant Hill. Montagne and Bell (2000) stated that the purpose of this system is to reduce the frequency and severity of downgrade truck accidents. The system consists of a WIM scale, CMS, and an automatic vehicle identification (AVI) reader. The advisory speed for each truck is based on vehicle weight. Only properly weighed transponder-equipped trucks receive an advisory speed. Bell (2001) indicated that the DSIS had not been deployed. No more updated literature was found on the progress of this project.

2.3.3 Traffic flow

- Michigan: Wilkie (1997) documented the use of VSL in Michigan. Twenty-one VSL signs were installed and operated over 3.2 miles of the John C. Lodge Freeway (M-10) from 1962 through 1967. The objectives of this system were to warn motorists to decelerate before reaching a congested area and to notify motorists leaving a congested area to accelerate to help disperse the congestion. The variable speed limits could range from 20 to 60 mph in increments of 5 mph. The speed limits were set based on occupancy and volume data from the closed circuit television (CCTV) images and real-time freeway speeds. The variable speed displays did not significantly increase or decrease vehicle speeds. This was presumed to be because motorists did not understand variable speed displays with no accompanying message.
- United Kingdom: A VSL system was installed on the M-25 London orbital to smooth traffic flows by reducing stop-start driving conditions. The system consists of VSL display stations spaced approximately 0.6 miles apart over 14 miles, loop detectors at

0.3 mile intervals, and CCTV. Robinson (2000) indicated that the system is intended to slow vehicles approaching a queue and that the system has additional logic to prevent frequent fluctuations in speed limits. Speed limits were originally changed according to the vehicle volume as shown in table 2.7. However, Harbord (1998) indicated that this algorithm was replaced by a more sophisticated algorithm after about the first month, but no document on the new algorithm has been found.

Table 2.7. Original Speed-limit-setting algorithm for U.K. (Nuttall, 1995)

Volume (vphpl)	Speed limit (mph)
< 1,650	70
1,650 to 2,050	60
> 2,050	50

As mentioned before, this system resulted in very high speed limit compliance (98 percent) during the first three months of operation in 1995 (Nuttall, 1995). But there were also a lot of complaints about very strict enforcement by speed cameras. Harbord (1997) indicated that the VSL system also resulted in a 21 percent reduction in injury accidents, more even lane usage, and more uniform headways. However, he stated that the accident reduction percentage may have been influenced by roadwork in the before period and that making an allowance for the effects of roadwork could reduce the improvements in accidents to 11 percent. Harbord also performed a postal survey of 1,600 drivers using the system. The results indicated that 60 percent of all drivers reported that the system had resulted in an improvement, while only 10 percent believed it had made traffic congestion worse.

2.3.4 Work zones

- Arkansas: Tudor et al. (2003) reported the use of the Smart Work Zone Technology system (ADAPTIR™ system) on I-40 in Lonoke County to improve safety and manage congestion in the work zone. The ADAPTIR™ system consisted of a central system controller, two highway advisory radios (HARs), five traffic sensors, five changeable message signs (CMSs), and two supplemental speed stations per lane closure. The system was designed for the CMSs to display downstream traffic speed information followed by delay information. If the speed differential between successive traffic sensors exceeded 10 mph, the upstream CMS would display "REDUCE SPEED TO XX MPH" and follow with the message "YY MINUTE DELAY." If the speed differential was below 10 mph, the CMS would only display the delay information. The central system controller was programmed for a 10-minute cycle time.

  A problem encountered was that the public reported that the delay estimations were not sufficiently accurate. Therefore, the delay messages were simplified to display the generic messages, "EXPECT DELAYS" or "EXPECT LONG DELAYS." Tudor et al. (2003) indicated that the ADAPTIR™ system resulted in a reduction in the fatal crash rate of about one crash per 100 million vehicle miles traveled when compared to two other work zones with similar traffic characteristics. However, this conclusion was based on only two fatal crashes that occurred in the VSL site during the study. Tudor et al. also reported that there was no significant reduction in the rear-end crash rate.

- Minnesota: Robinson documented the use of VSL in work zones on urban freeways in Minnesota. When construction workers are not present, the speed limit continues to be 65 mph. When construction workers arrive, a designated worker changes the regulatory speed limit to 45 mph. This system resulted in a significant reduction in work zone speeds compared to a conventional static work zone speed limit sign. However, the magnitude of the speed reductions was not reported.
- Virginia: Park and Yadlapati (2003) proposed a VSL control logic that accounts for both safety and mobility measures in work zones and tested it through a microscopic simulation program (VISSIM). In this logic, a method of finding the optimum speed with respect to a minimum safe distance equation (MSDE, the safety measure) and a travel time (the mobility measure) was described. This study evaluated this control logic under varying speed limit compliance rates (i.e., 70, 80, and 100 percent) and two demand conditions (i.e., undersaturated and oversaturated conditions). For the undersaturated condition, the proposed control logic only performed better than a VSL system that simply posts the average speed of vehicles in work zones when the compliance rate was 100 percent. The results were mixed for 70 and 80 percent compliance rates. For the oversaturated conditions, the proposed control logic produced lower travel times, but much smaller MSDE values.

2.3.5 Combination of 2 factors or more

- Nevada: Robinson reported the use of VSL on I-80 next to a coal-fired power generation plant in a canyon with a river where fog is likely to occur. The system consists of visibility detectors, speed loops, a Road Weather Information System (RWIS) weather station, and advance warning signs. The regulatory speed limits are set in increments of 10 mph based on the 85th percentile speed, visibility, and pavement condition. The signs display a speed limit and a warning message in adverse weather conditions and remain blank on clear days. Robinson indicated that the reliability of the visibility sensor limited the operation of this system.

- New Jersey: Wilkie (1997) documented the use of a VSL on the New Jersey Turnpike. In all, 120 VSL signs were installed over 148 miles to provide early warning of slow traffic or hazardous road conditions to motorists. The system also consists of loop detectors and weather sensing equipment, and advance warning signs. Swindler et al. (2001) reported that speed limits are set based on the average travel speed from the TRANSMIT system, which determines the speed by using the EZ Pass electronic toll equipment with 2-mile detector spacing. The regulatory speed limits are displayed automatically and can be overridden for lane closures and construction zones. Speed limits can be reduced from the normal speed limit in five-mph decrements, to 30 mph. The speed limit reductions are based on any of six reasons: crashes, congestion, construction, ice, snow, and fog. Wilkie reported that the State police officers feel that the signs are effective only when the reduced speed ahead message is also illuminated.
- New Mexico: The VSL system was installed and operated on eastbound I-40 in Albuquerque from 1989 through 1997 to provide a US test bed for VSL equipment and algorithms. Due to road widening, the system was dismantled in 1997. Harwick (1989) reported that the system consisted of three roadside stations, which contained a control cabinet, a VSL sign, and a hazard warning message board. Harwick indicated that the objective of this system was to reduce accident frequency by

advising motorists of hazards through posted speeds that reflect driver behavior. The regulatory speed limit was equal to the smoothed average speed plus an environmental constant rounded to the nearest 5 mph increment (Wilkie, 1997). The environmental constants are shown in table 2.8. The posted speeds ranged from 30 to 50 mph and were updated every minute. Wilkie reported that this system resulted in a slight reduction in accidents and that the ability of the system to post speed limits that reflected traffic conditions was hindered by high average speeds, which exceeded the National Maximum Speed Limit of 55 mph.

Table 2.8. Environmental Constants for New Mexico (Wilkie, 1997)

Environmental condition	Constant (mph)
Light	+7.5
Dark	+5.0
Light and Precipitating	+2.5
Dark and Precipitating	+0.0

- France (Marseille): Swindler et al. documented the use of a VSL system on 5 miles of the southbound lane of a major highway in Marseille. The posted speed limits are based on prevailing speed, weather conditions, and presence of trucks. Speed and volume data are collected by overhead radar and television surveillance. Speed limits are set by measuring the mean speed of each 20-vehicle group and rounding up to a multiple of 10 km/h up to 110 km/h. The speed limits of 80-90 km/h, which give the maximum served volume, were displayed when the volume reaches a specific level. The system also calculates the mean speed difference between two detection stations located 0.13 mile apart to warn the drivers of slow vehicles ahead. A 50 percent reduction of crash rates from 1976 to 1992 was achieved by cutting the mean speed by as little as 3.8 km/hr. Moreover, this system resulted in a decrease in speed limit violations.

- Germany: Zackor (1979) reported on the use of VSL systems in Germany. VSL systems were installed on A8 between Salzburg and Munich, A3 between Sieberg and Cologne, and A5 near Karlsruhe. The VSL sign spacing is 0.9 to 1.2 miles. The objectives of this system were to stabilize traffic flow, reduce crash probability, improve driver's comfort, and reduce environmental impacts. The regulatory speed limits are based on traffic flows, and environmental conditions, as shown in table 2.9. Zackor indicated that the speed dispersion and the frequency of critically short headways were reduced with the operation of the VSL. Motorists responded better to electronic signage than the fixed signage, because the electronic signs provided the advisory information. Warren (2000) indicated that the use of variable speed limits reduced the crash rate by 20 to 30 percent.

Table 2.9. Speed limit (km/h) setting algorithm for Germany (Warren, 2000)

Traffic Flows	Day Dry	Dark Dry	Day Wet	Dark Wet	Extreme
Low	130*	120	110	110	90..60
Mod	110	110	100	100	90..60
High	90	90	80	80	90..60
Unstable	70	70	70	70	60

* Unrestricted at very light traffic flow.

- Netherlands (between Amsterdam and Utrecht): Wilkie (1997) documented the use of a VSL system on the A2 highway between Amsterdam and Utrecht. The objective of the system was to create uniformity of speeds and volumes within and between lanes, thereby reducing the risk of shock waves, crashes, and congestion. The system consists of VSL signs spaced approximately 0.6 miles apart over 12.4 miles of road, loop detectors every 0.3 miles, and automatic incident detection. The standard speed limit is 120 km/h, while the variable posted speed is 50, 70, or 90 km/h depending on 1-minute average speed and volume across all lanes. . The regulatory speed limits are posted in a red circle and enforced by photo radar. The advisory speed limits are posted without a red circle. If an incident is detected, a speed limit of 50 km/h is displayed. In general, the drivers complied with the speed signs. The severity of shockwaves and speeds in all lanes were reduced, while the average occupancy increased during the speed control. The average headway difference among lanes became smaller and the variation in headways decreased.

- Sweden: A VSL system was installed on 20 km of rural highway E22 in southern Sweden. Swindler et al. reported that "the system aims to combine real time traffic data and data from the road weather information system (RWIS) with a local climate model predicting the road conditions on that special road section." The speed limits are displayed with different symbols to explain the reason for the speed reduction. Swindler reported that this system resulted in a 10 percent reduction in speed and a 20 percent reduction in speed variance. However, he did not indicate the reduction in the speed limit required to achieve this result.

2.3.6 Conclusions

The literature indicates that the use of VSL signs under specific weather related conditions (fog, icy or snow covered roads) results in a reduction in the average speed. However, the speed reduction is significantly less than the posted speed reduction. Most systems use an increment of 20 km/h to warn of various weather conditions, and achieve speed reductions of less than 10 km/h.

The use of VSL signs to advise truck drivers of the safe speed on grades showed similar results. Truck speeds decreased with the use of the signs, but the average speed exceeded the posted speed across various weight classes by an average of approximately 14 mph.

The literature also leads to the conclusion that the use of VSL signs without notifying the driver of the reason for the change in the speed limit was not effective, but this research was conducted nearly 40 years ago. More recently, a VSL system combined with strict enforcement with photo radar has been demonstrated to be effective in reducing speeds to the enforced speed (the posted speed plus the tolerance used for enforcement).

The literature does not contain any guidance on the time and/or distance frequency with which the posted speed limit can change and still be effective, nor on the lag time between a change in the posted speed and the speed adjustment by the motorists. All of the experiments have been with systems that do not change rapidly (weather, grade, congestion) except the tests in Detroit (which found no response) and Albuquerque (where the speed limit could not be displayed because it exceeded the NMSL).

The reports on the system used in London do not discuss the frequency with which the VSL sign changed, nor if the motorist speeds responded to each change, nor the delay time in the response. These are all critical issues that need to be understood if the system is to be effective in a work zone.

The minimum and maximum distance between VSL signs in also not known. The system in London used an average spacing of 0.6 miles (1 km), but this distance may not be appropriate in a work zone, where conditions could change over shorter distances.

Another unknown is whether motorists will increase speed above the speed they would choose to drive with static speed limit signs. The ADVISE system in Utah reported an increase in speed when the VSL signs are lighted under foggy conditions, but this may be the result of motorists responding to the visibility of the signs rather than the posted speed.

In this study, the system will be dynamic and will display both speed limit increases and speed limit decreases over relatively short distances. The response will be measured in short time increments to determine the ability of the system to encourage drivers to alter their speed frequently in response to the posted speed limit.

Chapter 3

DESIGN OF THE STUDY

This study was designed to evaluate the effectiveness of the VSL system in work zones by comparing field data collected "before," "during," and "after" VSL operation. The VSL system details, data collection methods, study plan, and speed-limit-setting algorithms are presented in this chapter.

3.1 VSL system details

The VSL system components, system configuration, system operation, and operational parameters will be discussed in this section.

3.1.1 System components

The VSL system called "the IRD Speed Ranger Safety System," which was manufactured by International Road Dynamics Incorporated (IRD), was used in this study. The VSL system as implemented in this study consists of one master trailer (trailer 1, shown in figure 3.1) and six slave trailers (trailers 2-7). The slave trailers contain controller electronics, a short-range wireless modem (SRWM), remote traffic microwave sensors (RTMS), simple system diagnostics, a user interface, a variable message sign (VMS), solar panels, and a battery pack. The master trailer contains everything that the slave trailers contain plus a long-range wireless modem (LRWM) and a highway surface condition monitor (HWCM). The number of slave trailers used at each site varies based on the length and geometry of the work zone section. The VSL trailers were classified into three types: downstream, middle, and upstream. The master trailer is used as the downstream trailer, while the slave trailers are used as the middle and upstream trailers.

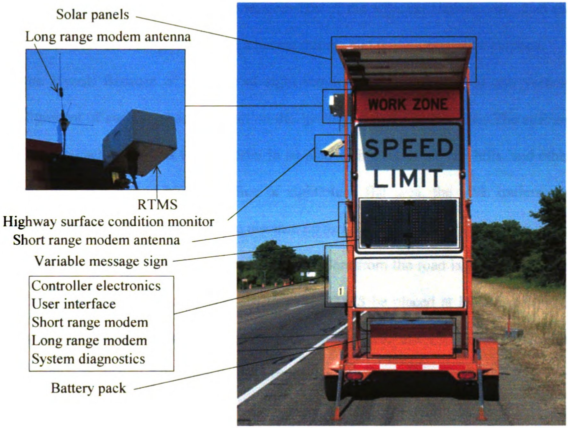


Figure 3.1. VSL master trailer

3.1.2 System configuration

The VSL trailers need to collect traffic data by using the RTMS and communicate those data with each other in order to set speed limits. The proper system configuration will ensure that the VSL trailers communicate with each other effectively and the RTMS collect traffic data accurately. To set the proper system configuration, the following factors need to be considered:

- Line of sight: A clear line of sight between short-range modem antennas on adjacent trailers is required for the system to communicate. If the adjacent antenna cannot be seen, either the trailer must be moved or the antenna must be raised. Each trailer is programmed with the short-range modem IDs of the adjacent trailers only, thus the communication must pass through adjacent trailers and trailers cannot be skipped.
- Site layout: Because of the line of sight requirement, the horizontal and vertical alignment of each site has an effect on the spacing between each trailer. The spacing between each trailer has to be shorter in an area with a lot of curves, hills, and other obstructions that can block the line of sight. In a flat area, the VSL trailers can communicate with one another at a distance up to 1.5 miles.
- Distance from the road: The distance of the trailers from the road is governed by the RTMS operation. It is recommended that the RTMS be placed at least 5 feet (1.52 meters) above the shoulder and no more than 10 feet (3.05 meters) from the edge of a driving lane. Figure 3.2 shows the RTMS placement.

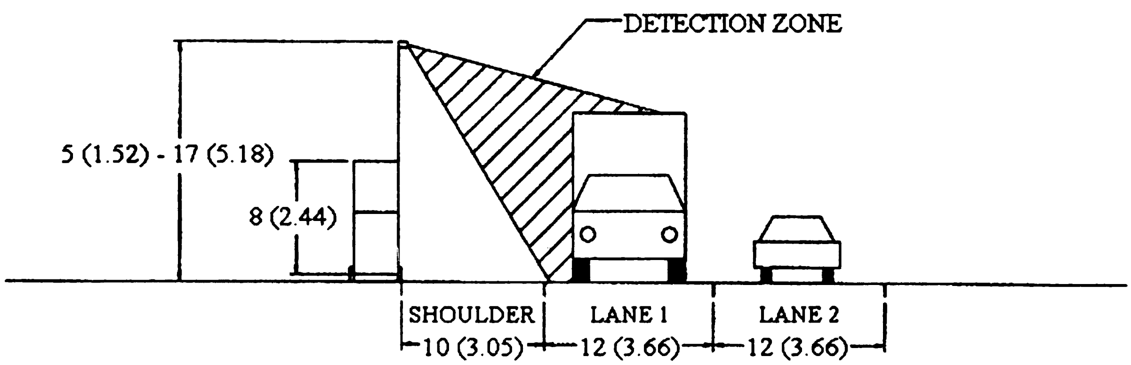


Figure 3.2. RTMS placement (IRD, 2002)

3.1.3 System operation

The speed limit on each VSL trailer is either set at a constant value or is based on the average speed plus five mph, which was found to be a good approximation of the 85th percentile speed (see section 4.1.4 of this report). The speed limit can be based on the speed measured at that trailer or the speed measured at the next downstream trailer. Periodically, the master trailer will transmit a speed limit to the closest upstream trailer based on traffic data from the RTMS for one or more of the trailers and a surface condition report from the HWCM. In turn, each of the middle trailers will transmit a speed limit to the closest trailer upstream as they receive an updated speed limit from the closest downstream trailer. When the most upstream trailer receives an updated speed limit, it will start a reverse transmission process by transmitting its traffic data to the closest trailer downstream. Each of the middle trailers will collect the data transmitted from the closest upstream trailer, append its traffic data and transmit all the data to the closest downstream trailer. When the data reaches the master trailer, it appends its own traffic data, uses all the data to set the speed limit at each trailer for the next period, and stores the data so that they can be transferred off site through the long-range wireless modem. When the speed limits are updated, the updated speed limits on all of the trailers can be automatically sent to police officers through pagers for enforcement purposes (IRD, 2002).

3.1.4 Operational parameters

In order to operate the VSL system effectively, the following parameters need to be determined and set. These parameters need to be set on each trailer individually.

- Maximum positive differential: A maximum positive differential is the maximum positive speed limit difference allowed between the speed limit on that trailer and the speed limit on the closest downstream trailer. Since this value has no effect on traffic disruption, it can be set as high as possible. A maximum positive differential of 30 mph, which is the maximum value allowed by the system, was used in this study.
- Maximum negative differential: A maximum negative differential is the maximum negative speed limit difference allowed between the speed limit on that trailer and the speed limit on the closest downstream trailer. The maximum negative differential of 10 mph was used in this study for a smooth transition in speed zones. A 10 mph negative differential is the maximum value specified in the Michigan State Police speed zoning guidelines.
- Maximum speed change: A maximum speed change is the maximum speed limit difference between two subsequent time periods. Since this value has no effect on traffic disruption, it can be set as high as possible. A maximum speed change of 25 mph, which is the maximum value allowed by the system, was used in this study.
- Trailer update period: The trailer update period indicates how often speed limits are updated. The system allows update periods of 5 to 15 minutes. The trailer update period was set to five minutes in this study, but in reality the speed limits were updated about every six minutes because it takes about one minute for the system to complete a communication cycle.
- Road Factor: A road factor defines a percentage of the calculated speed limits to display, based on the four following road conditions: dry, wet, snow, and ice. Because this study was conducted in the summer, snow and ice were not present. The dry and

wet road factors were set to 100 percent. In essence, this factor was not utilized in this study.

3.2 Data collection methods

There were three methods of traffic data collection proposed for use in this study: an Autoscope system, RTMS, and pneumatic tubes. However, the results from the initial test indicated that the Autoscope system did not provide accurate speed and volume measurements, particularly when shadows were present. This resulted in the decision not to use the Autoscope system for the data collection in this study.

3.2.1 Remote traffic microwave sensor (RTMS)

RTMS provides presence detection of vehicles in multiple zones. Its ranging capability is achieved by frequency modulated continuous wave (FMCW) operation. The sensor transmits a microwave beam and receives energy reflected by both moving and stationary objects in its path. At any given time there is a difference between the frequencies of transmitted and received target signals, this difference in frequencies is proportional to the distance between RTMS and the target. The RTMS detects and measures this difference and computes the distance to the target. The RTMS detects presence of objects in seven feet wide radial range slices in the path of the microwave beam as shown in figure 3.3.

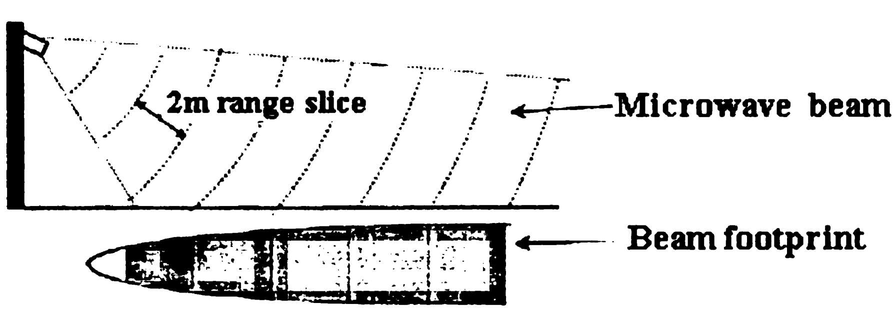


Figure 3.3. RTMS microwave beam and its footprint (EIS, 2000)

In this study, the RTMS was mounted in a forward-looking configuration with detection zones aligned along the direction of travel. Each detection zone consists of three consecutive range slices essentially forming a "speed trap". An average speed is determined from the transit time through the detection zones. The system can be used to detect vehicles approaching or after they have passed the transmitter. The RTMS was set up to detect vehicles after they have passed the transmitter in this study (Electronic Integrated Systems Inc. (EIS), 2000).

The RTMS was used to collect traffic data used for evaluation during the VSL operation and the data from RTMS was also used for setting the speed limit. The RTMS recorded the following traffic data at each VSL trailer: a 6-minute average speed, a 6-minute traffic volume, and a 6-minute lane occupancy. The average speed and volume were verified during the pre-deployment by a comparison with data from a radar gun and a manual traffic count, respectively. The average speed and volume were also verified during the VSL deployment by a comparison with data from pneumatic tube detectors.

3.2.2 Pneumatic tube system

The pneumatic tube based system consists of two rubber tubes that are placed about six feet apart across one or more lanes of traffic. One end of the tubes is sealed and the other is attached to a mechanism (detector) that is actuated by air pressure. An average speed is determined from the transit time between the two pneumatic tubes. The pneumatic tube detector can also classify vehicle types into the 13 FHWA vehicle-classification categories by determining the number of axles and their spacing. A recording mechanism includes a clock and a device for recording the time, the count, and the average speed over a specified time (15 minutes was used in this study). (French and Solomon, 1986)

Pneumatic tube detectors installed by MDOT were used to collect the traffic data "before," "during," and "after" the VSL operation. During the VSL deployment, they were installed at the same locations as the VSL trailers as shown in figure 3.4. The pneumatic tube data provided speed distributions for each vehicle type in 15-minute increments. The individual vehicle speeds were recorded in either a 16 or 30 speed bin format. The 15-minute average speed, 85^{th} percentile speed, and speed variance were estimated by assuming that all of vehicles in each bin traveled at the middle speed of that bin. Thus, the precision of these values depend on the number of speed bins. The average speed and volume were compared with the RTMS data for verification. The advantage of the pneumatic tube detector is that the output can be used to estimate the 85^{th} percentile speed and speed variance, while the output from the RTMS cannot. The disadvantages of the pneumatic tube detector are that it can not cover more than two lanes of traffic, and tubes are prone to ripping loose or tearing when a vehicle slides its wheels when crossing.

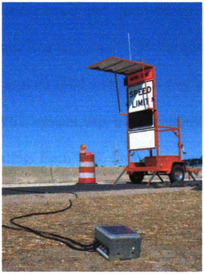


Figure 3.4. Pneumatic tube system

3.3 Study plan

This study was divided into 2 parts: the pre-deployment test and the VSL deployments in the work zones. The purpose of the pre-deployment test was to ensure that the VSL system worked properly, while the purpose of the VSL deployments in the work zones was to evaluate the impacts of the VSL system under various work zone conditions.

3.3.1 Pre-deployment test

The pre-deployment test was conducted to ensure that the VSL system worked properly before the field deployment in the work zones. The functional characteristics of the system were tested by verifying that the VSL trailers were able to communicate with each other, with the pagers, and with a remote computer. The abilities of the system to collect traffic data and road surface conditions and to use those data (along with a specific algorithm) to set speed limits were evaluated. The volume collected by RTMS was compared with the volume from a manual count, while the speed collected with RTMS was compared with the speed data collected by a radar gun.

The VSL system of one master and three slave trailers was deployed on the southbound direction of Okemos Road, south of I-96 from 04/11/02 to 05/11/02. Okemos Road is a two-way, two-lane asphalt road with 4 to 6 foot shoulders and a posted speed limit of 55 mph. Since the VSL system was being calibrated, the VMS was turned off during the pre-deployment testing. Each VSL trailer was located about 0.5 miles apart as shown in figure 3.5.

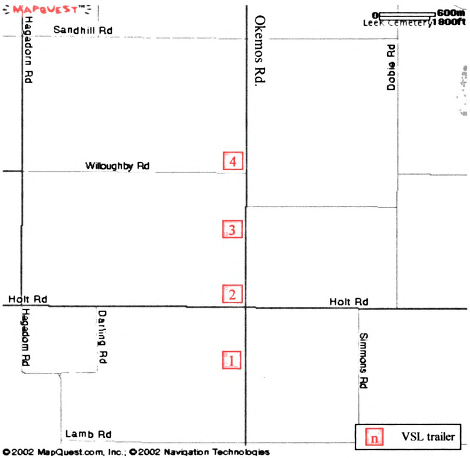


Figure 3.5. Location of VSL trailers during the pre-deployment testing

3.3.2 VSL deployment in work zones

In the work zone deployments, the VSL system first operated with static black on white speed limit signs (50 mph) covering the VMS on each trailer while the speed-limit-setting algorithm was checked and the "before" data were collected. Thus, "before" data was collected when the system was present but the VMS was covered with a static fixed speed limit sign. When the speed-limit-setting algorithm was operational and enough "before" data had been collected, the static speed limit signs were removed from the VMS on each trailer. The VSL system was then put in full operation (the VMS was uncovered) and the "during" data were collected for about one week in each deployment.

During the time period that the "before" and "during" data were collected by the VSL system, the pneumatic tube detectors were also used to collect data for comparison purposes.

After the VSL system was removed from the work zones and the regular static speed limit signs were replaced, the pneumatic tube detectors collected the "after" data for about one week. This study covered four deployments in four different work zone configurations. These four work zones were good candidates for the VSL deployments because there were variations in day-to-day and trailer-to-trailer average speeds in these work zones. The VSL can reflect these variations in the displayed speeds, while the static speed limit cannot. Example of the variations in day-to-day and trailer-to-trailer average speeds is shown in figure 3.6. All seven VSL trailers were used in the first three deployments, while only six trailers were used in the fourth deployment.

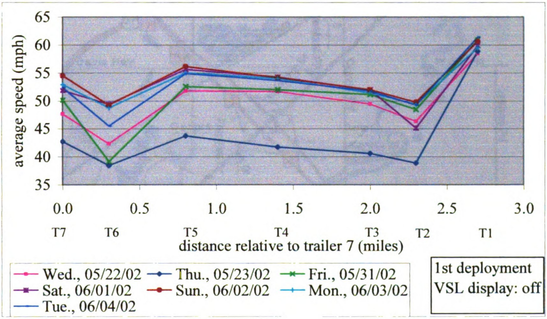


Figure 3.6. Example of the variations in day-to-day and trailer-to-trailer average speeds from 5PM to 6PM "before" the first deployment

➢ **First deployment:** The VSL system was installed on a 2.7-mile section of eastbound I-96 between the overpass ramp from I-69 to 0.7 miles east of Creyts Road as shown in figure 3.7. There was a total reconstruction of the eastbound lanes of I-96. The eastbound traffic was shifted to one of the normal westbound lanes through a traffic crossover. Two-way traffic (one lane in each direction) was maintained on the westbound lanes with a temporary concrete barrier wall separating the two lanes. The eastbound traffic was shifted back to the 2 eastbound lanes through the traffic crossover, which was located just west of trailer 1.

Figure 3.7. Map of the first deployment work zone

➢ **Second deployment:** The VSL system was installed on a 2.6-mile section of eastbound I-96 from 0.7 miles west of Wacousta Road to the on-ramp from exit 90 as shown in figure 3.8. There was concrete patching on the left lane, and only the right lane was open. Barrels were used to separate the two lanes. The construction activities were conducted between 6AM and 8PM.

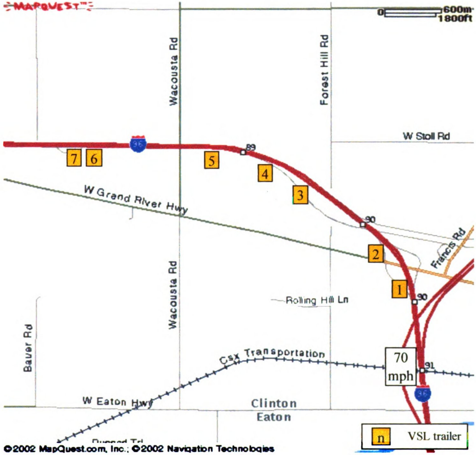


Figure 3.8. Map of the second deployment work zone

➢ **Third deployment:** The VSL system was installed on a 2.2-mile section of eastbound I-96 between the on-ramp from I-69 and 0.7 miles east of Creyts Road as shown in figure 3.9. There was a total reconstruction of the westbound lanes of I-96. The westbound traffic was shifted to one of the normal eastbound lanes through a traffic crossover, which was located just west of trailer 1. Two-way traffic (one lane in each direction) was maintained on the eastbound lanes through the deployment with a concrete barrier wall separating the two lanes.

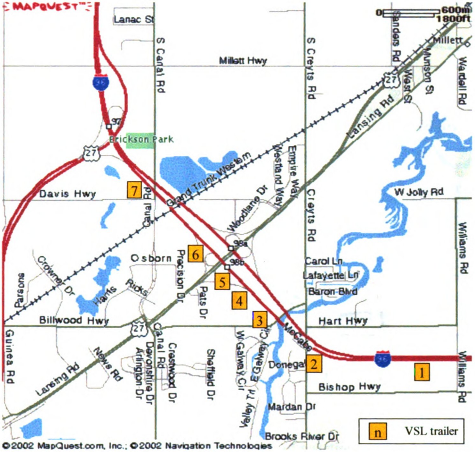


Figure 3.9. Map of the third deployment work zone

➢ **Fourth deployment:** The VSL system was installed on a 2.6-mile section of westbound I-96 between the on-ramp from exit 93a and Grand River Avenue as shown in figure 3.10. There was concrete patching on the right and middle lanes. Only the left lane was open. Barrels were used to separate the lanes. The construction activities were conducted between 6AM and 10PM. The construction zone ended and the westbound traffic became two lanes right before trailer 6.

Figure 3.10. Map of the fourth deployment work zone

The effect of police enforcement was also tested in this deployment. According to the literature review, the presence of a stationary patrol car is one of the most effective methods of speed limit enforcement. Thus, a stationary patrol car was programmed to be present at three locations in the work zone during the different time periods: 1) Grand River Avenue; 2) I-69 overpass; and 3) Eaton Highway (see figure 3.10). The police officers were notified of the updated speed limit through a pager. Traffic citations were issued only in extreme cases. The stationary patrol cars were scheduled to be present one day "during" the VSL operation and one day "after" the VSL operation for comparison purposes.

3.4 Speed-limit-setting algorithm

International Road Dynamics Inc. (IRD) designed the VSL system to vary the speed limit based on observed speeds, occupancy, and weather conditions. When the occupancy reaches user-specified low or high occupancy thresholds, the speed limit is set to the maximum and minimum (pre-set) speeds, respectively. Since this study focused on setting speed limits based mainly on the 85th percentile speed, not the occupancy, the low and high occupancy thresholds were set at values of 0 and 90 percent, respectively, which effectively "turned off" occupancy as a variable. Thus, when the occupancy was in the range of 0 to 90 percent, the speed limit was set based on the 85th percentile speed, which was estimated to be the average speed (v) plus 5 mph. The 85th percentile speed had to be estimated because the RTMS does not collect individual vehicle or "binned" speeds, which would be required to calculate the 85th percentile speed. This 85th percentile speed estimation was verified as discussed in the next chapter. Overall, the minimum and maximum speed limits used by the VSL system in this study were 40 mph and 70 mph, respectively although the maximum speed allowed at any trailer varied by deployment. Other factors used to determine the speed limit included geometric constraints and construction activity.

There were five different profiles used to set the speed limit as shown in table 3.1. Each speed profile indicates the maximum speed limit, the minimum speed limit, and the recommended speed limits for each observed average speed range. All of the speed profiles were restricted to using the same eight speed range format. The size of each range is 5 mph, except the opening range for the maximum and minimum speed. The speed-limit-setting algorithm in each deployment will be explained next.

Table 3.1. Speed-limit-setting profiles

PROFILE	1	2	3	4	5
L.O. THRESHOLD - 0%	50*	60	70	70	60
H.O. THRESHOLD – 90%	40	40	40	60	40
MID OCCUPANCY					
v < 40	40	40	40	60	60
40 ≤ v < 43	45	45	45	60	60
43 ≤ v < 48	50	50	50	60	60
48 ≤ v < 53	50	55	55	60	60
53 ≤ v < 58	50	60	60	60	60
58 ≤ v < 63	50	60	65	65	60
63 ≤ v < 68	50	60	70	70	60
v ≥ 68	50	60	70	70	60

v = average speed
* The numbers shown in the table are displayed speed limits.

3.4.1 First deployment

Since there were no construction activities near the traveled lane, the speed limits were mainly based on geometric constraints. The algorithm was set to increase the speed limits at the locations where there were no geometric constraints and decrease the speed limits at the locations where there were geometric constraints. The maximum speed limit MDOT allowed in this construction zone was 60 mph because the lane was narrower than normal.

The site layout and the speed-limit-setting algorithm for the first deployment are shown in figure 3.11 and table 3.2, respectively. The starting point in the VSL-controlled area was well after the start of the work zone, and the speed limit (using static signs) was 50 mph for traffic approaching trailer 7 (the first trailer encountered by the motorists traversing the site). The maximum speed limit allowed on trailer 7 was 50 mph because it was located in advance of an on-ramp from I-69. The maximum speed limit allowed on trailer 2 was also 50 mph because it was located at a traffic crossover. The speed limits at trailers 2 and 7 were based on the speeds recorded at these respective trailers.

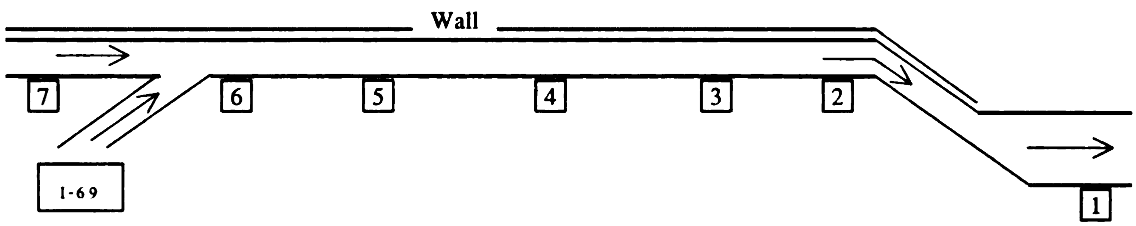


Figure 3.11. VSL site layout for the first deployment

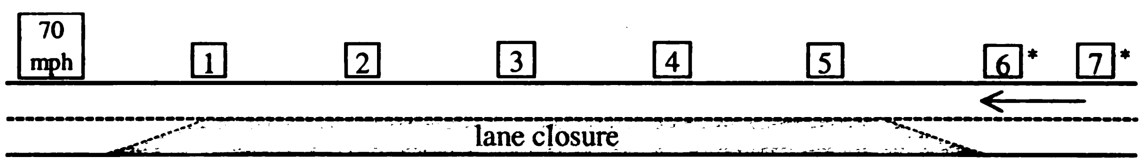
Table 3.2. Speed-limit-setting algorithm for the first deployment

Trailer	Displayed Speed	VSL based on avg. speed at trailer
1	Based on profile 3.	1
2	Based on profile 1.	2
3	Based on profile 2.	3
4	Based on profile 2.	3
5	Based on profile 2.	4
6	Based on profile 2.	5
7	Based on profile 1.	7

The speed limit on trailer 3 was also based on the speed at site 3 because the speed limit might have been too low if it was based on the downstream speed at trailer 2. The speed limits at trailers 4, 5, and 6 were set based on the speeds at the next downstream trailer. The work zone ended right before trailer 1, so the maximum speed limit allowed at trailer 1 was 70 mph, which was the same as in normal non-construction conditions.

3.4.2 Second deployment

Since the construction activities were only carried on between 6AM and 8PM during the weekdays, this deployment used two different speed-limit-setting algorithms: one during the daytime and one for nights and weekends. Because the construction workers worked on a concrete patching operation close to the traveled lane and only barrels separated them from adjacent traffic, the maximum speed limit allowed in the work zone during the daytime was 50 mph. The maximum speed limit allowed at night and on the weekends was 70 mph, which was the same as normal condition because there was no construction activity at these times. The site layout and the speed-limit-setting algorithm for the second deployment are shown in figure 3.12 and table 3.3, respectively.



*Signs 6 and 7 were located where the 50-mph and 60-mph static signs used to be, respectively.

Figure 3.12. VSL site layout for the second deployment

Table 3.3. Speed-limit-setting algorithm for the second deployment

Trailer	6AM - 8PM weekdays	8PM – 6AM weekdays & weekend	VSL based on avg. speed at trailer
1	Based on profile 1.	Based on profile 3.	1
2	Based on profile 1.	Based on profile 3.	1
3	Based on profile 1.	Based on profile 3.	2
4	Based on profile 1.	Based on profile 3.	3
5	Based on profile 1.	Based on profile 3.	4
6	50 mph	Based on profile 3.	5
7	60 mph	Based on profile 4.	6

Since the speed limit prior to the lane closure was 70 mph and the speed difference between any sign and the previous upstream sign could never be less than –10 mph, the speed limits on trailers 6 and 7 were fixed at 50 and 60 mph, respectively during the day and the speed limit on trailer 7 ranged between 60 and 70 mph during the night and on weekends. The speed limits at trailers 2 to 7 were set based on the speeds at the next downstream trailer. At the end of the construction zone, the existing static speed limit sign was used to post the normal speed limit of 70 mph.

3.4.3 Third deployment

Since there were no construction activities near the traveled lane, the speed limits were mainly based on geometric constraints. The site layout and the speed-limit-setting algorithm for the third deployment are shown in figure 3.13 and table 3.4, respectively. The starting point of the VSL-controlled area was already in the work zone, and the speed limit was set at 50 mph for vehicles approaching the VSL system.

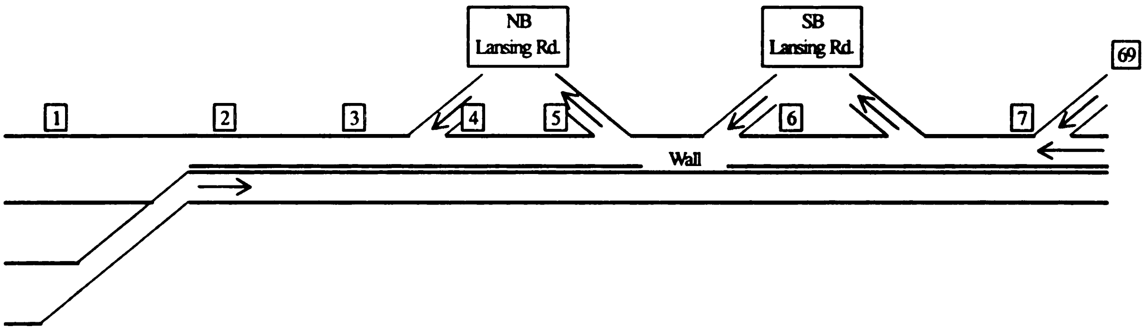


Figure 3.13. VSL site layout for the third deployment

Since there were many on and off ramps in the vicinity of trailers 4 to 7, the speed limits were governed by the location of the ramps. The speed limits on trailers 5 and 7 were programmed to be fixed at 60 mph unless the occupancy was higher than 90 percent. Due to a communication problem with a short-range modem cable, the speed limit on trailer 7 was fixed at 60 mph, regardless of the occupancy. The speed limit on trailer 5 was also fixed at 60 mph because the speed limit could not be set based on the speeds at that trailer or the downstream trailer, which was located in a merging area.

Table 3.4. Speed-limit-setting algorithm for the third deployment

Trailer	Displayed Speed	VSL based on avg. speed at trailer
1	70 mph	N/A
2	Based on profile 3.	1
3	Based on profile 3.	2
4	Based on profile 1.	4
5	Based on profile 5.	5
6	Based on profile 1.	6
7	60 mph	N/A

The maximum speed limit allowed at trailers 4 and 6 was 50 mph and the speed limit was set based on the speed recorded at these respective trailers because there were ramps immediately downstream from each trailer. If the speed limit on trailers 4 and 6 was set based on their downstream trailers, the speed limits could have been too high. The maximum speed limit allowed at trailers 2 and 3 was 70 mph because there were no ramps in the vicinity of these two trailers and the eastbound traffic did not need to cross over at the end of the work zone. The speed limits at trailers 2 and 3 were set based on the speeds at the downstream trailers. The work zone ended right before trailer 1, so the speed limit on trailer 1 was set at 70 mph, which was the same as in the normal condition.

3.4.4 Fourth deployment

Since the construction activities were only carried on between 6AM and 10PM, this deployment used two different speed-limit-setting algorithms, one for day and one for night. Because the construction workers worked on a concrete patching operation close to the traveled lane and only barrels separated them from the traffic, the maximum speed limit allowed in the work zone during the daytime was 50 mph. The maximum speed limit allowed at night was 70 mph, which was the same as normal conditions because there was no construction activity at night. The site layout and the speed-limit-setting algorithm for the fourth deployment are shown in figure 3.14 and table 3.5, respectively.

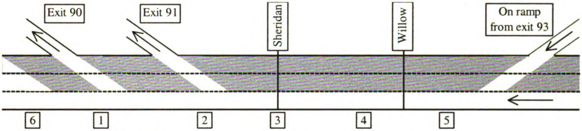


Figure 3.14. VSL site layout for the fourth deployment

Table 3.5. Speed-limit-setting algorithm for the fourth deployment

Trailer	6AM - 10PM	10PM – 6AM	VSL based on avg. speed at trailer
1	Based on profile 1.	Based on profile 3.	1
2	Based on profile 1.	Based on profile 3.	1
3	Based on profile 1.	Based on profile 3.	2
4	Based on profile 1.	Based on profile 3.	3
5	Based on profile 1.	Based on profile 3.	4
6	70 mph (fixed)	70 mph (fixed)	N/A

The starting point of the VSL controlled area was already in the work zone with a speed limit of 50 mph prior to that point. The speed limits at trailers 2 to 5 were set based on the speeds at the downstream trailers, while the speed limit at trailer 1 was set based on the speed at that site because trailer 1 was not set up to communicate with the downstream trailer (trailer 6). At the end of construction zone, VSL trailer 6 was used to display the normal fixed speed limit of 70 mph. Since trailer 6 was the only trailer that used a different speed-limit-setting profile than others, trailer 6 was set up to operate independently. This setting allowed the speed-limit-setting profile at trailers 1 to 5 to be changed remotely though the long-range modem.

Chapter 4

RESULTS OF DATA VERIFICATION AND PROBLEMS AND LIMITATIONS FACED IN THE VSL DEPLOYMENT

4.1 Results of data verification

The speed and volume measured by the RTMS system and the pneumatic tube system were verified to ensure that the data from these two systems are accurate enough for the VSL evaluation. The use of the average speed plus 5 mph as a surrogate measure of the 85th percentile speed is also verified in this section.

4.1.1 Remote Traffic Microwave Sensor (RTMS)

The average speed and volume measured by the RTMS system in the pre-deployment test on Okemos Road were compared with an average speed measured with a radar gun and a count of traffic. To be consistent with the RTMS data, an aggregation period of 6 minutes was used to determine the average speed and volume.

➢ The first RTMS data verification was performed at trailer 3 during the pre-deployment. The RTMS was set up to detect vehicles approaching the transmitter. The results of volume and speed comparisons are shown in figures 4.1 and 4.2, respectively. The volume comparisons showed a significant undercount by the RTMS system. The speeds measured by the RTMS were scattered about the radar speed measurements, averaging about 2 mph lower than the speed measured by the radar gun. Because of the significant undercount of traffic volume, some of the factors that affected the RTMS accuracy were adjusted in the next verification test.

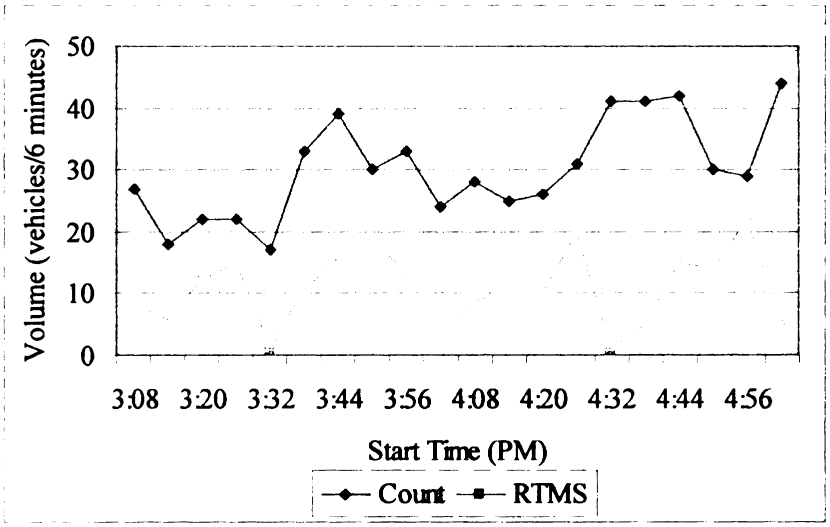


Figure 4.1. Volume comparisons at trailer 3 for the first RTMS data verification

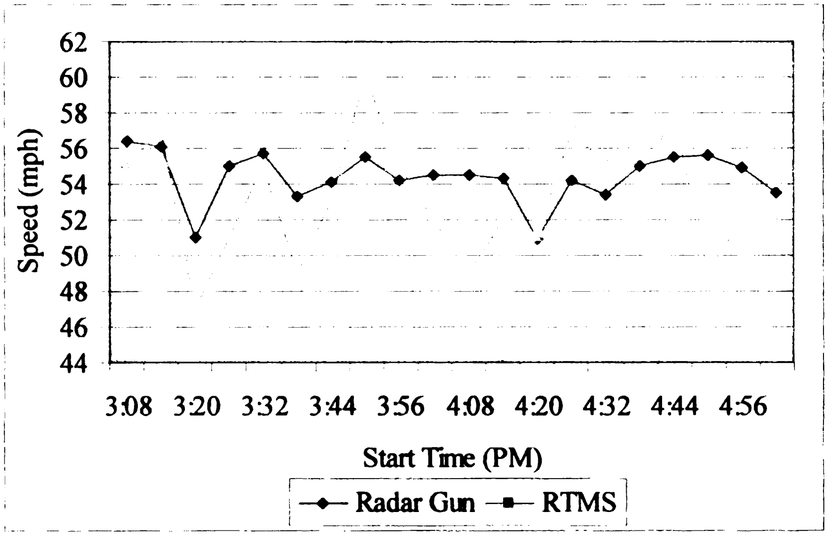


Figure 4.2. Speed comparisons at trailer 3 for the first RTMS data verification

- The second RTMS data verification was also performed at trailer 3 during the pre-deployment. The RTMS was still set up to detect vehicles approaching the transmitter, but the position of the RTMS relative to the traffic lane, the angle at which the sensor looks down onto the traffic, and the sensitivity of the system were adjusted to improve the traffic count. The results of volume and speed comparisons are shown in figures 4.3 and 4.4. The difference in the volume estimated by the RTMS system and the counts was greater than in the first test, and the RTMS reported a constant average speed of 44 mph for each interval. Since the accuracy of the speed and volume measurements was even worse than the first verification, the RTMS was rotated 180 degrees to sense vehicles after they had passed the trailer in the next verification.

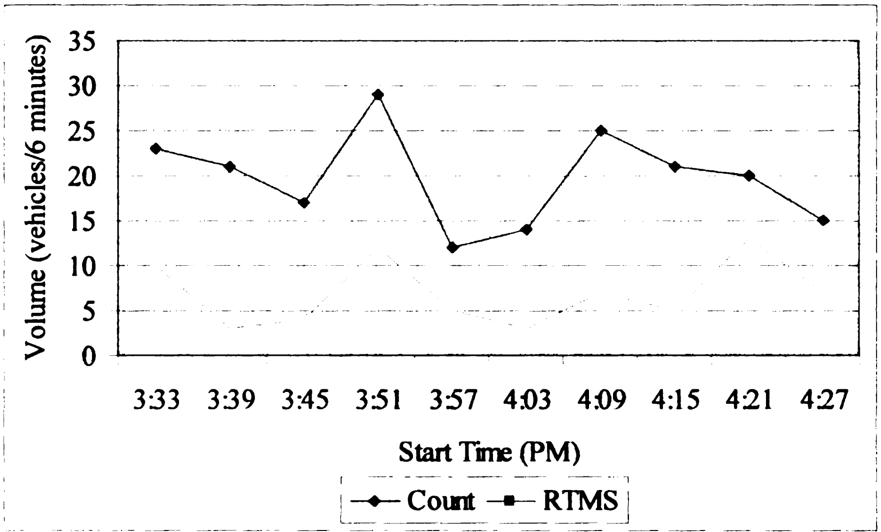


Figure 4.3. Volume comparisons at trailer 3 for the second RTMS data verification

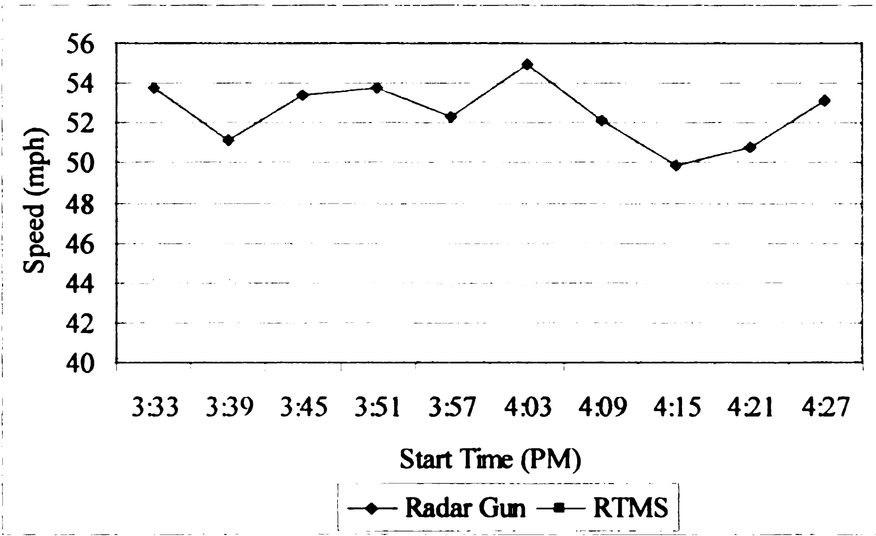


Figure 4.4. Speed comparisons at trailer 3 for the second RTMS data verification

➤ The third RTMS data verification was performed at trailers 1, 2, and 3. To improve the accuracy of the speed and volume measurements, the RTMS software was upgraded and the RTMS set up was changed to detect vehicles after they passed the transmitter. The RTMS setup at all three trailers were the same. The results of volume and speed comparisons are shown in figures 4.5, 4.6, 4.7, 4.8, 4.9, and 4.10.

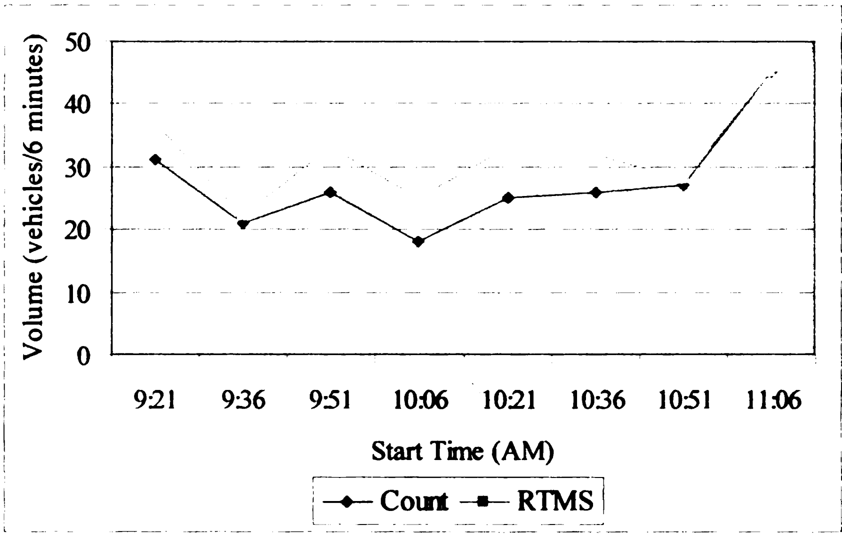


Figure 4.5. Volume comparisons at trailer 1 for the third RTMS data verification

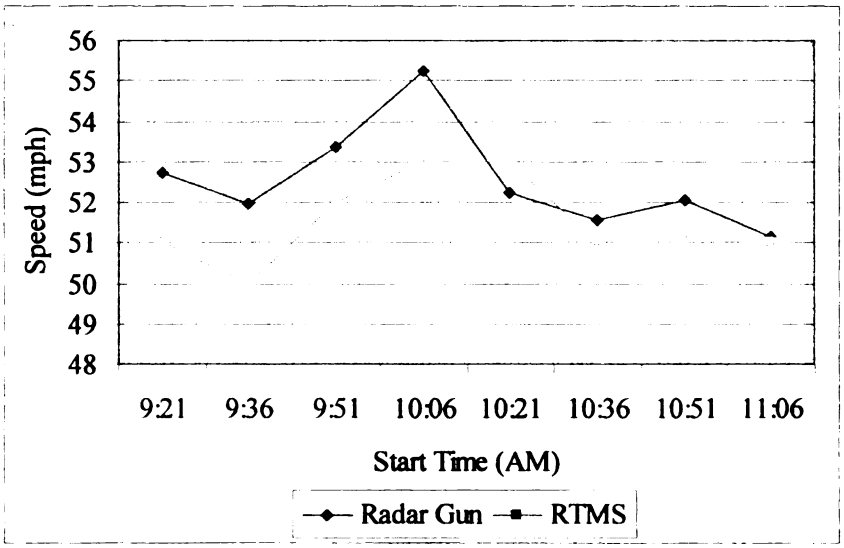


Figure 4.6. Speed comparisons at trailer 1 for the third RTMS data verification

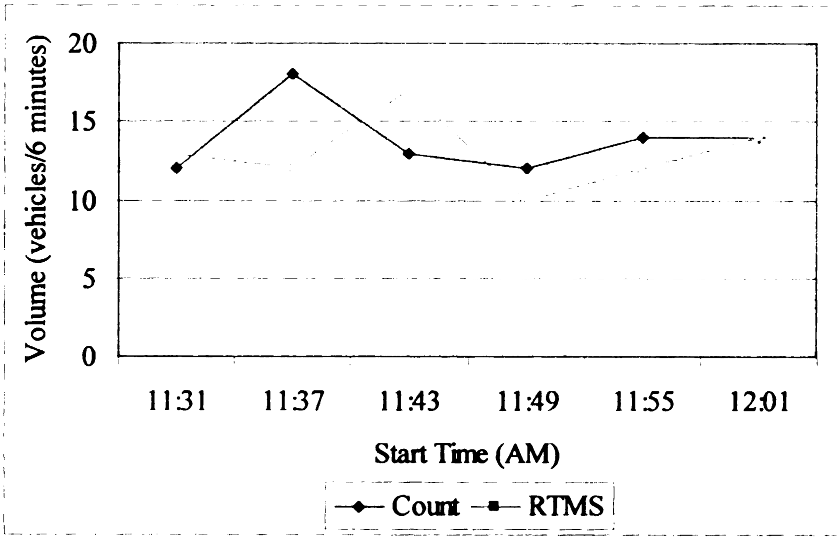


Figure 4.7. Volume comparisons at trailer 2 for the third RTMS data verification

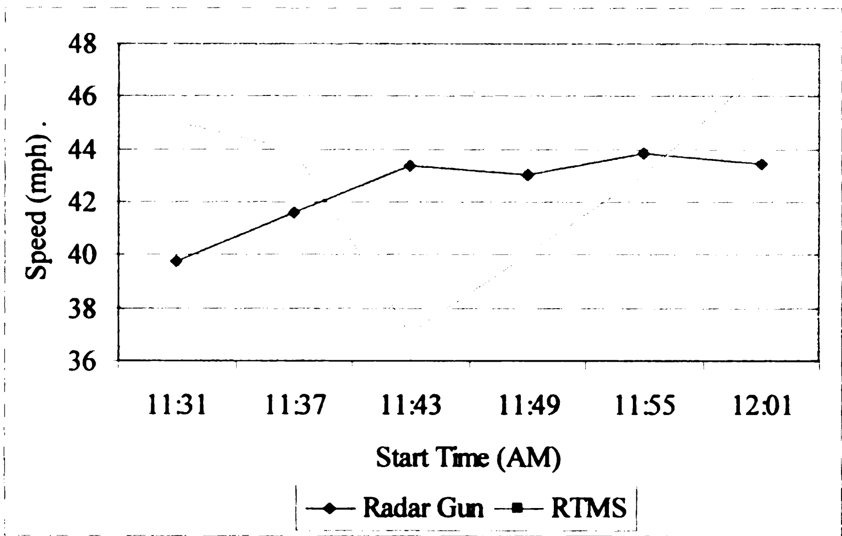


Figure 4.8. Speed comparisons at trailer 2 for the third RTMS data verification

The results from the third RTMS data verification showed that the volume detection accuracy improved considerably at each of the trailers tested. Although the volume measured by the RTMS was different by as many as 10 vehicles/6 minutes from the volume measured by the manual traffic count, the difference was clearly smaller than before. There was no improvement in the speed detection from the first verification. The speeds measured by the RTMS still averaged about 2 mph lower than the speed measured by the radar gun, but the range was from +1 mph to –2 mph at trailer 1; from +5 mph to –7 mph at trailer 2; and from +1 mph to –2 mph at trailer 3. Based on these results, the RTMS was set up to detect vehicles after they have passed the transmitter during the VSL deployment in the work zones.

Although the volume measured by the RTMS was still as high as 20 percent different from the volume measured by the manual traffic count, the accuracy was acceptable because the traffic volume was not used as an MOE in this study. The traffic volume was only used to provide a general idea about the level of congestion. The 2-mph accuracy of the speed measurement was also acceptable for the VSL evaluation. Moreover, the VSL evaluation focused more on the relative value of speed in "before" and "during" conditions than the absolute value of speed in each condition.

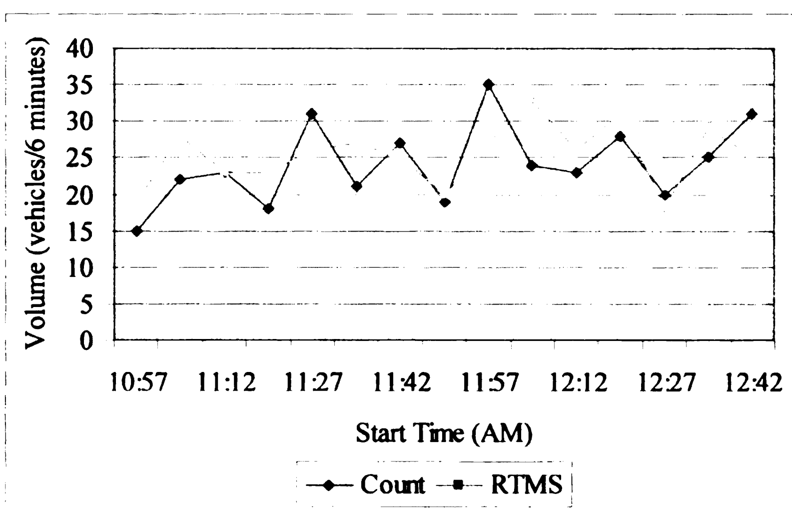


Figure 4.9. Volume comparisons at trailer 3 for the third RTMS data verification

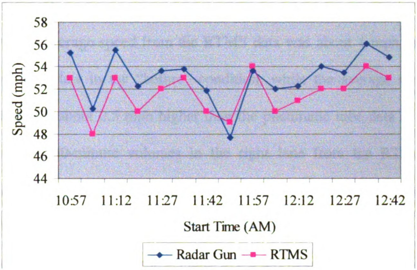


Figure 4.10. Speed comparisons at trailer 3 for the third RTMS data verification

4.1.2 Pneumatic tube system

The average speed and volume measured by the pneumatic tubes were compared with the RTMS data for verification in each of the VSL deployments in the work zones. Only the data in the "before" and "during" conditions were available for comparison, the RTMS data in the "after" condition was not available because the VSL trailers were removed form the work zones "after" the deployments. The RTMS system was set to report volume data in 6-minute increments, while the pneumatic tube system reported volume in 15-minute increments. Thus the volume in each 30-minute period was compared. At most of the trailers, the 30-minute volume from the RTMS data was higher than the pneumatic tube data about half of the time and lower the other half of the time because the reporting period from the RTMS data was not precisely 6 minutes. Some aggregate times for five RTMS volume periods were a little bit less than 30 minutes, while others were a little bit more than 30 minutes.

- First deployment

- Trailer 1: The average speed from the RTMS data was about 4 mph lower than the pneumatic tube data in the "before" condition, while the average speed from the RTMS data was about 0.5 mph higher than the pneumatic tube data in the "during" condition. The 30-minute volumes in the right lane from the RTMS data were approximately 100 percent higher than the pneumatic tube data most of the time in both the "before" and "during" conditions. The high RTMS volumes might occur because the RTMS counted some vehicles in the left lane.
- Trailer 2: The average speed from the RTMS data was about 5 mph lower than the pneumatic tube data in the "before" condition, while the average speed from the RTMS data was about 1 mph higher than the pneumatic tube data in the "during" condition. The 30-minute volumes from the RTMS data were about 5 percent higher than the pneumatic tube data about half of the time and 5 percent lower the other half of the time in both the "before" and "during" conditions.
- Trailer 3: As was the case in trailers 1 and 2, the average speed from the RTMS data was about 5 mph lower than the pneumatic tube data in the "before" condition. The average speed from the RTMS data was about 0.5 mph lower than the pneumatic tube data in the "during" condition. The 30-minute volumes from the RTMS data were about 15 percent higher than the pneumatic tube data about half of the time and 15 percent lower the other half of the time in both the "before" and "during" conditions.
- Trailer 4: Only the "during" data was available for comparison at his trailer. The average speed from the RTMS data was about 2 mph lower than the pneumatic tube

data. The 30-minute volumes from the RTMS data were about 7 percent lower than the pneumatic tube data.

- Trailer 5: Only the "during" data was available for comparison at this trailer. In the PM, the average speed from the RTMS data was almost the same as the pneumatic tube data, but in the AM the average speed from the RTMS data was about 20 mph lower than the pneumatic tube data. There might be an error in the pneumatic tube data collection because the average speed in the AM was much higher than in the PM, while the RTMS speeds were nearly equal. The 30-minute volumes from the RTMS data were about 10 percent higher than the pneumatic tube data about half of the time and 10 percent lower the other half of the time.
- Trailer 6: The pneumatic tube data at this trailer were not available.
- Trailer 7: The average speed from the RTMS data was about 5 mph lower than the pneumatic tube data in the "before" condition, while the average speed from the RTMS data was about 4 mph lower than the pneumatic tube data in the "during" condition. The 30-minute volumes from the RTMS data were about 10 percent higher than the pneumatic tube data about half of the time and 10 percent lower the other half of the time in both the "before" and "during" conditions.

- The "before" versus "during" average speed difference (between the RTMS and pneumatic tube) comparison is shown in figure 4.11. It can be noticed that the speed measurement of either the RTMS system or the pneumatic tube system was inconsistent because the average speed differences between the RTMS and pneumatic tubes in the "before" condition were not equal to the "during" conditions.

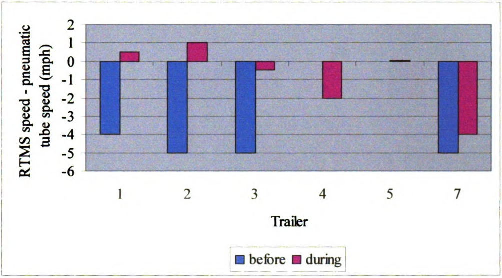


Figure 4.11. The difference between the RTMS and pneumatic tube average speed "before" and "during" the first deployment

- Second deployment

There was a problem with the VSL system during the second deployment. Thus the data were not collected. This problem will be explained in the next section.

- Third and fourth deployments

Only the "during" data were available for comparison in the fourth deployment. The "before" versus "during" average speed difference (between the RTMS and pneumatic tube) comparison from the third deployment is shown in figure 4.12. The results from the third and fourth deployments, along with the first deployment are included in tables 4.1 and 4.2.

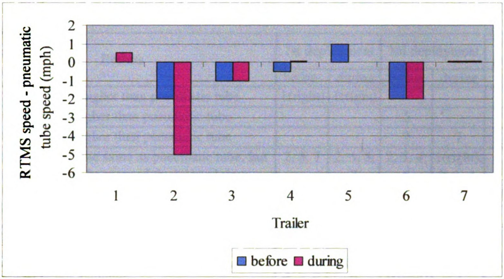


Figure 4.12. The difference between the RTMS and pneumatic tube average speed "before" and "during" the third deployment

Table 4.1. Pneumatic tube average speed verification summary

Results	1st deployment		3rd deployment		4th deploy.
	before	during	before	during	during
RTMS was 1 mph higher than pneumatic tube		2	5		
RTMS was 0.5 mph higher than pneumatic tube		1(right)		1(right)	
RTMS was almost the same as pneumatic tube		5	7	4, 7	
RTMS was 0.5 mph lower than pneumatic tube		3	4		
RTMS was 1 mph lower than pneumatic tube			3	3	1
RTMS was 2 mph lower than pneumatic tube		4	2, 6	6	3
RTMS was 2 mph lower than pneumatic tube, except 3PM-8PM (RTMS was 4 mph higher)					5
RTMS was 4 mph lower than pneumatic tube	1(right)	7			6(left)
RTMS was 5 mph lower than pneumatic tube	2, 3, 7			2	
The data were not available	4, 5, 6	6	1(right)	5	2, 4

The numbers in the table indicates the trailer numbers.
The direction in the parenthesis next to the trailer number indicates the lane used in the speed comparison.
The trailers with no parenthesis indicate that there was only one lane at those trailers.

Table 4.2. Pneumatic tube 30-minute volume verification summary

Results	1st deployment		3rd deployment		4th deploy.
	before	during	before	during	during
RTMS was 100 % higher than pneumatic tube	1(right)	1(right)			
RTMS was 30 % higher than pneumatic tube			5		
RTMS was 10 % higher than pneumatic tube			7	7	
RTMS was almost the same as pneumatic tube, but varied by time slice because of the interval time variation	2, 3, 7	2, 3, 5, 7	2, 3, 4, 6	1(right), 2, 3, 4, 6	1, 5
RTMS was 7 % lower than pneumatic tube		4			
RTMS was 10 % lower than pneumatic tube					3, 6 (left)
The data were not available	4, 5, 6	6	1(right)	5	2, 4

The numbers in the table indicates the trailer numbers.
The direction in the parenthesis next to the trailer number indicates the lane used in the volume comparison.
The trailers with no parenthesis indicate that there was only one lane at those trailers.

From tables 4.1 and 4.2, it is clear that the average speed differences between the RTMS and pneumatic tubes in the "before" condition were not equal to the "during" conditions, particularly in the first deployment. This indicated that the speed measurement of either the RTMS system or the pneumatic tube system was inconsistent. However, the 30-minute volume differences in both the "before" and "during" conditions were nearly equal. The volumes measured by the pneumatic tube were less than 10 percent different than the volumes measured by the RTMS at most of the locations. The accuracy of pneumatic tube volume measurement was good enough to provide a general idea about the level of congestion.

To identify the data collection method that provided the inconsistent average speeds, the average speeds during one hour on all of the available dates from both the RTMS and the pneumatic tubes were plotted over time. The average speeds during off-peak hours from 10AM to 11 AM and from 10PM to 11PM were used because the influence of traffic on the average speeds was lower during the off-peak hour. The data from trailer 1 in the first deployment was used for this comparison because the difference between the average speed differences between the RTMS and pneumatic tubes was very high at this trailer. "Before" the deployment, the RTMS average speeds were about 4 mph lower than the pneumatic tube average speeds, while "during" the deployment, the RTMS average speeds were about 0.5 mph higher than the pneumatic tube average speeds. The pneumatic tube versus RTMS average speed comparisons at trailer 1 are shown in figures 4.13 and 4.14.

From figures 4.13 and 4.14, it can be seen that the average speeds measured by the RTMS were consistent, while the average speeds measured by the pneumatic tubes were inconsistent. The pneumatic tube average speeds "before" the experiment (05/23/02-05/25/02) were about 4 mph higher than the pneumatic tube average speeds "during" the experiment (06/06/02-06/09/02). Since the pneumatic tubes were frequently ripped up, the errors in the pneumatic tube average speeds may come from the difference in the distance between the two tubes each time the pneumatic tubes were replaced. This difference in the distance between two tubes affected only the speed measurement. Thus the pneumatic tubes still provided consistent traffic volume measurements. Because of the inconsistent speed measurement, the pneumatic tube data were not used in the average speed analysis. However, the inconsistent speed measurement does not effect the speed variance because the speed variance only depended on the relative values of speeds, not the absolute values. Therefore the pneumatic tube data were still used in the speed variance analysis.

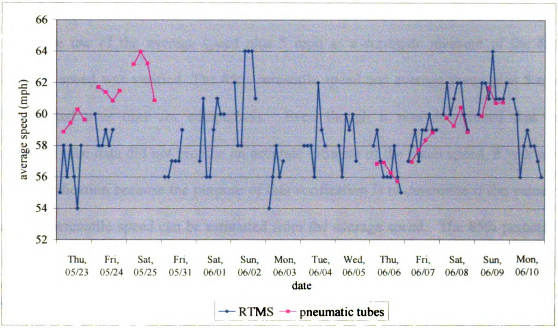


Figure 4.13. Pneumatic tube versus RTMS average speed comparison at trailer 1 from 10AM to 11AM in the first deployment

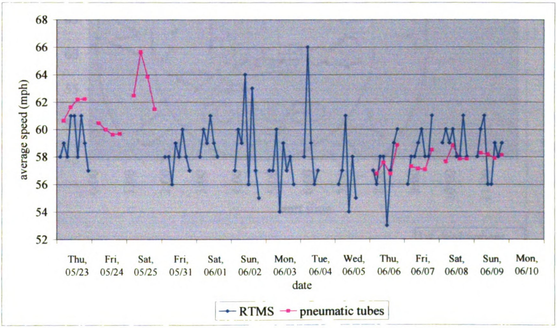


Figure 4.14. Pneumatic tube versus RTMS average speed comparison at trailer 1 from 10PM to 11PM in the first deployment

4.1.3 85th percentile speed estimation

The use of the average speed plus 5 mph as a surrogate measure of the 85th percentile speed was verified. The 85th percentile speed and average speed plus 5 mph were plotted over time for comparison. Even though it was determined that the pneumatic tube data did not provide an accurate estimate of the mean speed, it was used in this verification because the purpose of this verification is to determine if the value of the 85th percentile speed can be estimated from the average speed. The 85th percentile speed and the average speed plus 5 mph were compared using all of the available pneumatic tube data. Examples of the 85th percentile speed and average speed plus 5 mph comparisons are shown in figures 4.15 and 4.16.

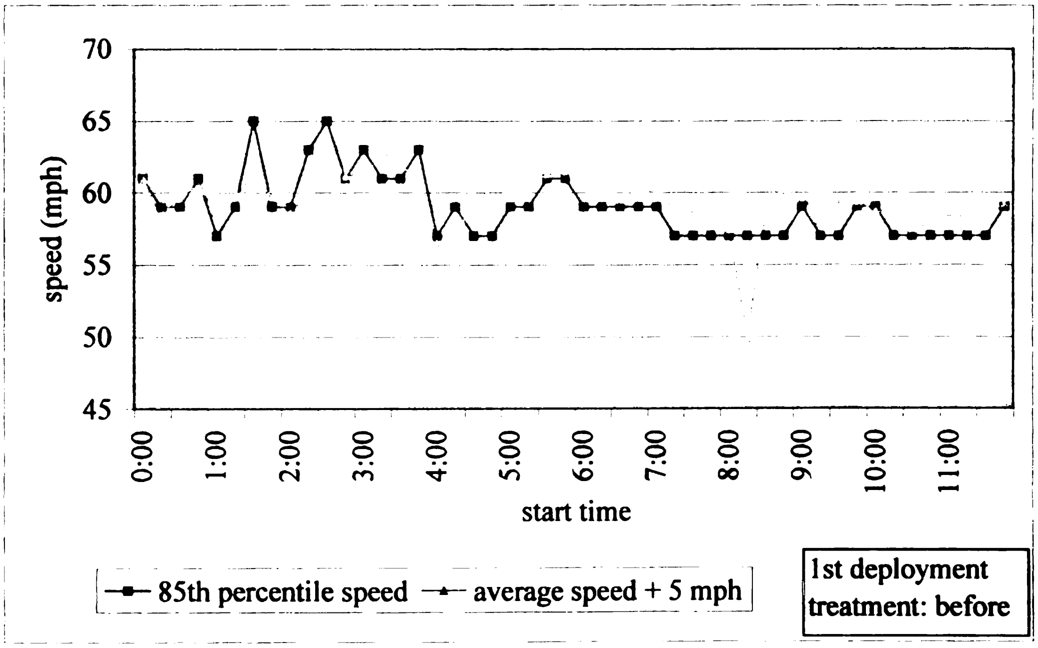


Figure 4.15. 85th percentile speed and average speed plus 5 mph comparison from trailer 3 before the first deployment (30-speed bin pneumatic tube data)

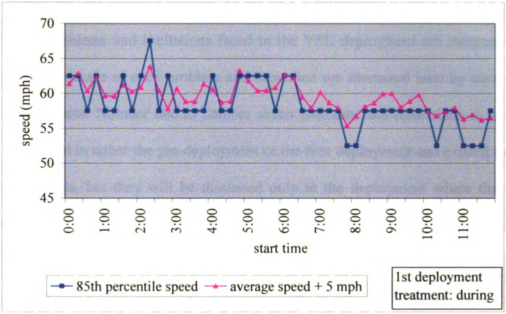


Figure 4.16. 85th percentile speed and average speed plus 5 mph comparison from trailer 3 during the first deployment (16-speed bin pneumatic tube data)

The results indicated that almost all of the differences between the 85th percentile speed and the average speed plus 5 mph were less than 1 mph when the 30-speed bin pneumatic tube data were used in the comparisons and that almost all of the differences between the 85th percentile speed and the average speed plus 5 mph were less than 2.5 mph when the 16-speed bin pneumatic tube data were used in the comparisons. The number of speed bins had an effect on the value of the 85th percentile speed relative to the average speed plus 5 mph in this verification with the more accurate results coming from the smaller speed bin. Thus, the average speed determined from the RTMS data plus 5 mph may provide a better estimate of the 85th percentile speed than the results in this verification indicated since the average speed determined from the RTMS data does not have to be estimated from "binned" data.

4.2 Problems and limitations faced in the VSL deployment

The problems and limitations faced in the VSL deployment are summarized in table 4.3. The details of each problem and limitation are discussed later by each of the VSL deployments. Number one to number seven problems and limitations in table 4.3 were first found in either the pre-deployment or the first deployment and existed in all of the deployments, but they will be discussed only in the deployment where they were discovered. A number in a parenthesis behind the bullet in the problem discussion section indicates the problem number from table 4.3.

Table 4.3. Problems and limitations faced in the VSL deployment

Problems and limitations	deployment				
	pre	1	2	3	4
1. inconsistent length of the speed limit update period	x	x	x	x	x
2. 1-minute communication time between the master trailer and pagers	x	x	x	x	x
3. data storage problem	x	x	x	x	x
4. trailer setting on slave trailers cannot be changed remotely		x	x	x	x
5. occasionally the remote computer could not connect to the VSL system		x	x	x	x
6. inaccurate occupancy measurement		x	x	x	x
7. repetitive VSL data set		x	x	x	x
8. short-range modem broke down		x		x	
9. problem with the fixture of the static speed limit signs over VMS		x			
10. problem with speed-limit setting algorithm		x	x	x	x
11. speed-limit round-off error		x	x	x	x
12. improper speed limit (e.g., 54, 64 mph)		x		x	x
13. pneumatic tubes were ripped up frequently		x		x	x
14. RTMS broke down				x	
15. battery on a VSL trailer failed				x	x

x indicates the deployment that had that problem

4.2.1 Pre-deployment test

- (1) The VSL trailers were able to communicate with each other, with the pagers, and with a remote computer. The pre-deployment testing confirmed that the VSL trailers communicated with one another at a distance of 0.5, 1, and 1.5 miles. A problem was that it took about one minute for the VSL trailers to communicate with each other to provide the data to the master trailer to update the speed limits. Thus, when the programmed speed limit update period was set at 5 minutes, the actual update time was 6 minutes instead. Moreover, the length of the speed limit update period was also inconsistent. The length of the speed limit update period was occasionally shorter or longer than 6 minutes. The length of the speed limit update period ranged from 2 to 15 minutes. IRD should solve this problem in the next version of the VSL system.
- (2) It took about one minute for the master trailer to transmit the updated speed limits to the pagers. During this one minute, the speed limit that the police would have enforced was different from the speed limit on the VSL trailer. This delay will have to be addressed in any enforcement program.
- (3) Data storage was also a problem. The downloaded data indicated some unusual results including incorrect data and missing data in some time periods. These errors happened randomly. This problem was prevented by downloading and saving data frequently. The data were downloaded approximately every three hours, except between 12AM and 7AM. The data were only downloaded once between 12AM and 7AM.

- There was no problem with the speed limit setting algorithm. The VSL system set the speed limit properly including during the rain, when the speed limit was set to be lowered by 20 percent to test the weather sensor.
- Since the problems and the limitations that were discovered in the pre-deployment test had no major impact on the operation of VSL system, the VSL system "passed" the pre-deployment test.

4.2.2 First deployment

- (4) When the operational parameters and speed limit setting profiles on the slave trailers were different from the master trailer, the operational parameters and speed limit setting profiles on the slave trailers (i.e., trailers 2 to 6) could not be changed by the remote computer. The changes had to be made at each trailer by connecting the computer directly to the trailer. Only the trailer setting on the master trailer could be changed remotely.
- (5) At random times, the remote computer could not connect to the VSL system through the long-range wireless modem because the modem signal was not strong enough. When this problem happened, the connection had to be made directly at the location of the master trailer.
- (6) The occupancy measured by the RTMS is not functioning properly. Examples are shown in table 4.4. For instance, in the first and the second examples, the average speeds and the occupancies were the same in both the first and the second observations, but the volumes in the first observations were much higher than the second observations. However, the occupancies were only used to trigger the VSL

system to display the minimum or the maximum speed limit and the inaccurate occupancy measurement did not affect this process.

Table 4.4. Examples of incorrect occupancies

Example	1st observation			2nd observation		
	speed (mph)	volume (veh./6min.)	occupancy (percent)	speed (mph)	volume (veh./6min.)	occupancy (percent)
1st	52	305	3	52	138	3
2nd	52	201	2	52	95	2
3rd	54	269	1	54	74	2

- (7) The data set from the same VSL trailer occasionally repeats itself in two or more consecutive periods. Examples are shown in figure 4.17. The data from trailers 2, 4, 5, 6, and 7 in these two time periods were exactly the same. The data from trailer 3 in these two time periods were almost the same. Only one value was different. IRD should solve this problem in the next version of the VSL system.

```
IRD Speed Ranger VSL SRWM#=1111111 Traffic Log
Date,Time,Trailer#,AvgSpd,DpySpd,Occ,Vol,VB1,VB2,VB3,VB4,VB5,VB6,VB7,VB8

07Jun2002,19:46:18,   1,56,60,04,0092,000,004,008,003,002,004,003,068
07Jun2002,19:46:18,   2,51,50,02,0118,003,066,005,006,003,000,003,031
07Jun2002,19:46:18,   3,54,60,05,0119,000,021,055,007,007,000,004,025
07Jun2002,19:46:18,   4,56,60,02,0111,002,053,009,002,003,002,001,040
07Jun2002,19:46:18,   5,56,60,03,0110,000,059,004,000,003,000,003,041
07Jun2002,19:46:18,   6,45,60,03,0122,010,033,005,000,002,001,002,072
07Jun2002,19:46:18,   7,51,50,03,0096,001,048,009,009,001,001,003,022

07Jun2002,20:01:21,   1,60,65,04,0196,000,011,018,003,005,004,003,151
07Jun2002,20:01:21,   2,51,50,02,0118,003,066,005,006,003,000,003,031
07Jun2002,20:01:21,   3,54,60,05,0119,000,021,055,007,006,000,004,025
07Jun2002,20:01:21,   4,56,60,02,0111,002,053,009,002,003,002,001,040
07Jun2002,20:01:21,   5,56,60,03,0110,000,059,004,000,003,000,003,041
07Jun2002,20:01:21,   6,45,60,03,0122,010,033,005,000,002,001,002,072
07Jun2002,20:01:21,   7,51,50,03,0096,001,048,009,009,001,001,003,022

A shaded line indicates that the data repeats itself.
```

Figure 4.17. Examples of data that repeat themselves

➢ (8) The short-range modems broke down for a few days during the first deployment testing period (while the static speed limit signs covered the VMS) because a bridge in the vicinity of trailers 5, 6, and 7 blocked the line of sight. During this period, the VSL system could only record the data from the master trailer because all of the VSL trailers could not communicate with each other. This problem was solved by using poles to raise the short-range modem antennas at trailer 5, 6, and 7 as shown in figure 4.18.

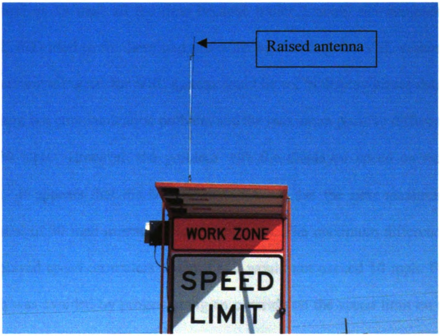


Figure 4.18. Raised short-range modem antenna at trailer 6

➢ (9) The static speed limit signs, which were used to cover the VMS, fell down because the Velcro that was used to hold them was not strong enough. This problem was solved by using plastic straps to hold the static speed limit signs.

➢ (10) During the first deployment test, while the static speed limit signs covered the VMS, the displayed speed on trailer 2 was 60 mph most of the time instead of ranging between 40 and 50 mph, as it was set. The assumption was that this problem occurred because the maximum positive differential was set at a default value of 10 mph and the displayed speed on trailer 1 was overridden to display 70 mph. (The speed limit on trailer 1 was overridden to display 70 mph at the beginning because the 70 mph speed limit sign was not available.) After the maximum positive differential on all of the trailers was changed to 25 mph, which was the maximum value allowed by the system at that time, the problem still existed. Moreover, when the short-range modems broke, the displayed speed on trailer 1 was equal to the maximum positive differential of 25 mph all the time because trailer 1 could not communicate with trailer 2. IRD tried to fix these two problems by updating the VSL system software. With the new software, the VSL system could be set to display preset default speeds when there is a communication problem and the maximum positive differential can be set at 30 mph. However, the problem with the displayed speed on trailer 2 still existed. It appears that the VSL system did not use the new maximum positive differential of 30 mph in setting the speed limits. The maximum difference between the displayed speed on trailers 1 and 2 still would not exceed 10 mph. Finally, this problem was avoided by programming an override on the speed limit on trailer 2 to display 50 mph all the time. The override did not have any negative impacts because the average speed at trailer 2 was more than 43 mph all the time and according to the algorithm, the displayed speed on trailer 2 would have been constant at 50 mph anyway.

- (11) The displayed speeds on trailers other than trailer 2 were wrong occasionally, when the average speeds were close to the borderline between two speed ranges (i.e., a round-off error). For example, when the average speed was 53 mph at trailer 3, the

VMS on trailer 3 displayed the wrong speed limit of 55 mph instead of the correct speed limit of 60 mph. IRD explained that a round-off error occurred because when the data to set the speed limit was sent to the master trailer, the average speed was lower than the borderline speed (e.g., 53 mph), but a few faster vehicles passed the VSL trailer during the speed limit setting process and increased the average speed to exceed the borderline speed. A round-off error can also occur the other way around. In this case, when the speed limit was set the average speed exceeded the borderline speed, but a few slower vehicles passed the VSL trailer during the speed limit setting process and decreased the average speed. Since this problem happens when the average speed is changed by a few vehicles, it usually happens when there is low traffic volume.

- (12) The displayed speed in the VSL data log sometimes (rarely) showed improper numbers, such as 54 and 64 mph. However, these improper speeds were seen only in the data log and were not actually seen on the VMS.
- (13) The pneumatic tubes that were used to collect traffic data along with the RTMS were ripped up frequently. Thus, the data collected by the pneumatic tubes is not complete. This problem was partially alleviated by checking the tubes regularly and notifying MDOT immediately to fix the tubes when a problem was found.

4.2.3 Second deployment

- (10, 11) During the second deployment test, the VMS at trailers 1 to 5 were covered with the 50-mph static speed limit signs and the VMS at trailer 6 and 7 were overridden to display 50 and 60 mph, respectively. The displayed speeds during this period exhibited some unexplained errors and some round-off errors. Furthermore, the volume data were irregular. The traffic volumes should be either the same or decrease trailer-to-trailer from 7 to 1 because there are only off-ramps in this area. But the traffic volume at trailer 1 in several time periods was higher than the volume at other trailers. Although the problems with the displayed speeds and volumes existed, they were not serious. Thus, the decision was made to uncover the displays and relax the override on trailers 6 and 7. That day was on Saturday so the algorithm for "no workers present" was used.

- (6) At about the same time that the override on trailer 7 was relaxed, the occupancy value at trailer 1 increased to above 80 percent and stayed there for about one and a half hours. This high occupancy resulted in the speed displayed on trailers 1 and 2 to be 40 mph (i.e., the minimum speed limit allowed at these 2 trailers) because the high occupancy threshold was set at 70 percent at that time. The 80 percent occupancy was unrealistic because the average speeds were still in the 50s, the volumes were around 100 vehicles per 6 minutes, and no heavy traffic volume was observed in the field. This problem was avoided in the next deployment by increasing the high occupancy threshold to 90 percent. Thus, the minimum speed limit will not be displayed unless the occupancy is at least 90 percent.
- (10) When the displayed speed on trailer 2 was 40 mph, the displayed speed on trailer 3 was programmed to be constrained to be no higher than 50 mph because the maximum negative differential was set at 10 mph. However, the VMS on trailer 3 occasionally displayed 55 mph or more.
- (10) About 2 hours after the VMS was uncovered, the VMS at trailer 7 displayed 40 or 45 mph when the minimum speed limit allowed at trailer 7 was set at 60 mph.

- Since there were so many unexplained problems and this construction zone was scheduled to last only 3 more days, the decision was made to abort this deployment. The assumption was that these problems might have resulted from the way the speed profiles were set up. Trailers 1 to 6 were set up to use the speed profile from the master trailer, while trailer 7 was set up to use its own speed profile. In the first deployment where there were no unexplained problems about the speed-limit setting, all of the trailers were set up to use their own speed profile. Thus, in the future deployments, all of the trailers should be set up to either use their own speed profile or use the speed profile from the master trailer.

4.2.4 Third deployment

- (8) During the third deployment test, the cable for the short-range modem antenna at trailer 7 was broken. Thus all of the trailers could not communicate with each other. This problem was solved by setting trailer 7 to operate independently and display a static speed limit of 60 mph. The rest of the trailers operated as a system using their own speed profile set up at each trailer.
- (10, 11) There were some errors noted in the displayed speed, particularly at trailers 2 and 3. Although most of the errors were round-off errors, there were also some errors that might come from the fact that the system did not take the preset value of the maximum positive differential into consideration when the speed limits were set. Even though the maximum positive differential between trailers 2 and 3 was set at 30 mph, the maximum positive differential would not exceed 10 mph during the first three days that the displays were revealed to the public. After that, the maximum

positive differential did exceed 10 mph without any adjustments to the VSL system and only an occasional round-off error occurred.

- (12) The improper displayed speed of 54 mph also found in the data log a few times during this deployment.
- (14) The RTMS at trailer 5 broke during the second day after the displays were revealed to the public. The traffic data at trailer 5 were not collected and the VMS at trailer 5 automatically displayed a default speed limit of 50 mph. After that, the displayed speed on trailer 5 was overridden to display 60 mph for the remainder of the deployment. However, trailer 5 was still able to communicate with trailers 4 and 6 and pass the data back and forth.
- (15) The battery at trailer 4 failed about 14 hours before the end of the third deployment. Only the data from trailers 1 to 3 were available after that.
- (13) The pneumatic tubes that were used to collect traffic data were ripped up frequently. Thus the data collected by the pneumatic tubes is not complete.

4.2.5 Fourth deployment

- (15) About 4 hours after the VSL system was installed on I-96, the traffic data from trailers 4 and 5 were missing and the displayed speed on trailer 3 was constant at 50 mph. This problem might have been caused by the loss of power at trailer 4, the same as at the end of the third deployment. IRD was able to fix this problem a few days later.
- (10, 11) The round-off errors occurred less frequently during this deployment. There were also a few displayed speed errors that cannot be explained. For example, in one

6-minute period, trailers 1 to 5 all displayed 40 mph. Although the average speed during that period was low, it was not low enough to display a speed limit of 40 mph.

- (12) The improper displayed speeds of 44 and 54 mph were also found occasionally in the data log during this deployment.
- (13) The pneumatic tubes that were used to collect traffic data were ripped up frequently. Thus the data collected by the pneumatic tubes is not complete.

4.2.6 Conclusion

Even though there were many problems and limitations faced during the VSL deployments, most of the problems and limitations could be overcome, avoided, or alleviated and the VSL deployments were evaluated, except in the second deployment where the unexplained speed-limit-setting problems led to the decision to abort the deployment. Most of the problems and limitations resulted from the limitations and unreliability of the current VSL system. IRD should be able to overcome these problems and limitations in the next version of the VSL system.

Chapter 5

DATA ANALYSIS AND RESULTS

The discussion in this chapter is organized by MOE within each of the VSL deployments. The effect of police presence, which was only tested in the fourth deployment, is discussed at the end of this chapter. The data were separated between weekend and weekday data for the analyses, with the weekday defined as Monday at 6:00AM to Friday at 6:00PM and the weekend defined as Friday at 6:00PM to Monday at 6:00AM.

Since the RTMS data provide only a 6-minute average speed, not individual vehicle speeds, the data from the display trailers can only be used to determine the average speed and the travel time through the work zone. The RTMS data are only available "before" and "during" each VSL deployment since the trailers were removed when the construction activity changed.

As was mentioned in the previous chapter, the pneumatic tube speed data were not reliable so they were not used in the average speed analysis, nor in the travel time analysis. In spite of the inconsistent speed measurements, the pneumatic tube data were used in the examination of the 85^{th} percentile speed, the speed variance, and the percentage of higher speed vehicles because they are the only disaggregate data available. Moreover, the analyses focused on the changes in the MOE, which should be reasonably accurate as long as the pneumatic tube data were collected using the same installation of the tubes. Since the pneumatic tubes were ripped up frequently, only limited pneumatic tube data were available for the "before" versus "during" and the "during" versus "after" comparisons. When data were available, the values of the MOE from the same time of the day and the same day of the week in two conditions ("before" and "during" or "during" and "after") were plotted for comparisons. The pneumatic tubes reported the data in either 16- or 30-speed bin format depending on which setting the MDOT used on a particular day. Sometimes the formats "before" and "during" the deployment were different. It should be noted that the number of speed bins available affects the estimation of the average speed, the 85th percentile speed and the speed variance. For the 16-speed bin format, the individual vehicle speed can be estimated to within 5 mph of the actual speed, while for the 30 speed-bin format, the individual vehicle speed can be estimated to within 2 mph of the actual speed. The available pneumatic tube data and the format of those data are shown in table 5.1.

Table 5.1. Available pneumatic tube data

deployment	trailer	"before" versus "during"		"during" versus "after"	
		weekday	weekend	weekday	weekend
1	1 (right lane)	30/16*	30/16		
	3	30/16			
	7	30/16			
2	No data was available.				
3	1 (left lane)	16/30			
	2	30/30			
	3	16/16			16/16
	4	16/16			16/16
	7	16/16			16/16
4	6 (left lane)			30/30	30/30

Notes:

*The numbers in each cell (n/n) indicate the number of speed bins, with the first number indicating the number of speed bins in the first condition (e.g., "before" in "before" versus "during") and the second number indicating the number of speed bins in the second condition.

A shaded cell indicates that the data were not available during that time period.

5.1 Average speed

The hypotheses to be tested are that the average speed will increase with an increase in the displayed speed and that the average speed will decrease with a decrease in the displayed speed. The 6-minute average speeds and 6-minute average displayed speeds in the "before" and "during" conditions were compared. F-tests within the ANOVA procedure in the SPSS software were performed to determine whether there were significant differences in the average speeds between the "before" and "during" conditions. The average speed at the preceding upstream trailer was used as a covariate in the F-tests to account for the effect of the "entry" speed from the preceding trailer. The covariate was used to reduce any possible bias caused by a difference in the entry speed between vehicles in the "before" and "during" or "during" and "after" data sets. The time periods that the average speeds and average displayed speeds were compared were selected based on the time when VSL effects were expected to be interesting, and on data availability. The four time periods used in the analyses were 6:00AM to 8:30AM (AM peak), 10:30AM to 12:30PM (off-peak daytime), 4:00PM to 6:00PM (PM peak), and 8:00PM to 10:00PM (off-peak nighttime).

Since there were variations in day-to-day and trailer-to-trailer average speeds in this work zone, the average speed profiles and average displayed speed profiles were also compared to determine how the displayed speed reacted to the average speed changes.

5.1.1 First deployment

A. Average speed and displayed speed

The average speed profiles in the "before" and "during" conditions are compared in figures 5.1 to 5.4. The 6-minute average speeds at each trailer averaged over the noted

time period were plotted over the length of the VSL deployment area. The horizontal axis showed the distance through the zone and the trailer locations. Each line in the figures represents an average speed profile during the noted time period on each day. Vehicles were proceeding through the zone from trailer 7 to trailer 1 (left to right). It should be noted that the maximum speed limit allowed on trailers 7 and 2 was 50 mph because they were located in advance of an on-ramp from I-69 and the traffic crossover, respectively. The displayed speeds at these 2 trailers in the "during" condition were 50 mph most of the time, which were the same as in the "before" condition.

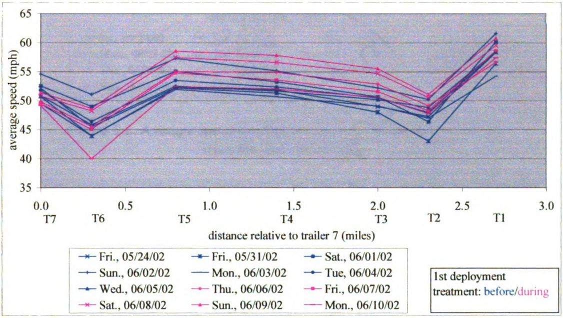


Figure 5.1. Average speed profiles between 6:00AM and 8:30AM from the first deployment

In figures 5.1 to 5.4, there was a day-to-day variation both within and between "treatment groups". The average speeds were somewhat higher in the "during" condition. However, the average speeds at the first two trailers encountered by the motorist (trailers 7 and 6) in the "during" condition were slightly lower than the "before" condition. These average speed differences were more apparent in the off-peak nighttime period. In both the "before" and "during" conditions, the motorists slowed down at trailers 2 and 6 where there was a ramp and a traffic crossover, respectively in the vicinity.

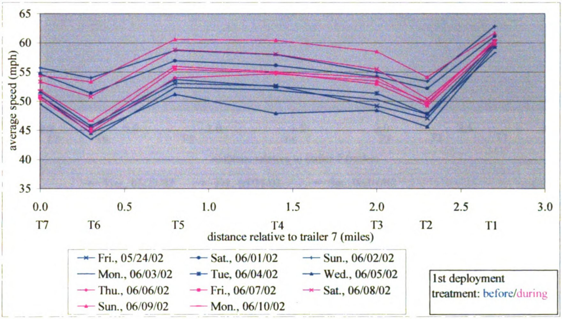


Figure 5.2. Average speed profiles between 10:30AM and 12:30PM
from the first deployment

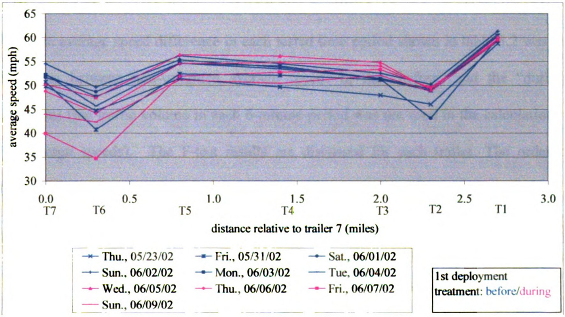


Figure 5.3. Average speed profiles between 4:00PM and 6:00PM
from the first deployment

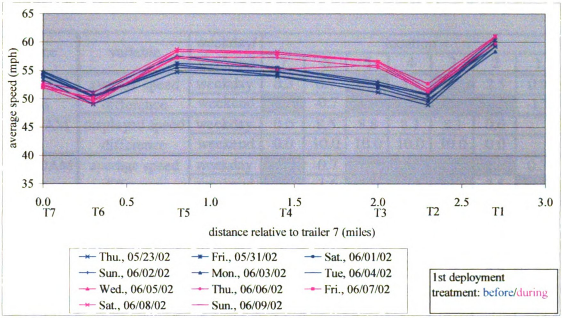


Figure 5.4. Average speed profiles between 8:00PM and 10:00PM
from the first deployment

Besides the graphical comparisons, F-tests were performed on the average speeds "before" and "during" the deployment. The differences between the displayed speeds "before" and "during" the deployment were also examined. The results are shown in table 5.2. The average speed difference in each tested time period shown in table 5.2 was the difference between non-weighted average speeds in the "before" and the "during" conditions (the traffic volume in each 6-minute period was not used in the calculation of the average speeds). The F-test results are discussed for each trailer. The order of discussion was based on the order that the motorists encountered the trailers.

Table 5.2. Results of the F-tests on the average speeds from the first deployment

time	variable	weekday/ weekend	location						
			7	6	5	4	3	2	1
6:00AM to 8:30AM	average speed difference	weekday	0.3	0.7	2.5	3.7	3.7	2.5	0.9
		weekend	-1.3	-0.7	1.9	2.2	2.5	-0.5	-1.1
	displayed speed difference	weekday	0.0	8.5	8.8	8.1	8.1	0.0	
		weekend	0.0	10.0	10.0	10.0	10.0	0.0	
10:30AM to 12:30PM	average speed difference	weekday	-1.5	-0.7	2.0	2.2	2.5	1.5	0.3
		weekend	-2.4	-1.6	1.9	3.1	3.7	2.5	-0.6
	displayed speed difference	weekday	0.0	9.3	9.0	6.7	6.7	0.0	
		weekend	0.0	10.0	10.0	10.0	10.0	0.0	
4:00PM to 6:00PM	average speed difference	weekday	-5.4	-3.1	0.7	1.9	3.3	0.8	-0.1
		weekend	-9.1	-6.8	-4.6	-3.7	0.2	2.2	-1.3
	displayed speed difference	weekday	-1.0	8.7	8.5	8.5	8.5	0.0	
		weekend	-1.9	6.3	6.6	8.1	8.1	0.0	
8:00PM to 10:00PM	average speed difference	weekday	-1.6	-0.2	2.1	1.8	3.8	1.5	0.9
		weekend	-2.0	-0.5	1.9	3.1	4.1	1.6	0.8
	displayed speed difference	weekday	0.0	10.0	9.4	9.9	9.9	0.0	
		weekend	0.0	10.0	10.0	10.0	10.0	0.0	

A shaded cell indicates that the difference was statistically significant with 95% confidence.

A blank cell indicates that the data was not available.

Cell values are the difference in speed (or displayed speed, during-before) in mph.

- In the 6:00AM to 8:30AM period, even though the displayed speed on trailer 7 (the first trailer encountered by the driver) was 50 mph in both the "before" and "during" conditions, the average speed exceeded 50 mph for both the weekdays and the weekends. However, the average weekend speed in the "during" condition was significantly lower (1.3 mph) than the "before" condition. The average speed increased during the weekdays but the difference (0.3 mph) was not significant. In the 10:30AM to 12:30 PM period, the displayed speed (50 mph) was also the same during the two periods. The average speed exceeded the posted speed both "before" and "during." There was a small (but significant) speed reduction in both the weekdays and the weekends when the VSL signs were activated. In the afternoon peak hour, the average displayed speed was slightly lower in the "during" condition (49.0 and 48.1 mph) with a relatively large (5.4 and 9.1 mph) reduction in the average speed of motorists. In the 8:00PM to 10:00PM period, there was no change in the displayed speed but a small (and significant) reduction in the average speed. At this trailer, speeds were lower in the "during" period than the "before" period for seven of the eight comparisons; even though the speed limit remained constant in six of these conditions. Thus, it appears that a lighted display of the same speed limit as a static sign resulted in a speed reduction.

- The results at trailer 6 are interesting. In each of the four time periods the average displayed speed increased to between 56.3 and 60 mph, yet the average speed decreased or was not changed significantly. It appears that drivers are not selecting their speed based on the display at this location.
- The results at trailer 5 are consistent with the hypotheses (both the displayed speed and the average speed were higher in the "during" condition), but the magnitude of the change was different. An 8-10 mph increase in the average displayed speed resulted in only a 1-2 mph increase in the average speed. Trailers 4 and 3 showed this same phenomenon, although the increase in the average speed was slightly higher than at trailer 5.
- Even though the displayed speed on trailer 2 was 50 mph in both the "before" and "during" conditions, the average speed "during" the deployment was slightly higher (0.8 –2.5 mph) than "before" the deployment. However, the motorists slowed down at this trailer in both the "before" and "during" conditions.

➢ The average speeds at trailer 1 in the "before" and "during" the deployment were only slightly different and most of the differences were not statistically significant. The displayed speed difference at trailer 1 is not meaningful because a blank sign was used to cover the VMS in the "before" condition.

An example of the average speed and average displayed speed profile comparison from 5:00PM to 6:00PM "during" the first deployment is shown in figure 5.5. The average speed and average displayed speed profiles from a congested day (06/07/02) and from a less-congested day (06/06/02) are shown. Figure 5.5 illustrates that the system was operating as designed because the displayed speeds responded well to both the day-to-day and trailer-to-trailer variations in the average speeds. The fact that the displayed speeds respond to existing traffic condition increases the credibility of the displayed speeds.

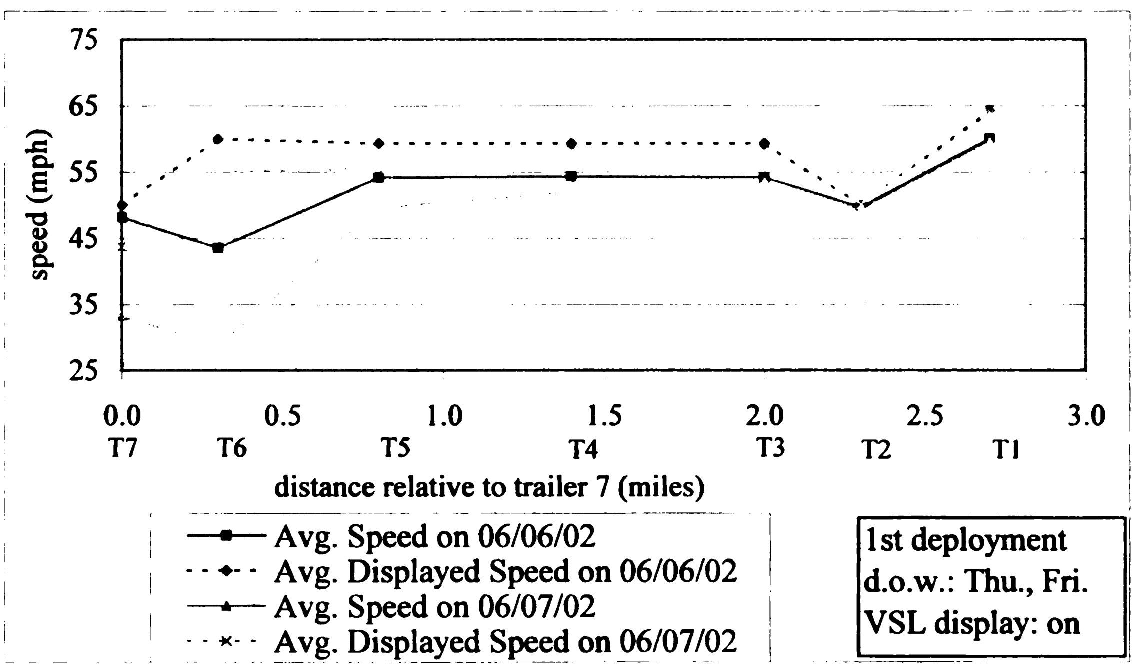


Figure 5.5. Average speed and average displayed speed profile comparison from 5:00PM to 6:00PM "during" the first deployment

B. Average speed and geometry

Since there was a traffic crossover immediately downstream trailer 2, the average speed at trailer 2 was expected to decrease significantly from the average speed at trailer 3. The speed reduction at the crossover in the "before" and "during" conditions were compared as shown in figure 5.6. F-tests were performed to determine whether there were significant differences in the speed reductions between the "before" and "during" conditions. The average speed at trailer 3 was used as a covariate to account for the effect of the "initial" speed. The results of the F-tests are shown in table 5.3. Although the displayed speed at trailer 2 was constant at 50 mph both "before" and "during" the VSL operation, the speed reduction at the crossover in the "during" condition was 1.0 to 3.0 mph greater than in the "before" condition and almost all of the differences were significant. These results indicate that the motorists gave more credibility to the speed limit displayed on the variable message signs than the speed limit displayed on the static signs.

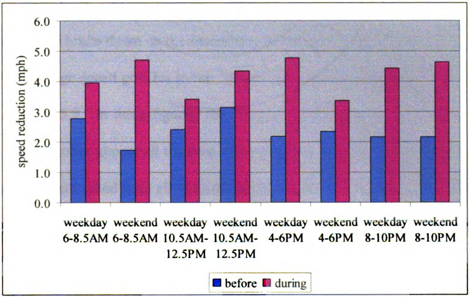


Figure 5.6. "Before" and "during" speed reduction at the crossover comparison from the first deployment

Table 5.3. Results of the F-tests on the speed reductions at the crossover from the first deployment

time	speed reduction "during" - speed reduction "before"	
	weekday	weekend
6:00AM - 8:30AM	1.2	3.0
10:30AM - 12:30PM	1.0	1.2
4:00PM - 6:00PM	2.6	1.1
8:00PM - 10:00PM	2.3	2.5

A shaded cell indicates that the difference was significant with 95% confidence.

5.1.2 Third deployment

Average speed and displayed speed

The third deployment work zone was in the same part of the eastbound I-96 as the first deployment work zone, but two-way traffic was maintained on the eastbound lanes instead of the westbound lanes. In this deployment, the RTMS data were only available during three time periods: 10:30AM to 12:30PM, 5:00PM to 6:00PM, and 8:00PM to 10:00PM. The short-range modem at trailer 7 broke down for a few days during the "before" period, so the "before" data during the weekend were not available, and "before" data exist for only one weekday. The trailer 5 data were also limited because the RTMS at trailer 5 broke down on the second day of the deployment.

The average speed profiles in the "before" and "during" conditions are compared in figures 5.7 to 5.9. In these figures, the "during" speed profiles were higher than the "before" speed profile almost all the time. However, the "before" data are limited to one day. The maximum speed limit allowed at trailers 4 and 6 was limited to 50 mph because of the on- and off- ramps in the vicinity. This low speed limit resulted in low average speeds through the first six trailers (trailers 7 to 2). The motorists increased their speeds between the last two trailers, where the highway was clear and the maximum speed limit allowed was 70 mph.

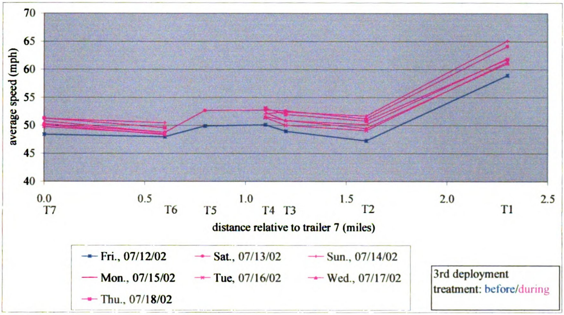


Figure 5.7. Average speed profiles between 10:30AM and 12:30PM from the third deployment

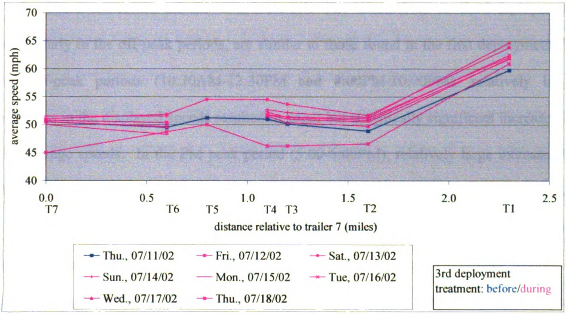


Figure 5.8. Average speed profiles between 5:00PM and 6:00PM from the third deployment

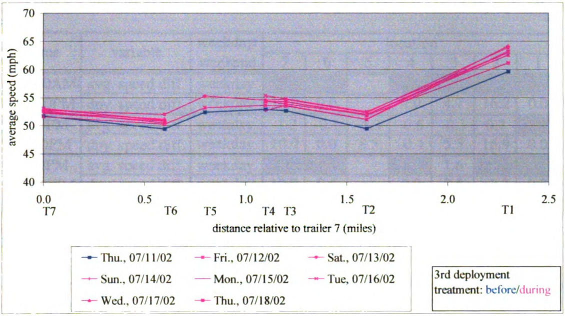


Figure 5.9. Average speed profiles between 8:00PM and 10:00PM
from the third deployment

The F-test results are shown in table 5.4. The results from the third deployment, particularly in the off-peak periods, are similar to those found in the first deployment. In the off-peak periods (10:30AM-12:30PM and 8:00PM-10:00PM), relatively large increases in the displayed speeds resulted in small but statistically significant increases in the average speeds. In the PM peak period (5:00-6:00PM), relatively large increases in the displayed speeds resulted in small and insignificant decreases in the average speeds. However, these same small decreases in the average speeds also occurred when there was no change in the displayed speed. The F-test results indicate that the motorists' responses to the changes in the displayed speeds were more consistent during the non-peak hours than during the peak hours.

Table 5.4. Results of the F-tests on the average speeds from the third deployment

time	variable	weekday/ weekend	location						
			7	6	5	4	3	2	1
10:30AM-12:30PM	avg. speed diff.	weekday	2.1	0.8		1.9	2.0	2.6	2.6
	dpy. speed diff.	weekday	10.0	0.0		0.0	4.7	16.2	0.0
5:00PM-6:00PM	avg. speed diff.	weekday	-1.2	-0.1	-1.3	-0.6	-0.3	0.7	2.1
	dpy. speed diff.	weekday	10.0	0.0	8.5	-0.4	5.5	16.9	0.0
8:00PM-10:00PM	avg. speed diff.	weekday	1.0	1.4		1.7	1.6	2.6	2.8
	dpy. speed diff.	weekday	10.0	0.0		0.0	7.5	17.7	0.0

A shaded cell indicates that the difference was statistically significant with 95% confidence.

A blank cell indicates that the data was not available.

Cell values are the difference in speed (or displayed speed, during-before) in mph.

An example of the average speed and average displayed speed profile comparison from 2:00PM to 3:00PM "during" the third deployment is shown in figure 5.10. Figure 5.10 illustrates that the displayed speeds responded well to both the day-to-day and trailer-to-trailer variations in the average speeds, particularly between trailer 1 and trailer 3. The displayed speeds at trailers 4, 5, 6 and 7 were almost the same on both days, even though the average speeds at these trailers differed by approximately 2-3 mph. The responsiveness of the displayed speeds to the day-to-day and trailer-to-trailer average speed variations at trailers 4 to 7 was not as good as at trailers 1 to 3 because the displayed speeds at trailers 4 to 7 were dictated by the locations of on and off-ramps in the vicinity.

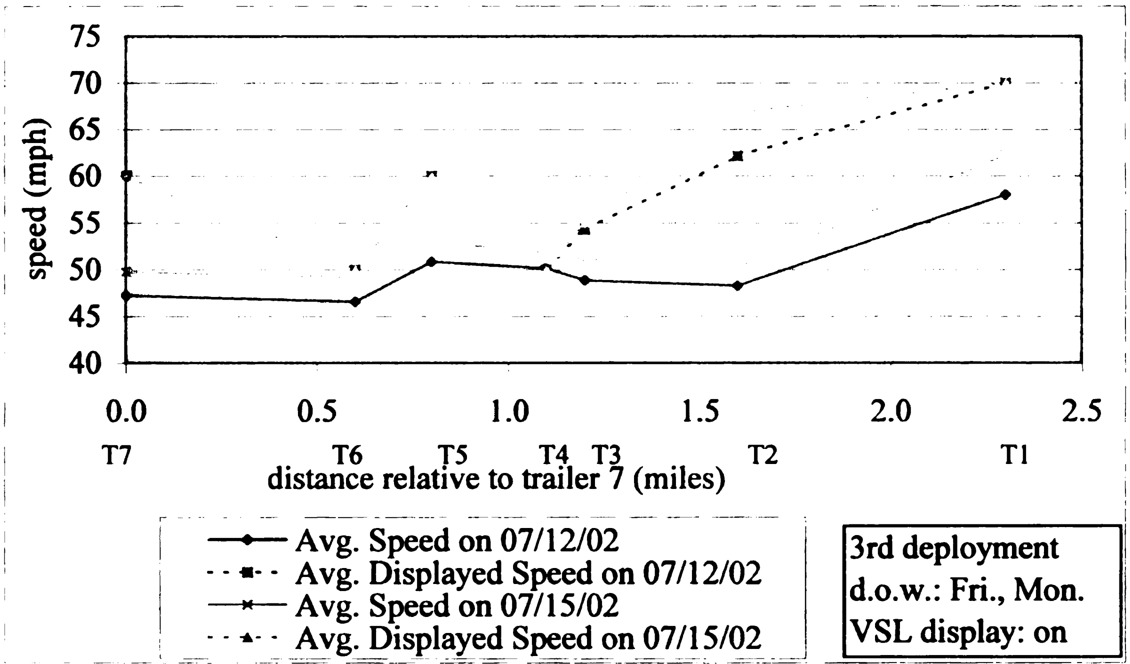


Figure 5.10. Average speed and average displayed speed profile comparison from 2:00PM to 3:00PM "during" the third deployment

5.1.3 Fourth deployment

Average speed and displayed speed

The fourth deployment used two different speed-limit-setting algorithms, one for day (6AM-10PM) and one for night (10PM-6AM) because the construction activities were only carried on between 6AM and 10PM. The maximum speed limit allowed during the day was 50 mph, while the maximum speed limit allowed at night was 70 mph. In this deployment, the RTMS data were only available during two time periods: 10:30AM to 12:30PM and 8:00PM to 10:00PM. Only one day of the weekend "before" data were available because the battery at trailer 4 failed during the "before" deployment.

The average speed profiles in the "before" and "during" conditions are compared in figures 5.11 and 5.12. The average speeds at trailers 4 and 5 ranged from 15 mph to about 50 mph because there was traffic congestion at the beginning of the VSL deployment area during some of the observation periods. The motorists increased their speed as they traveled through the work zone. At the end of construction zone, trailer 6 displayed a speed limit of 70 mph in both the "before" and "during" conditions (the static sign was used in the "before" condition).

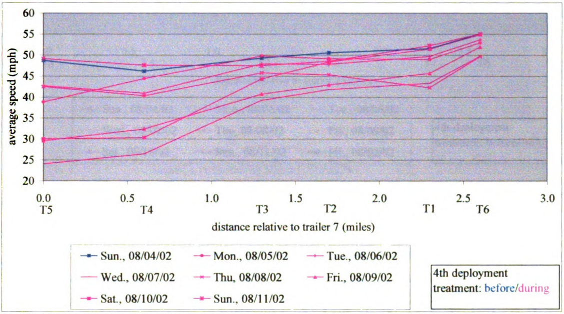


Figure 5.11. Average speed profiles between 10:30AM and 12:30PM from the fourth deployment

The F-test results are shown in table 5.5. There were only a few significant changes in the average speed "during" this deployment and the inconsistency in the direction of change was even greater than in the first and third deployment. In the 8-10PM period, the average "during" displayed speed at trailer 5 was 6.1 mph lower than the "before" period, but the average speed was 9.3 mph higher in the "during" period. During the morning period at this same sign location, a 3.8 mph decrease in the displayed speed resulted in an 8.8 mph reduction in the average speed. Most of the other changes were not significant for this deployment. However, these results were based on only one day of "before" data.

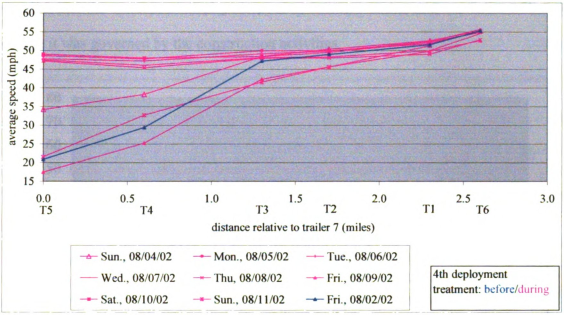


Figure 5.12. Average speed profiles between 8:00PM and 10:00PM from the fourth deployment

Table 5.5. Results of the F-tests on the average speeds from the fourth deployment

time	variable	weekday/ weekend	location					
			5	4	3	2	1	6
10:30AM-	avg. speed diff.	weekend	-8.8	-7.0	-3.3	-2.1	0.3	-0.1
12:30PM	dpy. speed diff.	weekend	-3.8	-0.5	0.0	0.0	0.0	0.0
8:00PM-	avg. speed diff.	weekend	9.3	6.4	-2.2	-1.3	-0.1	-1.0
10:00PM	dpy. speed diff.	weekend	-6.1	-1.8	-0.7	0.0	0.0	0.0

A shaded cell indicates that the difference was statistically significant with 95% confidence.
A blank cell indicates that the data was not available.
Cell values are the difference in speed (or displayed speed, during-before) in mph.

An example of the average speed and average displayed speed profile comparison from 8:00PM to 9:00PM "during" the fourth deployment is shown in figure 5.13. The average speed and average displayed speed profiles from a congested day (08/09/02) and a less-congested day (08/10/02) are shown. The displayed speeds and the actual speeds were both lower on the congested day. Figure 5.13 illustrates that the displayed speeds responded well to the day-to-day and trailer-to trailer average speed variations. It should be noted that the maximum displayed speed at trailer 5 to 1 could not exceed 50 mph because it was governed by the construction activities.

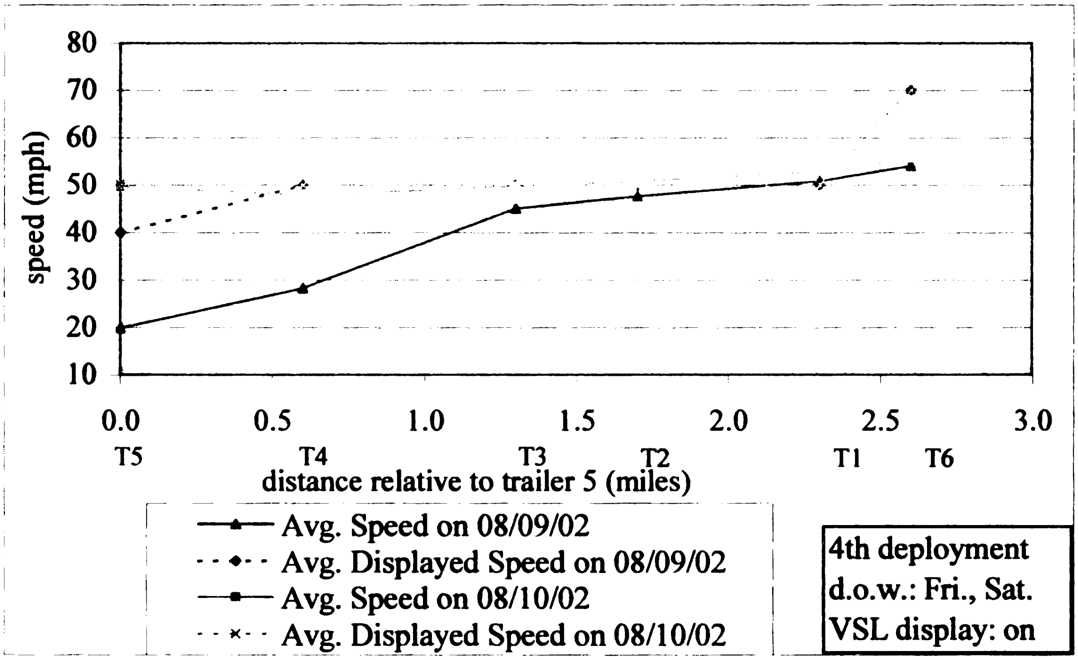


Figure 5.13. Average speed and average displayed speed profile comparison from 8:00PM to 9:00PM "during" the fourth deployment

5.1.4 Average speed analysis conclusion

The results were most consistent with the hypotheses at locations in the work zone where there were no ramps in the vicinity. In the first deployment, this condition existed at trailers 3, 4, and 5. The average speeds at these trailers changed in the same direction as the changes in the displayed speeds, but relatively large increases in the displayed speeds resulted in only small changes in the average speeds. In contrast, there were many ramps in the vicinity of trailers 4, 5, and 6 in the third deployment and the average speeds at these locations were not consistent with the hypothesis that these changes would be in the same direction as the displayed speeds.

The motorists apparently gave more credibility to the speed limit displayed on the variable message signs than the speed limit displayed on the static signs. For example, the speed limit at trailer 7 in the first deployment was constant at 50 mph in both the "before" and the "during" conditions but the average speed in the "during" condition was significantly lower than the "before" condition. The VMS on the VSL trailer also resulted in a significantly greater speed reduction at the crossover (trailer 2) in the first deployment than did the static sign.

The motorists' responses to the changes in the displayed speeds were more consistent during the non-peak hours than during the peak hours. For example, in the third deployment at trailer 7, an increase in the displayed speed resulted in an increase in the average speed in every time period, except between 5:00PM and 6:00PM. The explanation is that during the peak hour, the motorists follow the traffic stream without looking at the displayed speeds. Thus, changes in the displayed speeds do not affect the average speeds.

The average speed and average displayed speed profile comparison indicates that the VSL responded to the day-to-day and trailer-to-trailer average speed variations, and thus the used of the VSL system should improve the credibility of the speed limit.

5.2 Travel time through the work zone

The hypothesis is that the travel time through the work zone will decrease if there is an increase in the displayed speeds at most of the VSL trailers. Travel times were calculated from the average speeds at all of the trailers by assuming that vehicles traveled between any two adjacent trailers at a constant speed, which was the non-weighted average of the average speeds at those two trailers during that six minute time period.

The travel times through the work zone in the "before" and "during" conditions were compared. F-tests were performed using the RTMS data to determine whether there were significant differences in the travel times between the "before" and "during" conditions.

5.2.1 First deployment

The F-tests were performed using weekday and weekend data from four time periods: 6:00AM to 8:30AM, 10:30AM to 12:30PM, 4:00PM to 6:00PM, and 8:00PM to 10:00PM. The entry speed at trailer 7 was used as a covariate to account for the effect of the "initial speed" on the travel time. The results of the F-tests on travel time through the work zone are shown in table 5.6.

Table 5.6. Results of the F-tests on the travel times through the work zone from the first deployment

time	Avg. "during" travel time (seconds)		travel time difference (during-before)			
			weekday		weekend	
	weekday	weekend	seconds	percent	seconds	percent
6:00AM - 8:30AM	184.9	171.3	-10.6	-5.4	-2.8	-1.6
10:30AM - 12:30PM	188.7	177.7	-5.0	-2.6	-5.3	-2.9
4:00PM - 6:00PM	192.0	205.6	1.8	1.0	20.9	11.3
8:00PM - 10:00PM	177.7	174.5	-5.2	-2.9	-5.8	-3.2

A shaded cell indicates that the difference was significant with 95% confidence.

All of the differences in each of the four time periods were significant, but the travel time between 4:00PM and 6:00PM was significantly longer in the "during" condition, while the travel times in the other time periods were significantly shorter in the "during" condition. Although the differences in travel time were statistically significant, they were not operationally significant. The maximum travel time saved by the VSL system was only 5.4 percent (10.6 seconds of 195.5 seconds travel time over the 2.7-mile test site) and the maximum increase in travel time with the VSL system was only 11.3 percent (a 20.9-second increase in a 184.7-second travel time). The average speeds through the work zone "during" the deployment for the periods with the maximum travel time saved and the maximum increase in travel time were 52.6 and 47.3 mph, respectively.

5.2.2 Third deployment

The third deployment work zone was similar to the first deployment work zone, but there were more on-ramps and off-ramps, particularly in the first half of the work zone (trailers 7 to 4). In the "before" condition, only the weekday data were available so F-tests were performed with RTMS data during three available time periods on weekdays: 10:30AM to 12:30PM, 5:00PM to 6:00PM, and 8:00PM to 10:00PM. The trailer 5 data were only available between 5:00PM and 6:00PM. During the periods when the average speed at trailer 5 was not available, the travel times were calculated by assuming that vehicles traveled between trailers 6 and 4 at a constant speed, which was the non-weighted average of the average speeds at those two trailers. Since trailer 7 was set up to operate independently in this deployment (because of the short-range modem problem), the trailer 7 data collection periods were different from other trailers, and the travel time between trailers 7 and 6 was not included. The travel time considered in this deployment was only the travel time between trailers 6 and 1. The entry speed at trailer 6 was used as a covariate to account for the effect of the "initial" speed on the travel time. The results of the F-tests on travel time through the work zone are shown in table 5.7.

Table 5.7. Results of the F-tests on the travel times through the work zone from the third deployment

time	Avg. "during" weekday travel time (seconds)	weekday travel time difference (during-before)	
		seconds	percent
10:30AM - 12:30PM	116.6	-4.4	-3.7
5:00PM - 6:00PM	117.5	-0.6	-0.5
8:00PM - 10:00PM	111.9	-4.0	-3.4

A shaded cell indicates that the difference was significant with 95% confidence.

All of the average travel times through the work zone in the "during" condition were significantly shorter than the "before" condition, except 5-6:00PM. The average travel time through the work zone between 5 and 6PM in the "during" condition was shorter than the "before" condition, but the difference was not significant. As was the case in the first deployment, the travel time saved by the VSL system was not operationally significant. The maximum travel time saved by the VSL system was only 3.7 percent (4.4 seconds of 121 seconds travel time) over the 1.7-mile test site. The average speed through the work zone "during" the deployment for this period was 52.5 mph.

5.2.3 Fourth deployment

The fourth deployment used two different speed-limit-setting algorithms, one for day (6AM-10PM) and one for night (10PM-6AM) because the construction activities were only carried on between 6AM and 10PM. The maximum speed limit allowed during the day was 50 mph, while the maximum speed limit allowed at night was 70 mph. In the "before" condition, only the weekend data were available so F-tests were performed with RTMS data during two available time periods on weekends: 10:30AM to 12:30PM and 8:00PM to 10:00PM. Because the maximum speed limit allowed during the day was 50 mph, the displayed speeds "during" the deployment were either equal to or lower than the displayed speed "before" the deployment (50 mph). Since trailer 6 was set up to operate independently in this deployment (because the speed limit-setting algorithm at this trailer was different from other trailers), the trailer 6 data collection periods were different from other trailers and the travel time between trailers 1 and 6 (last 2 trailers) cannot be calculated. The travel time considered in this deployment was only the travel time between trailers 5 and 1. The entry speed at trailer 5 was used as a covariate to account for the effect of the "initial" speed on the travel time. The results of the F-tests on travel time through the work zone are shown in table 5.8.

Table 5.8. Results of the F-tests on the travel times through the work zone from the fourth deployment

time	Avg. "during" weekend travel time (seconds)	weekend travel time difference (during-before)*	
		seconds	percent
10:30AM - 12:30PM	194.7	24.5	14.4
8:00PM - 10:00PM	213.8	-12.9	-5.7

*No difference was significant with 95% confidence.

Since the displayed speeds "during" the deployment were either equal to or lower than the displayed speed "before" the deployment, the travel times were expected to be longer "during" the deployment. However, the results indicate that the VSL system resulted in an increase in travel time in one time period, and a decrease in travel time in the other time period. The travel time differences in the fourth deployment were longer than the previous two deployments, but the differences were not statistically nor operationally significant. There was also a large variation between the two travel time differences. The variation may result from the limited "before" data.

5.2.4 Travel time analysis conclusion

When the displayed speeds at most of the VSL trailers increased in the first and third deployments, the travel time through the work zone decreased in six out of seven time periods tested. Among the six decreases, five were statistically significant. However, all of the statistically significant travel times saved were less than 6 percent and are not considered to be operationally significant. In contrast, when the displayed speeds at the VSL trailers either decreased or stayed the same in the fourth deployment, the effect of the displayed speed decrease on travel times is not clear because of the limited data.

5.3 85th percentile speed

The hypotheses to be tested are that the 85th percentile speed (like the average speed) will increase with an increase in the displayed speed and decrease with a decrease in the displayed speed. The 85th percentile speed in the "during" condition was compared with similar data from the same time periods in the "before" and "after" conditions. Mann-Whitney Tests were performed during the same four time periods that the average speeds were tested (6:00AM to 8:30AM, 10:30AM to 12:30PM, 4:00PM to 6:00PM, and 8:00PM to 10:00PM) to determine whether the differences in the 85th percentile speed were statistically significant. According to Norusis (1999), the Mann-Whitney test is the nonparametric test alternative to the independent-samples T-test. The nonparametric test was used because it does not require detailed assumptions about the populations from which the samples are selected.

5.3.1. First deployment

The results of the Mann-Whitney tests are shown in table 5.9. It should be noted that the pneumatic tube data were in the 30-speed bin format in the "before" condition and in the 16-speed bin format in the "during" condition. For the 16-speed bin format, the 85th percentile speed can only be estimated to within 5 mph of the actual value, while for 30 speed-bin format, the 85th percentile speed can be estimated to within 2 mph of the actual value.

Table 5.9. Results of the Mann-Whitney tests on the 85th percentile speeds "before" and "during" the first deployment

trailer	time	weekday/ weekend	avg. 85th percentile			avg. displayed speed		
			before	during	diff.*	before	during	diff.*
1 (right)	6:00AM-8:30AM	weekday	67.00	64.02	-2.98	70.00	65.00	-5.00
		weekend	68.40	63.50	-4.90	70.00	65.00	-5.00
	10:30AM-12:30PM	weekday	66.00	61.81	-4.19	70.00	62.41	-7.59
		weekend	66.00	62.50	-3.50	blank	64.64	
	4:00PM-6:00PM	weekday	67.25	62.75	-4.50	70.00	64.39	-5.61
		weekend	68.25	62.50	-5.75	blank		
	8:00PM-10:00PM	weekday	67.75	63.00	-4.75	70.00	65.29	-4.71
		weekend	67.63	64.38	-3.25	blank	66.14	
3	6:00AM-8:30AM	weekday	58.00	57.50	-0.50	50.00	56.67	6.67
	10:30AM-12:30PM	weekday	57.13	56.56	-0.56	50.00	56.83	6.83
	4:00PM-6:00PM	weekday	57.00	58.13	1.13	50.00	58.75	8.75
	8:00PM-10:00PM	weekday	59.50	61.25	1.75	50.00	59.71	9.71
7	6:00AM-8:30AM	weekday	61.57	61.07	-0.50	50.00	50.00	0.00
	10:30AM-12:30PM	weekday	60.75	58.75	-2.00	50.00	50.00	0.00
	4:00PM-6:00PM	weekday	63.00	58.13	-4.88	50.00	50.00	0.00
	8:00PM-10:00PM	weekday	65.50	62.50	-3.00	50.00	50.00	0.00

*different is (during - before)

A shaded cell indicates that the difference was statistically significant with 95% confidence.

A blank cell indicates that the data was not available.

From the results of the Mann-Whitney tests in table 5.9, the 85th percentile speeds at trailer 1 changed in the same direction as the changes in the displayed speeds as hypothesized. The decreases in the average displayed speeds which ranged from 4.71 to 7.59 mph resulted in decreases in the 85th percentile speeds ranging from 2.98 to 5.75 mph. However, when the displayed speeds increased at trailer 3, the changes in the 85th percentile speeds were inconsistent. The 85th percentile speeds at trailer 3 increased in the two AM periods and decreased in the two PM periods. All of these changes in the 85th percentile speeds at trailer 3 were small, but two of them were statistically significant. However, the pneumatic tubes at trailers 1 and 3 did not provide consistent speed measurements.

At trailer 7 where the displayed speed was constant at 50 mph, the 85th percentile speeds were lower "during" the deployment. The decreases in the 85th percentile speeds at trailer 7 were statistically significant in three out of four time periods. The results at trailer 7 support the point that the motorists give more credibility to the speed limit displayed on a variable message sign than the same speed limit displayed on a static sign.

5.3.2. Third deployment

The results of the Mann-Whitney tests in the "before" and "during" conditions and the "during" and "after" conditions are shown in tables 5.10 and 5.11, respectively. It should be noted that the data at trailer 1 were in the 16-speed bin format in the "before" condition and in the 30-speed bin format in the "during" condition and that the speeds measured by the pneumatic tubes at trailer 2 in the "during" condition may be about 3 mph higher than the actual speeds.

From the results of the Mann-Whitney tests in table 5.10, the 85th percentile speeds at trailer 1 (left lane) "during" the deployment were higher than "before" the deployment, while the displayed speed was 70 mph both "before" and "during" the deployment. Only the increases in the 85th percentile speeds between 4PM and 6PM were statistically significant.

Table 5.10. Results of the Mann-Whitney tests on the 85th percentile speeds "before" and "during" the third deployment

trailer	time	weekday/ weekend	avg. 85th percentile			avg. displayed speed		
			before	during	diff.*	before	during	diff.*
1 (left)	4:00PM-6:00PM	weekday	67.50	70.00	2.50	70.00	70.00	0.00
	8:00PM-10:00PM	weekday	69.38	70.50	1.13	70.00	70.00	0.00
2	6:00AM-8:30AM	weekday	58.20	60.10	1.90	50.00	66.79	16.79
	10:30AM-12:30PM	weekday	58.88	59.38	0.50	50.00	66.18	16.18
	4:00PM-6:00PM	weekday	58.50	59.00	0.50	50.00	66.79	16.79
	8:00PM-10:00PM	weekday	61.50	61.25	-0.25	50.00	67.89	17.89
3	4:00PM-6:00PM	weekday	57.50	56.88	-0.63	50.00	55.00	5.00
	8:00PM-10:00PM	weekday	58.75	59.38	0.63	50.00	57.19	7.19
4	4:00PM-6:00PM	weekday	55.00	56.88	1.88	50.00	50.00	0.00
	8:00PM-10:00PM	weekday	58.75	58.75	0.00	50.00	50.00	0.00
7	4:00PM-6:00PM	weekday	56.25	52.50	-3.75	50.00	60.00	10.00
	8:00PM-10:00PM	weekday	57.50	55.63	-1.88	50.00	60.00	10.00

*different is (during - before)

A shaded cell indicates that the difference was statistically significant with 95% confidence.

Table 5.11. Results of the Mann-Whitney tests on the 85th percentile speeds "during" and "after" the third deployment

trailer	time	weekday/ weekend	avg. 85th percentile			avg. displayed speed		
			during	after	diff.*	during	after	diff.*
3	8:00PM-10:00PM	weekend	60.63	61.25	-0.63	58.50	50.00	8.50
4	8:00PM-10:00PM	weekend	57.50	61.88	-4.38	50.00	50.00	0.00
7	8:00PM-10:00PM	weekend	57.50	56.88	0.63	60.00	50.00	10.00

*different is (during - after)

A shaded cell indicates that the difference was statistically significant with 95% confidence.

While the displayed speeds "during" the deployment were higher than the displayed speeds "before" and "after" the deployment at trailers 2, 3, and 7, most of the changes in the 85th percentile speeds were small and inconsistent. There were only two statistically significant changes. The increase in the average displayed speed at trailer 2 of 16.79 mph resulted in the increase in the 85th percentile speed of 1.90 mph and the increase in the average displayed speed at trailer 7 of 10.00 mph resulted in a decrease in the 85th percentile speed of 3.75 mph.

At trailer 4 where the displayed speed was constant at 50 mph, the changes in the 85th percentile speeds were also inconsistent. The 85th percentile speeds "during" the deployment were higher than "before" the deployment between 4PM and 6PM and equal to "before" the deployment between 8PM and 10PM. The 85th percentile speed between 8PM and 10PM "during" the deployment was significantly lower than "after" the deployment.

The results from the third deployment indicate that the changes in the displayed speeds did not have a consistent impact on the changes of the 85th percentile speeds. The 85th percentile speeds changed in the same direction as the changes in the displayed speeds only in some of the tested time periods and most of the changes in the 85th percentile speeds were small and not significant.

5.3.3. Fourth deployment

Only the data at trailer 6 (left lane) were available for the "during" versus "after" comparison, and the displayed speed at this trailer was fixed at 70 mph. Thus no comparison of the 85th percentile speed was possible at this deployment site.

5.3.4. 85th percentile speed analysis conclusion

The 85th percentile speeds at almost all of the trailers did not change in the same direction as the changes in the displayed speeds as hypothesized. There was only one trailer (trailer 1 in the first deployment) that the changes in the displayed speeds resulted in consistent changes in the 85th percentile speeds in the same direction. However, the pneumatic tubes at that trailer did not provide consistent speed measurements.

5.4 Speed variance

The hypothesis is that the variable speed limit will lower the speed variance. The literature review indicated that an accident involvement rate increases with an increase in the speed variance. Thus, the lower speed variance may lead to a lower accident involvement rate and an improvement in traffic safety. The "before" versus "during" and the "during" versus "after" speed variance were plotted over time for comparisons.

5.4.1 First deployment

The examples of "before" versus "during" speed variance comparisons at trailers 1 (right lane) and 3 are shown in figures 5.14 and 5.15. The horizontal axis in these figures was labeled "start time" because the times that were used to plot the speed variances were the start time of the data collection updated periods. It should be noted that the data were in the 30-speed bin format in the "before" condition and in the 16-speed bin format in the "during" condition. For the 16-speed bin format, the individual vehicle speed can only be estimated to within 5 mph of the actual speed, while for 30 speed-bin format, the individual vehicle speed can be estimated to within 2 mph of the actual speed.

- At trailer 1 (right lane), the speed variance on both the weekday and weekend "during" the deployment was lower than "before" the deployment.
- At trailers 3 and 7 (figure not shown), the speed variances on the weekday "during" the deployment were higher than "before" the deployment half of the time and lower the other half.
- The variable speed limit had no consistent impact on the speed variance.

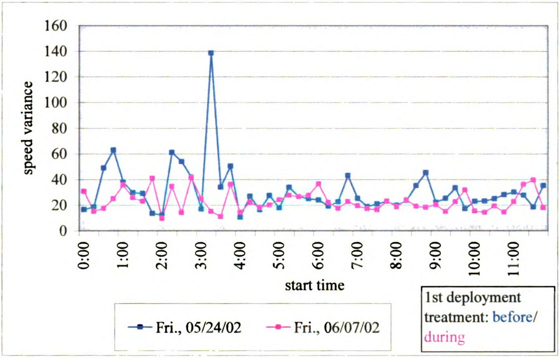


Figure 5.14. "Before" versus "during" speed variance comparison between 12:00AM and 12:00PM from trailer 1 (right lane) in the first deployment

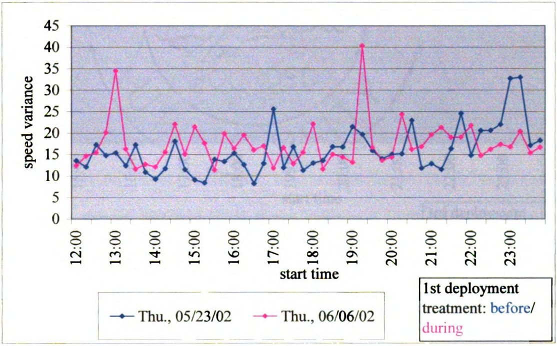


Figure 5.15. "Before" versus "during" speed variance comparison between 12:00PM and 12:00AM from trailer 3 in the first deployment

5.4.2 Third deployment

The examples of "before" versus "during," and "during" versus "after" speed variance comparisons at trailers 7 and 4 are shown in figures 5.16 and 5.17, respectively. It should be noted that the data at trailer 1 were in the 16-speed bin format in the "before" condition and in the 30-speed bin format in the "during" condition.

- At trailers 1 (left lane), 2, 3, 4 and 7, with the exception of a few "spikes" in the speed variance, the speed variances on the weekday "during" the deployment were slightly higher than "before" the deployment half of the time and slightly lower the other half.
- The results at trailers 3 and 7 on the weekend "during" the deployment were slightly higher than "after" the deployment half of the time and slightly lower the other half.

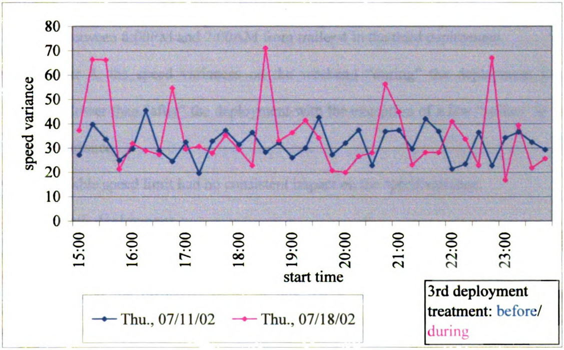


Figure 5.16. "Before" versus "during" speed variance comparison between 3:00PM and 12:00AM from trailer 7 in the third deployment

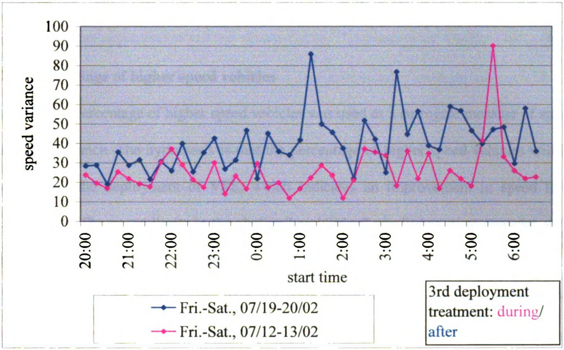


Figure 5.17. "During" versus "after" speed variance comparison
between 8:00PM and 7:00AM from trailer 4 in the third deployment

- At trailer 4, the speed variances on the weekend "during" the deployment were slightly lower than "after" the deployment with the exception of a few "spikes" in the speed variance.
- The variable speed limit had no consistent impact on the speed variance.

5.4.3 Fourth deployment

Only the data at trailer 6 (left lane) were available for the "during" versus "after" comparison, and the displayed speed at this trailer was fixed at 70 mph. Thus no comparison of the speed variance was possible at this deployment site.

5.4.4 Speed variance analysis conclusion

The variable speed limit had no consistent impact on the speed variance. At many of the trailers tested, the speed variances "during" the deployment were slightly higher than "before" and “after” the deployment half of the time and slightly lower the other half.

5.5 Percentage of higher speed vehicles

The percentage of higher speed vehicles was used as a surrogate measure of speed limit compliance. The hypothesis is that the percentage of higher speed vehicles will be lower with the deployment of VSL, which indicates an improvement in speed limit compliance. The speed limits in the “before” and “after” conditions were constant at 50 mph, while the speed limits in the “during” condition varied from 40 mph to 70 mph as shown in table 5.12 (only trailers with available pneumatic tube data are shown). The percentage of vehicles with a speed higher than 60 mph and 70 mph in the “during” condition was compared with similar data from the same time periods in the “before” and “after” conditions. Mann-Whitney Tests were also performed during the same four time periods that the average speeds were tested (6:00AM to 8:30AM, 10:30AM to 12:30PM, 4:00PM to 6:00PM, and 8:00PM to 10:00PM) to determine whether the differences in the percentage of vehicles with a speed higher than 60 mph and 70 mph was statistically significant.

Table 5.12. Speed limits “during” the VSL deployments

deployment	trailer	speed limit
1	1	Varied between 60 and 65 mph most of the time
	3	60 mph most of the time
	7	Constant at 50 mph almost all the time
3	1	Constant at 70 mph
	2	Varied between 65 and 70 mph most of the time
	3	Varied between 55 and 60 mph most of the time
	4	Constant at 50 mph almost all the time
	7	Constant at 60 mph
4	6	Constant at 70 mph

5.5.1 First deployment

The examples of the "before" versus "during" percentage of vehicles with a speed higher than 60 mph and 70 mph at trailer 1 (right lane) are shown in figures 5.18 and 5.19, and the results from all trailers are summarized in table 5.13. The results of the Mann-Whitney tests are shown in table 5.14. It should be noted that the speeds measured by the pneumatic tubes at trailers 1 and 3 in the "before" condition may be about 4 mph higher than the actual speeds (based on the comparisons with the RTMS data as discussed in chapter 4). This inaccurate measurement resulted from the fact that the devices were re-set after the tubes were ripped up by traffic.

The summary of results shown in table 5.13, the percentage of vehicles with a speed higher than 60 mph and 70 mph "during" the deployment at trailers 1 and 7 was lower than "before" the deployment, with the differences ranged from 2 to 30 percent.

From the results of the Mann-Whitney test in table 5.14, the percentage of vehicles with a speed higher than 60 mph and 70 mph at trailer 1 was significantly lower "during" the deployment. The percentage of vehicles with a speed higher than 60 mph at trailer 3 "during" the deployment only changed significantly (higher) in the 4:00PM to 6:00PM time period. However, the pneumatic tubes at trailers 1 and 3 did not provide consistent speed measurements.

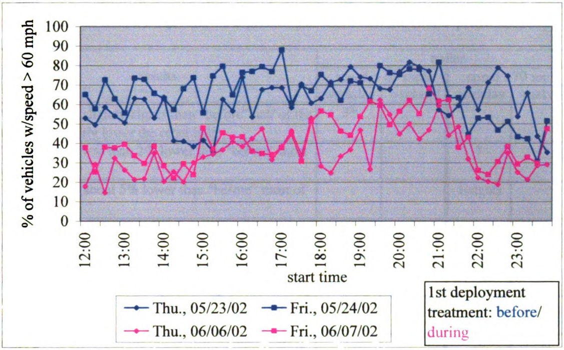


Figure 5.18. "Before" versus "during" percentage of vehicles with a speed higher than 60 mph comparison between 12:00PM and 12:00AM from trailer 1 (right lane) in the first deployment

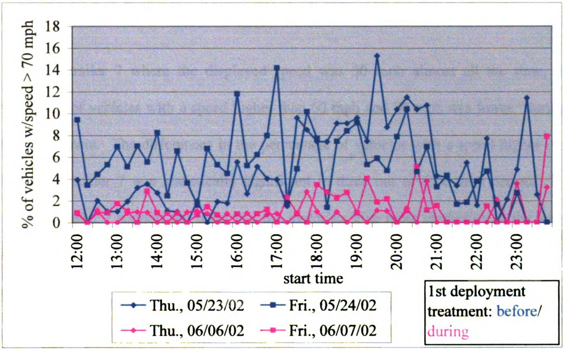


Figure 5.19. "Before" versus "during" percentage of vehicles with a speed higher than 70 mph comparison between 12:00PM and 12:00AM from trailer 1 (right lane) in the first deployment

Table 5.13. Results of the "before" versus "during" percentage of vehicles with a speed higher than 60 mph and 70 mph comparisons from the first deployment

results	trailer			
	speed > 60 mph		speed >70 mph	
	weekday	weekend	weekday	weekend
"During" was slightly higher than "before" half of the time and slightly lower the other half.	3*			
"During" was less than 2% lower than "before" most of the time.			7	
"During" was about 5% lower than "before" most of the time.			1(right)	
"During" was about 10% lower than "before" most of the time.	7			1(right)
"During" was about 20% lower than "before" most of the time.		1(right)**		
"During" was about 30% lower than "before" most of the time.	1(right)			
Only a few drivers drove faster than 70 mph "before" and "during" the deployment.			3	
The data were not available.	2, 4, 5, 6	2, 3, 4, 5, 6, 7	2, 4, 5, 6	2, 3, 4, 5, 6, 7

* The numbers in the table indicates the trailer numbers.

** The direction in the parenthesis next to the trailer number indicates the lane used in the speed comparison, while the trailers with no parenthesis indicate that there was only one lane of travel at those trailers.

At trailer 7 where the displayed speed was 50 mph almost all the time, the percentage of vehicles with a speed higher than 60 mph and 70 mph was lower "during" the deployment. The differences in the percentage of vehicles with a speed higher than 60 mph at trailer 7 was statistically significant in three out of four time periods. The results at trailer 7 support the point that the motorists give more credibility to the speed limit displayed on a variable message sign than the same speed limit displayed on a static sign.

Table 5.14. Results of the Mann-Whitney tests on the percentage of vehicles with a speed higher than 60 mph and 70 mph "before" and "during" the first deployment

trailer	time	weekday/ weekend	% speed > 60 mph			% speed >70mph		
			before	during	diff.*	before	during	diff.*
1 (right)	6:00AM-8:30AM	weekday	68.16	40.67	-27.49	5.87	1.06	-4.81
		weekend	70.89	52.11	-18.78	10.55	2.47	-8.08
	10:30AM-12:30PM	weekday	57.27	22.46	-34.81	4.14	0.35	-3.80
		weekend	64.76	40.06	-24.70	4.14	0.87	-3.27
	4:00PM-6:00PM	weekday	69.73	40.21	-29.53	6.45	0.75	-5.70
		weekend	77.37	50.39	-26.98	7.42	0.93	-6.49
	8:00PM-10:00PM	weekday	68.93	50.86	-18.07	6.33	0.88	-5.46
		weekend	74.07	52.86	-21.21	9.12	2.69	-6.44
3	6:00AM-8:30AM	weekday	7.09	6.74	-0.35	0.00	0.06	0.06
	10:30AM-12:30PM	weekday	3.14	2.56	-0.57	0.03	0.00	-0.03
	4:00PM-6:00PM	weekday	1.72	8.41	6.68	0.09	0.00	-0.09
	8:00PM-10:00PM	weekday	12.57	17.13	4.56	0.23	0.00	-0.23
7	6:00AM-8:30AM	weekday	23.82	20.38	-3.44	1.27	0.75	-0.52
	10:30AM-12:30PM	weekday	19.83	11.52	-8.31	1.32	0.57	-0.75
	4:00PM-6:00PM	weekday	31.43	10.69	-20.74	2.27	0.56	-1.71
	8:00PM-10:00PM	weekday	41.75	28.49	-13.26	4.43	2.52	-1.91

*different is (during - before)

A shaded cell indicates that the difference was statistically significant with 95% confidence.

5.5.2 Third deployment

The examples of the "before" versus "during," and the "during" versus "after" percentage of vehicles with a speed higher than 60 mph and 70 mph at trailers 2 and 7 are shown in figures 5.20 to 5.23, and the results from all trailers are summarized in tables 5.15 and 5.16. The results of the Mann-Whitney tests in the "before" and "during" conditions and the "during" and "after" conditions are shown in tables 5.17 and 5.18, respectively. It should be noted that the speeds measured by the pneumatic tubes at trailer 2 in the "during" condition may be about 3 mph higher than the actual speeds.

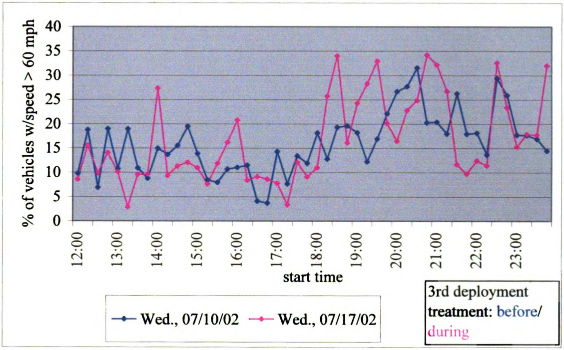


Figure 5.20. "Before" versus "during" percentage of vehicles with a speed higher than 60 mph comparison between 12:00PM and 12:00AM from trailer 2 in the third deployment

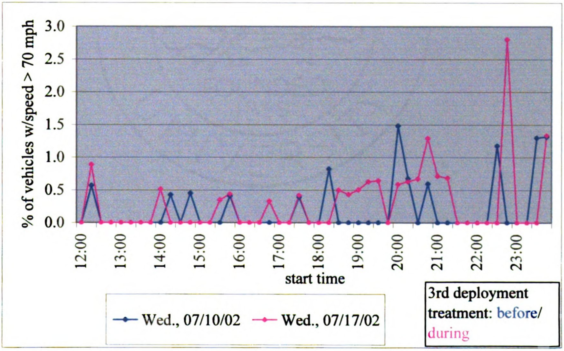


Figure 5.21. "Before" versus "during" percentage of vehicles with a speed higher than 70 mph comparison between 12:00PM and 12:00AM from trailer 2 in the third deployment

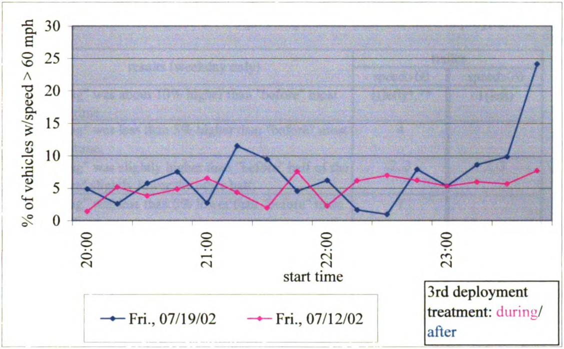


Figure 5.22. "During" versus "after" percentage of vehicles with a speed higher than 60 mph comparison between 8:00PM and 12:00AM from trailer 7 in the third deployment

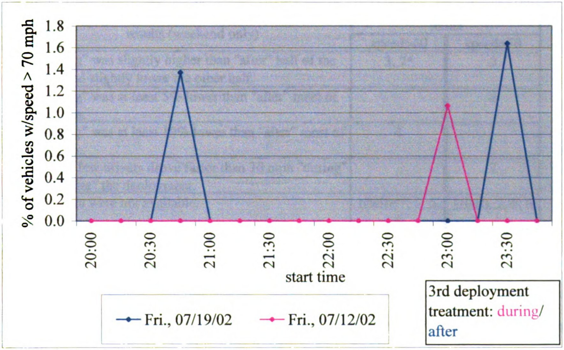


Figure 5.23. "During" versus "after" percentage of vehicles with a speed higher than 70 mph comparison between 8:00PM and 12:00AM from trailer 7 in the third deployment

Table 5.15. Results of the “before” versus “during” percentage of vehicles with a speed higher than 60 mph and 70 mph comparisons from the third deployment

results (weekday only)	trailer	
	speed>60	speed>70
"During" was about 10% higher than "before" most of the time.	1(left)*,**	1(left)
"During" was less than 5% higher than "before" most of the time.	4	
"During" was slightly higher than "before" half of the time and slightly lower the other half.	2, 3	2, 3
"During" was less than 5% lower than "before" most of the time.	7	
Only a few drivers drove faster than 70 mph "before" and "during" the deployment.		4, 7
The data were not available.	5, 6	5, 6

* The numbers in the table indicates the trailer numbers.

** The direction in the parenthesis next to the trailer number indicates the lane used in the speed comparison, while the trailers with no parenthesis indicate that there was only one lane of travel at those trailers.

Table 5.16. Results of the “during” versus “after” percentage of vehicles with a speed higher than 60 mph and 70 mph comparisons from the third deployment

results (weekend only)	trailer	
	speed>60	speed>70
"During" was slightly higher than "after" half of the time and slightly lower the other half.	3, 7*	3
"During" was at least 5% lower than "after" most of the time.		4
"During" was at least 10% lower than "after" most of the time.	4	
Only a few drivers drove faster than 70 mph "during" and "after" the deployment.		7
The data were not available.	1(left)**, 2, 5, 6	1(left), 2, 5, 6

* The numbers in the table indicates the trailer numbers.

** The direction in the parenthesis next to the trailer number indicates the lane used in the speed comparison, while the trailers with no parenthesis indicate that there was only one lane of travel at those trailers.

Based on the summary of results from the “before” versus “during” comparisons in table 5.15, the percentage of vehicles with a speed higher than 60 mph and 70 mph at trailer 1 (left lane) “during” the deployment was higher than “before” the deployment.

However, the results of the Mann-Whitney tests indicate that only the difference in the percentage of vehicles with a speed higher than 70 mph between 4PM and 6PM was statistically significant.

Table 5.17. Results of the Mann-Whitney tests on the percentage of vehicles with a speed higher than 60 mph and 70 mph "before" and "during" the third deployment

trailer	time	weekday/ weekend	% speed > 60 mph			% speed >70mph		
			before	during	diff.*	before	during	diff.*
1 (left)	4:00PM-6:00PM	weekday	87.67	93.45	5.78	9.37	15.93	[illegible]
	8:00PM-10:00PM	weekday	86.15	91.97	5.82	10.82	18.57	7.76
2	6:00AM-8:30AM	weekday	10.28	17.90	7.62	0.25	0.27	0.01
	10:30AM-12:30PM	weekday	9.85	11.22	1.36	0.15	0.09	-0.07
	4:00PM-6:00PM	weekday	9.69	9.89	0.20	0.05	0.09	0.05
	8:00PM-10:00PM	weekday	23.58	22.31	-1.27	0.35	0.57	0.23
3	4:00PM-6:00PM	weekday	5.14	3.39	-1.75	0.23	0.08	-0.15
	8:00PM-10:00PM	weekday	15.04	11.29	-3.75	0.76	0.51	-0.26
4	4:00PM-6:00PM	weekday	2.26	4.65	2.40	0.00	0.00	0.00
	8:00PM-10:00PM	weekday	11.10	11.07	-0.03	0.00	0.31	0.31
7	4:00PM-6:00PM	weekday	4.36	1.05	[illegible]	0.00	0.00	0.00
	8:00PM-10:00PM	weekday	8.14	2.52	[illegible]	0.35	0.00	-0.35

*different is (during - before)

A shaded cell indicates that the difference was statistically significant with 95% confidence.

Table 5.18. Results of the Mann-Whitney tests on the percentage of vehicles with a speed higher than 60 mph and 70 mph "during" and "after" the third deployment

trailer	time	weekday/ weekend	% speed > 60 mph			% speed >70mph		
			during	after	diff.*	during	after	diff.*
3	8:00PM-10:00PM	weekend	18.11	20.53	-2.42	2.33	0.99	1.34
4	8:00PM-10:00PM	weekend	8.25	22.48	-14.23	0.40	1.17	-0.77
7	8:00PM-10:00PM	weekend	4.47	6.12	-1.66	0.00	0.17	-0.17

*different is (during - after)

A shaded cell indicates that the difference was statistically significant with 95% confidence.

The percentage of vehicles with a speed higher than 60 mph and 70 mph at trailers 2, 3, 4, and 7 in both the "before" and "during" conditions was only slightly different (about 5 percent or less). Nevertheless, half of the differences in the percentage of vehicles with a speed higher than 60 mph at these trailers were statistically significant.

For example, the percentage of vehicles with a speed higher than 60 mph at trailer 2 in the "during" condition between 6:00AM and 8:30AM was 7.62 percent higher than the "before" condition. However, the speed limit at trailer 2 varied between 65 mph and 70 mph so this increased percentage does not mean there was a decrease in the speed limit compliance. At trailer 7 where the displayed speed was fixed at 60 mph, the percentage of vehicles with a speed higher than 60 mph "during" the deployment was significantly (statistically) lower than "before" the deployment in both of the time periods tested.

Based on the comparisons, the percentage of vehicles with a speed higher than 60 mph and 70 mph at trailers 3, 4, and 7 in both the "during" and "after" conditions was also only slightly different, with the exception of the percentage of vehicles with a speed higher than 60 mph at trailer 4. The percentage of vehicles with a speed higher than 60 mph at trailer 4 between 8PM and 10PM "during" the deployment was 14.23 percent lower than "after" the deployment and the difference was statistically significant. Almost all of the percentage of vehicles with a speed higher than 60 mph and 70 mph decreased "during" the deployment (relative to "after").

The results indicate that the VSL resulted in an improvement in the percentage of higher speed vehicles at trailer 3, 4, and 7. The magnitude of improvement varied and depended on the time periods and the conditions under which the data were compared (i.e., "before" versus "during" or "during" versus "after"). However, the VSL also resulted in a higher percentage of higher speed vehicles at some locations, particularly at trailer 1.

5.5.3 Fourth deployment

Only the data at trailer 6 (left lane) were available for the "during" versus "after" comparison, and the displayed speed at this trailer was fixed at 70 mph. Thus no comparison of the percentage of higher speed vehicles was possible at this deployment site.

5.5.4 Percentage of higher speed vehicles analysis conclusion

Even though the results from the first deployment were promising, the pneumatic tube data used at 2 of the trailers were not reliable. However, the result at trailer 7 where the data were reliable supported the point that the motorists give more credibility to the speed limit displayed on the variable message signs than the speed limit displayed on the static signs. In the third deployment, the VSL resulted in an improvement in the percentage of higher speed vehicles at trailer 3, 4, and 7, but the VSL also resulted in the higher percentage of higher speed vehicles at trailer 1. Among all of the data tested, the effects of the VSL on the speed limit compliance were somewhat positive but the VSL also had negative impact at a few trailers. However, this conclusion was based on very limited data.

5.6 Effect of police presence

The police patrol vehicles were only present in the work zone during part of the fourth deployment. The average speeds, the speed variances, and the percentage of higher speed vehicles at the two trailers near the patrol vehicle locations, which were trailers 1 and 6, were compared. The RTMS data were used in the average speed comparison, while the pneumatic tube data were used in the speed variance and the percentage of higher speed vehicles comparisons. The hypotheses are that the average speed, the speed variance, and the percentage of higher speed vehicles will be lower with the presence of the police enforcement. The police patrol vehicles were present one day “during” the VSL operation and one day “after” the VSL operation, unfortunately data were only available for comparison “during” the VSL operation. The data “with” and “without” the police presence came from different days of the week because data from the same day of the week were not available.

The locations of the patrol vehicles are shown in figure 3.10 (page 47) and the times that the patrol vehicles were present are shown in table 5.19. The patrol vehicles were supposed to be stationary in each time period, but the patrol vehicles were actually moving back and forth on I-96 between M-43 and Grand River Avenue “during” the VSL deployment between 6PM and 10PM.

Table 5.19. Times that the patrol vehicles were present in the fourth deployment

date	time	location
8/7/2002 ("during")	10:00 AM - 2:00 PM	I-96WB at Grand River Avenue (1*)
	6:00 PM - 10:00 PM	Moving back and forth on I-96 between M-43 and Grand River Avenue.
	10:00 PM - 2:00 AM	I-96WB at I-69 overpass (2*)
8/13/2002 ("after")	10:00 AM - 2:00 PM	I-96WB at Eaton Highway (3*)
	6:00 PM - 10:00 PM	I-96WB at I-69 overpass (2*)
	10:00 PM - 2:00 AM	I-96WB at Eaton Highway (3*)

* Map of the locations can be found in figure 3.11.

The speed limit on trailer 1 “during” the fourth deployment was 50 mph most of the time between 6AM and 10 PM, and 60 mph most of the time between 10PM and 6AM. Thus the percentage of vehicles with a speed higher than 60 mph was used to measure the effect of police presence at this trailer. The speed limits at trailer 6 “during” the fourth deployment were constant at 70 mph. Thus the percentage of vehicles with a speed higher than 70 mph was used to measure the effect of police presence at this trailer.

Examples of the effect of police presence on the average speed, the speed variance, and the percentage of vehicles with a speed higher than 60 mph from trailer 1 are shown in figures 5.24 to 5.26.

At trailer 1, the average speed with the police present was ~2 mph higher than when they were not present. The percentage of vehicles with a speed higher than 60 mph with the police present was also higher than without the police, but the speed variance with the police present was slightly lower (than without).

At trailer 6 (left lane), the average speed with the police present was about 3 mph higher than without the police. The percentage of vehicles with a speed higher than 70 mph with the police was also higher than without the police, but at this trailer the speed variance with the police was slightly higher than without the police about half of the time and slightly lower the other half.

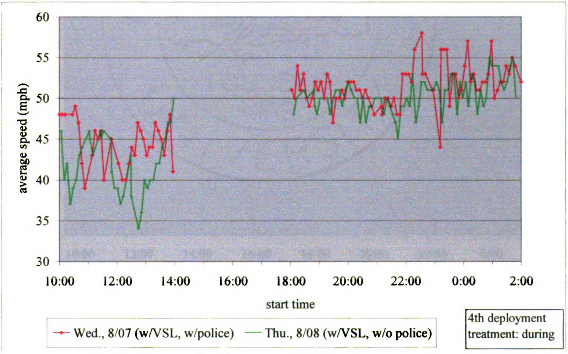


Figure 5.24. Effect of police presence on the average speed between 10:00AM and 2:00AM from trailer 1 in the fourth deployment

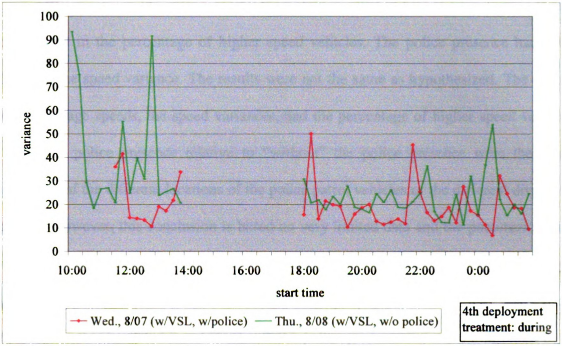


Figure 5.25. Effect of police presence on the speed variance between 10:00AM and 2:00AM from trailer 1 in the fourth deployment

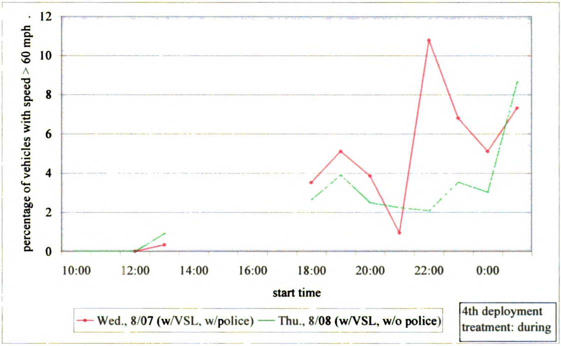


Figure 5.26. Effect of police presence on the percentage of vehicles with a speed higher than 60 mph between 10:00AM and 2:00AM from trailer 1 in the fourth deployment

In conclusion, the presence of60 the police resulted in higher average speeds and an increase in the percentage of higher speed vehicles. The police presence had little effect on the speed variance. The results were not the same as hypothesized. The values of the average speeds, the speed variances, and the percentage of higher speed vehicles "with" the police presence relative to "without" the police presence were the same regardless of the different locations of the police patrol vehicles or the different displayed speeds. However, this conclusion is based on very limited data and the pneumatic tubes provide inconsistent speed measurements. Moreover, the differences in the average speed, the speed variance, and the percentage of higher speed vehicles may result from the fact that the data "with" and "without" the police presence came from different days of the week.

Chapter 6

CONCLUSIONS AND RECOMMENDATIONS

6.1 Conclusions

This study of the effectiveness of the VSL system under various work zone conditions is based on data collected during a field test in work zones in Michigan. The goals of the VSL system deployment were to increase the speed limit compliance, increase the credibility of the speed limits, improve safety, and improve traffic flow in the work zone. The measures of effectiveness used in this evaluation were changes in the average speed, the travel time through the work zone, the 85th percentile speed, the speed variance, and the percentage of higher speed vehicles. Data "before," "during," and "after" the VSL operation were compared. The data came from two sources and each was used differently. The RTMS (system) data were used in the evaluation of the average speeds and the travel time through the work zone, while the MDOT pneumatic tube data were used in the analysis of the 85th percentile speed, the speed variance, and the percentage of higher speed vehicles.

Based on the analysis of the average speed and the travel time through the work zone, it was determined that the VSL system works well at locations in the work zone where there were no geometric features that limited the speed choice of motorists, like on-ramps and off-ramps. The average speeds at these locations changed in the same direction as the changes in the displayed speeds. However it required relatively large increase in the displayed speed to generate small change in the average speed. For example, an 8 to 10 mph increase in the average displayed speed resulted in only a 1-2 mph increase in the average speed at trailers 3, 4, and 5 in the first deployment. The increase in the average speed at these locations resulted in statistically significant reductions in travel times through the work zone. However, these travel time reductions may not be operationally significant because the magnitude of these reductions ranged from 2.8 seconds in deployment one to 12.9 seconds in deployment four. The motorists responded to the changes in the displayed speeds more consistently during the non-peak hours than during the peak hours. They also gave more credibility to the speed limit displayed on the variable message signs than the speed limit displayed on the static signs during the non-peak hours. The VSL responded to the day-to-day and trailer-to-trailer average speed variations, and thus improved the credibility of the speed limit.

Based on the analyses with the pneumatic tube data, the 85th percentile speeds at almost all of the trailers did not change in the same direction as the changes in the displayed speeds as hypothesized. The effect of the variable speed limit on speed variance was inconsistent. However, the percentage of higher speed vehicles at most of the trailers either stayed the same or became lower "during" the VSL deployments. This occurred even when the variable speed limit was often higher than the static speed limit. This analysis of the percentage of higher speed vehicles supports the conclusion that the motorists give more credibility to the speed limit displayed on the variable message signs than the speed limit displayed on the static signs.

All of these conclusions were based on very limited data from the pneumatic tubes, which did not provide consistent speed measurements. Thus some of the differences in the 85^{th} percentile speed and the percentage of higher speed vehicles may be at least partly due to errors in the pneumatic tube data.

The effect of police presence along with the VSL system was tested in the fourth deployment. The presence of police resulted in higher average speeds and a higher percentage of higher speed vehicles. The police presence had no significant effect on the speed variance. The values of the average speed, the speed variance, and the percentage of higher speed vehicles "with" the police relative to "without" the police were the same regardless of the different locations of the police patrol vehicles or the different displayed speeds. However, these conclusions are based on very limited data. Moreover, the differences in the average speed and the percentage of higher speed vehicles may result from the fact that the data "with" and "without" the police presence came from different days of the week.

6.2 Recommendations

Although the ability of a VSL system to alter the average speed and the travel time through the work zones appears promising, particularly at locations in the work zone where there are no ramps in the vicinity of the trailer, the impact of the VSL system on the 85^{th} percentile speed, the speed variance, and the speed limit compliance is still unclear. Recommendations to resolve these issues in future researches on the evaluation of the VSL system follow.

- The pneumatic tubes that were used to collect traffic data were ripped up frequently and when reset provided inconsistent speed measurements, more reliable systems that can provide accurate individual vehicle speed measurements should be used.
- The data "before" the deployment in this study were collected, with the VSL trailers present but with the VMS covered by static speed limit signs. Thus, the "before" versus "during" comparisons actually tested the trailers with VMS against trailers with static signs. A better comparison of static signs with a variable speed limit system would have the trailers present in the work zone only "during" the deployment. This would require a separate system (independent from the VSL trailer) to collect individual vehicle speed and traffic data "before," "during," and "after" the deployment.
- Deploy and evaluate the VSL system in work zones that last at least 4 weeks. The "before" data could then be collected in the first week. The VSL system could then be installed and calibrated, and the speed limit-setting algorithm checked during the second week. The "during" data could be collected in the third week and the "after" data in the fourth week after the trailers are removed from the work zone.

In addition to the recommendations for when the VSL system is used for research purpose, the International Road Dynamics Inc., the manufacturer of the VSL system, should consider the following recommendations to improve the operation of the VSL system.

- The VSL system communication should be improved. This includes the communication between trailers, the communication between the master trailer and a remote computer, and the communication between the master trailer and pagers. The

VSL system frequently experienced communication problems between trailers and between the master trailer and the remote computer. Moreover, it took the current VSL system about one minute for the master trailer to transmit the updated speed limit to the pagers. During this one minute, the speed limit that the police enforce may be different from the speed limit displayed on the VSL trailers.

- The consistency in the speed limit update period should be improved. In this study the speed limit update period was set to 5 minutes, but the actual update time was approximately 6 minutes instead. The length of the speed limit update period was occasionally shorter or longer than 6 minutes, and ranged from 2 minutes to 15 minutes.
- The flexibility of the speed limit-setting algorithm should be increased. Users should be able to set different algorithms for each slave trailer from the remote computer. The system should allow users to set different algorithms for different time periods and the system should be able to change the algorithms automatically at preset times.
- The speed limit setting mechanism should be more reliable. The VSL system occasionally did not take some specified operational parameters (e.g., a maximum positive differential) into consideration when the speed limit was set.
- The battery used to provide power to the VSL system should be more reliable or there should be a reserve battery. The battery at trailer 4 failed in both the third and fourth deployment.

BIBLIOGRAPHY

Aljanahi, A. A. M., A.H. Rhodes, and A.V. Metcalfe (1999) Speed, speed limits and road traffic accidents under free flow conditions. *Accident Analysis and Prevention,* Vol. 31, pp 161-168.

Bell, C.A. (2001) Oregon Green Light CVO evaluation final report executive summary. *Transportation Research Report No. 00-21,* Transportation Research Institute, Oregon State University, Corvallis, OR.

Cirillo, J.A. (1968) Interstate system accident research study II, Interim report II. *Public Roads*, Vol. 35, August, pp 71-75.

Committee for Guidance on Setting and Enforcing Speed Limits (1998) *Managing speed: review of current practice for setting and enforcing speed limits.* Transportation Research Board Special Report 254. National Research Council, Washington, D.C.

EIS Electronic Integrated Systems Inc. (2000) *RTMS user manual.*

Fildes, B.N., G. Rumbold, and A. Leening (1991) *Speed behavior and drivers' attitude to speeding*. Report 16. Monash University Accident Research Center, Monash, Victoria, Australia, June.

French, A. and D. Solomon (1986) Traffic data collection and analysis: methods and procedures. *Synthesis of Highway Practice 130.* National Cooperative Highway Research Program, Washington, D.C.

Garber, N.J. and R. Gadiraju (1989) Factors affecting speed variance and its influence on accidents. *Transportation Research Record 1213*, pp 64-71.

Graham-Migletz Enterprise, Inc. (1996) Procedure for determining work zone speed limits. *Research Results Digest*, No. 192. National Cooperative Highway Research Program, Washington, D.C.

Harbord, B. and J. Jones (1996) Variable speed limit enforcement – the M25 controlled motorway pilot scheme. Computing and Control Division Colloquium on Camera Enforcement of Traffic Regulations, Institution of Electrical Engineers, London, England.

Harbord, B. (1998) M25 Controlled Motorway – results of the first 2 years. *Road Transport Information and Control*, Conference Publication No. 454, 21-23 April.

Harkey, D.L., H.D. Robertson, and S.E. Davis (1990) Assessment of current speed zoning criteria. *Transportation research Record 1281*, pp 40-51.

Harwick, N. K. (1989) Albuquerque variable speed limit system. *Proceedings of the 26th Paving and Transportation Conference and Symposium on Chip Seal Practice*, University of New Mexico.

Hauer, E. (1971) Accidents, overtaking and speed control. *Accident Analysis and Prevention,* Vol. 3, pp 1-13.

Hines, M. (2002) Judicial enforcement of variable speed limits. *Legal Research Digest,* No. 47. National Cooperative Highway Research Program, Washington, D.C.

Hool, J.N., S. Maghsoodloo, A.D. Veren, and D.B. Brown (1983) Analysis of selective enforcement strategy effects on rural Alabama traffic speeds. *Transportation research Record 910*, pp 74-81.

International Road Dynamics Inc. (2002) *Speed Ranger Safety System operator manual.*

Janson, B.N. (1999) Evaluation of downhill truck speed warning system on I-70 west of Eisenhower Tunnel. Transportation Research Center, Department of Civil Engineering, University of Colorado at Denver.

Kloeden, C.N., A.J. McLean, V.M. Moore, and G. Ponte (1997) *Traveling speed and the risk of crash involvement.* Vol. I-findings. NHMRC Road Accident Research Unit, University of Adelaide, Australia, November.

Lave, C. A. (1985) Speeding, coordination, and the 55 mph limit. *The American Economic Review,* Vol. 75, Issue 5, pp 1159-1164.

Luoma, J. and P. Rama (1998) Effects of variable speed limit signs on speed behaviour and recall of signs. *Traffic Engineering and Control*, April.

Lyles, R.W., W.C. Taylor, and V. Sisiopiku (2002) *Field test of variable speed limits in work zones: Michigan variable speed limit deployment plan*, Michigan State University.

Manual on Uniform Traffic Control Device Millennium Edition (2001). U.S. Department of Transportation, Washington D.C.

Michalopoulos, P., R. Fitch, and B. Wolf (1989) Development and evaluation of a breadboard video imaging system for wide area vehicle detection. *Transportation Research Record 1225*, pp 140-149.

Michalopoulos, P., B. Wolf, and R. Benke (1990) Testing and field implementation of the Minnesota video detection system (Autoscope). *Transportation Research Record 1287*, pp 176-184.

Migletz, J., J.L. Graham, I.B. Anderson, D.W. Harwood, and K.M. Bauer (1999) Work zone speed limit procedure. *Transportation Research Record 1657,* pp 24-30.

Montagne, P.E. and C.A. Bell (2000) Oregon Green Light CVO evaluation: evaluation of the downhill speed information system. *Transportation Research Report No. 00-14,* Transportation Research Institute, Oregon State University, Corvallis, OR.

Norusis, M.J. (1999) SPSS® 9.0 Guide to data analysis. Prentice Hall, Upper Saddle River, NJ.

Nuttall, I. (1995) Slow, slow, quick, quick, slow: taking the 'stop-start out of the London Orbital. *Traffic technology International*, Winter.

Park, B.B. and S.S. Yadlapati (2003) Development and testing of variable speed limit logics at work zones using simulation. *Transportation Research Board 2003 Annual Meeting CD-ROM*, January.

Perrin, J., P.T. Martin, and W. Cottrell (2000) Effects of variable speed limit signs on driver behavior during inclement weather. ITE 2000 Annual Meeting and Exhibit: August 6-9, Opryland Hotel, Nashville, Tennessee, USA.

Placer, J. and A. Sagahyroon (1998) *Fuzzy variable speed limit device project.* U.S. Department of Transportation, Federal Highway Administration, Washington D.C.

Placer, J. (2001) Pre-deployment review of critical issues for variable speed limits. *http://www.cet.nau.edu/~jpl/VSLProject/VSLPropPhaseIII.htm*, Northern Arizona University.

Rama, P. and J. Luoma (1997) Driver acceptance of weather-controlled road signs and displays. *Transportation Research Record 1689,* pp 72-75.

Rama, P. (1998) Effects of weather-controlled variable speed limits and warning signs on driver behavior. *Transportation Research Record 1573,* pp 53-59.

Rama, P., J. Luoma, and V. Harjula (1999) Distraction due to variable speed limits. *Traffic Engineering and Control*, September.

Richards, S.H., R.C. Wunderlich, and C.L. Dudek (1985) Field evaluation of work zone speed control techniques. *Transportation Research Record 1035,* pp 66-78.

Robinson, M. (2000) *Examples of variable speed limit applications.* U.S. Department of Transportation, Washington D.C.

Solomon, D. (1964) *Accidents on main rural highways related to speed, driver, and vehicle.* U.S. Department of Commerce, Bureau of Public Roads, July.

Smulders, S. (1992) Control by variable speed signs: the Dutch Experiment. *Proceedings of the 6th International Conference on Road Traffic Monitoring and Control,* Institution of Electrical Engineers, London, pp. 99-103.

Swindler, K., E. Hardouin, J. Soderstorm, R. Raub, and J. Schofer (2001) Review of literature and recent practice on variable speed limits and automated speed enforcement. *National Cooperative Highway Research Program Project 3-59: Assessment of variable speed limit implementation issues.* Northwestern University, March.

Tudor, L.H., A. Meadors, and R. Plant (2003) Deployment of Smart Work Zone technology in Arkansas. *Transportation Research Board 2003 Annual Meeting CD-ROM*, January.

Ulfarsson, G.F., V.N. Shankar, P. Vu, F.L. Mannering, L.N. Boyle, and M.H. Morse (2002) *Summary: Travel Aid*, Washington State Transportation Center, University of Washington, February.

Ullman, G.L. (1991) Effect of radar transmissions on traffic operations at highway work zones. *Transportation Research Record 1304,* pp 261-269.

Warren, D. (2000) Variable speed limits. *Speed Management Workshop,* Dallas, Texas, March 6th.

West, L.B. and J.W. Dunn (1971) Accidents, speed deviation and speed limits. *Traffic Engineering,* pp 52-55.

Wilkie, J.K. (1997) Using variable speed limit signs to mitigate speed differentials upstream of reduced flow locations. *Compendium: Graduate student papers on advanced surface transportation systems.* Southwest Region University Transportation Center, College Station, TX.

Zackor, H. (1979) Self sufficient control of speed on freeways. *ITE Proceeding of the International Symposium on Traffic Control System,* Vol. 2A, Berkeley, California, pp 226-247.