NDOT Research Report

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Testing and Evaluating the Effectiveness of Advanced Technologies for Work Zones in Nevada

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Nevada Department of Transportation
1263 South Stewart Street
Carson City, NV 89712

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TESTING AND EVALUATING THE EFFECTIVENESS OF ADVANCED TECHNOLOGIES FOR WORK ZONES IN NEVADA

FINAL REPORT

Nevada Department of Transportation
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CHAPTER 1 INTRODUCTION

This chapter includes the problem that NDOT was facing, some project background, purpose, and the approaches taken.

1.1 Problem Statement

During the last five years before 2003, an average of nine motorists a year have lost their lives in highway work zone crashes in Nevada. Nationwide, the number of people killed in work zone crashes has increased from 789 in 1995 to an all-time high of 1,093 in 2000. Also, more than 40,000 injuries occur as a result of crashes in work zones each year. With the trend of continued growth in Nevada, which will result in more travel demand, and the expansion of the transportation network, which will create more construction on the existing roadway system, it is expected that the number of crashes in work zones will continue to increase. One major problem is that motorists, for the most part, ignore the legal speed limits while driving through work zones. Congestion also contributes to the high likelihood of crashes. To mitigate the problem, advanced technologies such as red-light cameras issuing citations to speeding vehicles, radar detectors measuring vehicle speeds, variable message signs displaying measured speeds or traffic information, and web sites for disseminating traffic information (e.g., travel time, queue length, and accidents) to a large region have been developed. Some of the technologies attempt to reduce vehicle speed while others route traffic around work zones. Even though these technologies have been tested in several states including California, Nebraska, Arizona, Arkansas, Illinois and Michigan, their effectiveness has not been fully quantified. This research project was aimed at testing two systems: Speed Monitoring Display and Automatic Work Zone Information System. Their effectiveness in improving safety and mobility was examined. A cost and benefit study was conducted for these technologies to determine the conditions (roadways, work zone characteristics, time of day, etc.) under which the Speed Monitoring Display and the Automatic Work Zone Information System can best be used in work zones. Guidelines for their use in Nevada work zones were developed based on the field tests and the cost and benefit study.

1.2 Background Summary

Developing safety devices to improve work zone safety started with the 1984 Strategic Highway Research Program in which six priority research and development areas, including work zones, were identified. By 1995 when the Strategic Highway Research Program was concluded, ten devices for three areas of work zones were developed. They are:

- Signs: flashing stop/slow paddle, direction indicator barricade, opposing traffic lane divider, portable all-terrain sign stand,
- Detectors: two different intrusion alarms, queue-length detector, and
- Protection devices: portable crash cushion, portable rumble strip, and remotely driven vehicle.

It should be noted that these safety devices are primarily lightweight (not like concrete barriers) that would effectively protect workers. They were also designed for quick installation and removal, giving crews more time to do their work.

Recognizing that safety can be improved significantly if speed is controlled, Speed Monitoring Displays, as shown in Figure 1, have been field tested in many places in the U.S. (Garber and Patel 1995, McCoy et al. 1995, Garber and Srinivasan 1998, Pesti and McCoy 2002, Saito and Bowie 2003). This system primarily consists of a speed trailer. Speeds of individual vehicles entering a work zone can be measured by using the radar device in the system. When the measured speed is above the speed limit set up for a work zone, it will be displayed on the board to alert motorists of their speed. Note that speed monitoring display is usually viewed as a replacement of stationary police in work zones. It is also used to alert the drivers of the speed at which they are traveling and to influence their driving behavior. In addition to Speed Monitoring Displays, there are other techniques for reducing vehicle speed such as rumble strips and narrowing lane width. Because of their additional side effects on safety (e.g., sometimes motorists may change lanes to avoid rumble strips), they are not considered for this study.

Figure 1.1 An Example of a Speed Monitoring Display

Since 1995, many studies testing Speed Monitoring Displays have been performed. In these studies, the type of roadway where the tests were conducted varies, from freeway, primary roadway, or ramp, as well as where different speed limits were associated. The duration of the tests varied from only peak periods to several weeks. The number of sites tested in these studies ranged from one to ten work zones. In addition to testing whether speeds were significantly reduced after the installation of the Speed Monitoring Display, they also investigated whether the location of the display in work zones or the duration of the deployment on sites (short- and long-term) have any significant impacts on the performance of the system. As suggested in the most recent study in Utah (Saito and Bowie 2003), there is a need to improve the system by increasing the size of the signs for roadways with higher speed limits. In a personal discussion with one of those researchers, setting up additional speed monitoring displays in work zones promises to improve system performance. Intuitively, it was also worthwhile to look into the impact of the flashing rate of the speed sign.

In recent years, a different system for improving work zone safety and mobility has been tested in the U.S. (McCoy and Pesti 2001, Horowitz et al. 2003, Tudor et al. 2003, and Chu et al. 2005) This system, as shown in Figure 1.2, is called the Automated Work Zone Information System and consists of traffic sensors, variable message sign (or other information dissemination tools), and a communication link between the sensors and the sign. In this system, traffic sensors are installed in work zones to measure traffic variables such as travel time, traffic delay, average speed and volume. This information is then transmitted to variable message signs upstream of work zones or to a website established for work zones. By receiving real-time traffic information in work zones, drivers entering work zones could be alerted and be prepared to respond to the message. Drivers could also reduce their anxiety and thus improve their comfort level when they travel through work zones. If the variable message signs are located upstream of sites where vehicle diversion can occur at exits, traffic demand through work zones may be reduced, and thus reduce crashes. In this case, the travel time through work zones can be reduced and thus the level of service can be improved.

Figure 1.2 Examples of Automatic Work Zone Information Systems for Disseminating Travel Time Information and Route Diversion

Automatic Work Zone Information Systems have been tested as part of the Midwest States Smart Work Zone Initiative (McCoy and Pesti 2001) since 1999, and in other states such as Arkansas (Tudor et al. 2003), California (Chu et al. 2005), and Michigan (Horowitz et al. 2003). It has also been recommended by AASHTO (2004) as one of the best practices for improving safety in work zones. Most of the tests had technical problems when either traffic sensors or system communication links took substantial time to fix. All the tests were conducted on freeway systems with available frontage roads. Some results indicated that work zone operating speeds were reduced or a significant portion of traffic was diverted from the work zone. However, conclusive results could not be found in the current literature; hence, this project was developed to test the system.

1.3 Research Objectives and Methodology

The objective of this study was to evaluate two advanced technologies for improving safety in work zones: 1) speed monitoring display and 2) automatic work zone information system. In the evaluation of the speed monitoring display (also called a speed trailer), different features of the speed trailer were tested: the size of the speed sign and flashing of the measured speed. In addition, the study also tested the performance of a second speed trailer in a work zone. Two test sites in the Las Vegas Area were chosen to test the speed trailer, one on a fully controlled access segment of Cr-215, a county principal arterial, and the other on I-15, a major Interstate highway. The basic scenarios tested at these two sites were (1) no new feature, 2) smaller sign, 3) bigger sign without flashing, 4) bigger sign with a fast flashing rate, and 5) bigger sign with a slow flashing rate. On Cr-215, an additional scenario for the warning message “Slow Down” was also included. To evaluate the performance of the tested systems, speed and vehicle classification data were collected using Nu-metrics detectors on Cr-215. On I-15, however, these data were collected using videos processed in house. Comparisons were made on the speeds collected in these scenarios. The comparisons were first made between a ‘before’ condition where a speed monitoring display was not deployed and an ‘after’ condition using one of the scenarios. From these comparisons, it can be seen whether these technology features were effective in reducing vehicle speeds. The speeds were compared later between different scenarios to identify the relative performance of the features. The comparisons considered different types of vehicles and whether they ran in free flow conditions. These comparisons were based on both the hypothesis testing method and regression modeling. The hypothesis tests were looking into whether average speeds and speeding rate changed significantly between scenarios. The regression modeling investigated the likelihood of speeding and the speed at which a vehicle would run. The results from these two methods supported each other, which was a way to vary the results of the tests conducted in this study.

The evaluation of the automatic work zone information system was performed by first developing such a system. In this study, a simple automatic work zone information system was developed which consisted of video detection at two locations, line-of-sight radio frequency wireless communication, and one portable variable message sign. The system was tested on I-515 and evaluated from the perspectives of traffic diversion and speed reduction. The analysis used for evaluation was based only on hypothesis testing for traffic flow and speed.

This report consists of four chapters in addition to this introduction to the report. In the second chapter, literature is reviewed on the two technologies tested in this study. The third chapter describes the testing of speed monitoring display on Cr-215 including the test plan, test in the field, data analysis, and benefit and cost analysis. In the fourth chapter, the tests of the speed monitoring display on I-15 are presented, covering the additional efforts on data collection and processing using vision detection technology in the system evaluation. Findings, conclusion, recommendations and implementation guidelines for the speeding monitoring display are also provided in this chapter. The fifth chapter was devoted to testing the automatic work zone information system on I-515. Findings, conclusions, recommendations, and implementation guidelines for the automatic work zone information system are included after the benefit and cost analysis in this chapter.

CHAPTER 2 LITERATURE REVIEW

In this chapter, the existing studies on the speed monitoring display and the automatic work zone information system are reviewed. Some studies distinguished the speed trailer like that shown in Figure 1.1 and the changeable message sign with radar detection as shown in Figure 1.2 since messages other than speeds can also be displayed on the changeable message sign. In this chapter, the studies on these two different technologies are viewed respectively in the first two sections. The review on the automatic work zone information system is presented in the third section.

2.1.1 Speed Monitoring Display

The study described in McCoy and Kollbam (1995) is an early investigation on the effectiveness of the Speed Monitoring Display in reducing traffic speeds. The tests on the Speed Monitoring Display were conducted in a work zone on a freeway in South Dakota. The speeds of vehicles operating in free flow condition were collected before and after the installation of the Speed Monitoring Display. Data analysis shows that the Speed Monitoring Display reduced mean speeds and excessive speeds on the work zone approach significantly.

Pesti and McCoy (2002) focused on the long-term effect of the Speed Monitoring Display on speed. Speed data were collected for three time periods, the first before the deployment of the Speed Monitoring Displays, the second during the deployment (five times, each for one week), and the last after the deployment. The trend of these seven speed data points was analyzed. The results indicated that the speeds were reduced significantly during the deployment. After the removal of the test's Speed Monitoring Displays, speeds increased, but were still lower than before Speed Monitoring Displays were deployed.

In Saito and Bowie (2003), instead of testing at one site, their Speed Monitoring Displays were tested in seven different work zones. In addition, police patrol was coordinated with the tests on the Speed Monitoring Displays so its performance in controlling speed in work zones could be compared with that of the Speed Monitoring Displays. In their analysis, the factors considered to influence the evaluation of the performance of the Speed Monitoring Displays included the location of the Speed Monitoring Display in work zone sites (before taper or within work zones), types of vehicles, and speed data collection location in a work zone. The analysis indicated that police patrols can result in more speed reduction than the Speed Monitoring Displays. Their impacts on speed were reduced after their tests.

2.1.1 Changeable Message Signs with Radar

The study by Richards et al. (1985) tested changeable message signs with radar at several sites. Speed data were collected at three locations on each test site: upstream of the changeable message signs with radar, immediately downstream of a changeable message signs with radar, and farther downstream of the changeable message signs with radar. Two message options were tested: speed only or speed plus related information. Depending on the sites, both messages options reduced mean speeds from 0 to 5 mph (0 - 9 percent). The changeable message sign with radar was effective only when it was located closer to the actual work area.

The effectiveness of changeable message signs with radar on speed was tested in Garber and Patel (1995) at seven work zones in Virginia. At each work zone, speed data for *speeding vehicles* were collected at three locations: (1) the advance warning area, (2) approximately the midpoint of the activity area, and (3) just before the end of the work zone. A changeable message sign with radar was placed at the first location. During the data collection, four different messages were tested. It was concluded that the changeable message signs with radar were more effective than the static message signs in altering driver behavior in a work zone, and there were no significant differences between the four different messages with regard to their effect on high-speed vehicles as well as the whole population.

The study in Garber and Srinivasan (1998) focused on evaluating the long term performance of the changeable message sign with radar, and collected speed data for three, four and seven weeks. It was found that the changeable message signs with radar remained an effective speed control technique even when used for prolonged periods of time (up to 7 weeks).

In the study by Wang et al. (2003), a changeable message sign with radar was set up before the work zone. Three data collection sites were used, one in advance and two after the tested changeable message sign with radar. Speeds collected during the before and after studies were compared to see the speed reduction. The impact of vehicle type, day time and night time, and free flow conditions was evaluated. It was found that vehicles responded to the tested message sign immediately. Their speeds increased again soon after passing the message sign. Long term effects of the message sign can also be observed from the test.

Dixon (2005) tested a changeable message sign with radar that was set up within a work zone. Two sites were chosen, one for each of the two traveling directions in the work zone. Three data collection phases were designed: before the technology was deployed, immediately after the deployment, and later after the deployment. The impact of vehicle type, time of day, and free flow conditions was also included in the evaluation. The results indicated that the changeable message sign with radar did reduce speeds significantly for a substantial period of time. The performance of the tested sign varied between day and night and for different vehicle types.

From the literature review, it can be seen that the effectiveness of the changeable message sign with radar has been tested focusing on the effects of the technology's location in a work zone and its long term effect. The technology has also been tested for different types of messages displayed on the message board. The issues that have not been investigated that relate to the changeable message sign with radar's effectiveness include: the size of the speed board, the flashing of the speed sign, the use of a warning message, deployment of more than one changeable message signs with radar in work zones. These issues are important to the performance of the technology in different highway infrastructures, and are worth investigating.

2.2 Automatic Work Zone Information System

Instead of one-on-one, direct and immediate communications between a traffic control device and motorists at one point in a work zone, automatic work zone information system attempts to disseminate the traffic information to motorists in a large area so that they can be prepared for the occurrence of irregular traffic conditions such as speed slow downs. The typical components of such a system include traffic data collection, data communications, and data dissemination system. The devices for data collection are located in work zones where road and traffic conditions are different from regular conditions. The collected data are transmitted to certain locations and distributed to motorist in different ways, depending on the location of the motorists the system intends to serve.

So far the following systems, manufactured by different companies, have been tested in previous studies: Traffic Information and Prediction System, Automated Data Acquisition and Processing of Traffic Information in Real-Time, Computerized Highway Information Processing System, and IntelliZone. Each of them has been tested in more than one state. In addition to these major systems, there were other systems that were developed for research or less extensively tested. They are also reviewed in this study.

Traffic Information and Prediction System was developed by Dr. Prahlad D. Pant of the University of Cincinnati. It was jointly evaluated in Pant (2001) and Zwahlen (2001). Basically, the system was designed to collect speed data and disseminate the derived travel time information to motorists traveling immediately upstream of a work zone. Thus, changeable message signs were used in the system for information dissemination. Every motorist passing the signs can be informed of travel time through work zone downstream. Relatively short range communications were employed for passing information between where the information was collected and where the information was accessed. This system has been tested in other studies such as Horowitz et al. (2003), Pigman and Agent (2004), and Dixon (2005). Horowitz et al. (2003) evaluated the system from the perspective of its impact on traffic diversion. It found diversion was not significant. Pigman and Agent (2004) evaluated the system in the following aspects: (1) performance and reliability, (2) travel time estimation, (3) diversion, (4) crash data, and (5) driver opinion. It notes that the location to set up a changeable message sign relative to a work zone influenced the travel time estimated and the display. There were some drivers who tended to use local roads other than the road where the work zone existed. The diverted traffic didn’t show a significant impact on safety on the local road. Drivers expressed their concern about the route diversion message when no viable alternative route existed.

Automated Data Acquisition and Processing of Traffic Information in Real-time was developed with the messages displayed on portable message signs. In Tudor et al. (2003), the Automated Data Acquisition and Processing of Traffic Information in Real-time was evaluated in Arkansas. The system used the Remote Traffic Microwave Sensors to collect speed data, which were then transmitted to changeable message signs for display. In addition, the speed data and relevant information was transmitted to two highway advisor radio stations for broadcasting. Speed and traffic information were also sent to selected staff. McCoy and Pesti (2002) evaluated this system in Nebraska. The system collected speed data using Remote Traffic Microwave Sensors mounted on top of portable message signs. The collected speed data were processed to determine the messages to be displayed on changeable message signs located at different places in advance of a work zone. The messages displayed on the message signs were speed advisory in nature. The system in McCoy and Pesti (2002) was evaluated primarily on whether such changeable message signs could reduce vehicle speed. It was found that motorists reduced their speed during congestion when they were aware of the presence of work zone. It was not known whether the reduction of speed was caused by the presence of congestion or groups of staff via pager. A radar traffic microwave sensor initially used was found to be inaccurate and replaced by a Doppler radar sensor to make the system work. Travel times estimated by the system were also found to be inaccurate. Instead of displaying travel time information, the system was modified to present generic messages such as “Congestion” or “Delay.” With these adjustments, the engineer overseeing the construction commented that the system generally worked well. Two similar work zone projects were compared with the tested work zone on safety. Fewer crashes occurred in the work zone with the information system installed.

Computerized Highway Information Processing System was a product from the ASTI Transportation Systems. The system tested in Chu et al. (2005) used Remote Traffic Microwave Sensors to detect whether there was congestion at several places in advance of a work zone. The congestion information was transmitted to a portable changeable message sign on site or a system at a central location. In that way motorists both on and off site could receive the messages and respond accordingly. Trailer-mounted CCTV cameras were also installed at some places, and live videos were transmitted to a remote central location from which motorists away from the tested work zone could obtain traffic information in the work zone. In the test, traffic information was also sent to motorists through email and paging. Noticeable diversions were made by motorists responding to the message from the system. The driving environment after the installation of the system seems safer. Drivers made positive responses about the system.

The Computerized Highway Information Processing System evaluated in Tudor et al. (2003) had system components similar to those the Automated Data Acquisition and Processing of Traffic Information in Real-time jointly tested in their study. Instead of using a landline to transmit information to highway advisory radio, it used a cell phone. It also included an email service to disseminate traffic information such as traffic condition, delay, and diversion advisories to a selected group of staff. Like their evaluation for the Automated Data Acquisition and Processing of Traffic Information in Real-time, Tudor et al. (2003) evaluated Computerized Highway Information Processing System focusing on the operation and safety issues of the system. The message displayed in the system matched actual road conditions very well. Significant amounts of traffic diverted from the work zone area.

IntelliZone was an automatic work zone information system manufactured by Quixote Transportation Safety (King et al. 2003). In this system, magnetic detectors were installed in each lane to measure traffic variables such as speed and volume. A mobile command center located on site received the collected traffic data through wireless communications and determined the messages (primarily related to speed) to be shown on the portable changeable message signs in the system. The system was evaluated by King, et. al. (2003) for its impact on speed and speed variance. Their evaluation indicated that speeds during congestion were reduced with the installation of this system. Drivers demonstrated a willingness to slow down when they saw the system. This system was also evaluated by Horowitz and Notbohm (2003). Instead of using magnetic detectors, this system integrated microwave detectors to measure speed. Drivers surveyed responded positively to the system. No significant increase in the number of crashes was observed while the system was tested. Because there was significant coverage of the work zone by the media, it was difficult to decide whether traffic diversion was caused by the system installation or media activity. When there was congestion, the messages displayed on the message board did not accurately reflect actual road conditions.

The D-25 Speed Advisory Sign System from MPH Industries was tested by Pesti (2002). It is a similar system to the one McCoy and Pesti (2002) tested, except the speed sign is also mounted on the speed trailer. When the downstream speed differential was less than 15 mph, a strobe on each side of the speed trailer would flash and the measured speed would be displayed. When the downstream speed differential was greater than 15 mph, the slowest speed measured or the speed limit would be displayed with flashing. The purpose of the study was to evaluate the effectiveness of the speed trailer in reducing speed and speed differential upstream of a work zone. The effect of the sign with flashing was not separately evaluated but was part of the entire operation scenario. The evaluation showed vehicle speeds were significantly reduced. In particular, drivers changed their deceleration patterns by doing so early, right after they observed the messages on the message signs.

Research Build System: Systems were developed by the research teams for evaluation. An example is the system developed by Pesti et al. (2002), which used video detection technology to collect traffic data such as speed and vehicle classification. These traffic data were transmitted to a controller where they were analyzed to determine the messages to be displayed on the changeable message signs employed in advance of a work zone. A website was also developed to broadcast traffic information from the work zone to a wider area. In this study, Pesti et al. (2002) focused their effort on the diversion issue, extensively reviewing previous studies that evaluated the diversion impact of the automatic work zone systems. Their evaluation indicated that no significant diversion was observed during the time tests were performed. It was recommended to test the system during peak periods and expect to see more diversion.

2.3 Summary of Literature

It can be seen from the literature review that several manufacturers have been providing automatic work zone information systems: Traffic Information and Prediction System, Automated Data Acquisition and Processing of Traffic Information in Real-time, Computerized Highway Information Processing System, and IntelliZone. A typical automatic work zone information system consists of three system components: traffic data collection, data transmission, and message presentation. A simple system has these three components all on site.

The purposes of such a system could be speed advisory, travel time and delay information provision, and incident alerts. The popular traffic data collection technologies are portable non-intrusive detectors such as Remote Traffic Microwave Sensors. Magnetic sensors which were used in a study are intrusive in nature, and may not be easily installed in a work zone. Video detection may be a choice, but may suffer from the data reliability problem. Speed was the most basic information that can be measured directly by the system. Other information such as queue, congestion, travel time, travel delay, and incidents has to involve transforming the speed data collected at several places within or upstream of a work zone. The transformation of the data may bring in the reliability issue to the derived information. In most cases, all the detectors were placed upstream of a work zone. The number of detectors and the portable changeable message signs for a work zone could vary, depending upon the accuracy of the information the system intends to provide. The major aspects of these automatic work zone information systems evaluated include speed control, traffic diversion, crashes, operation reliability, and information accuracy.

A more complicated automatic work zone information system involved disseminating traffic information to a large area outside of the work zones. Such information would be helpful in trip planning such as route choice or departure time choice. The popular ways to disseminate the information were through highway advisory radio, web site, fax, email, and paging. The population of motorists able to access the information varies from some chosen staff to travelers in a large area. The evaluation of such a system is very challenging.

The system evaluated in this study was a simple one. Video detection obtained traffic data such as speed, volume, and occupancy. Line-of-sight wireless communication passed the data to a processor located at the portable changeable message signs. Two vision detectors fed information to an algorithm that determined the messages to be displayed on the changeable message sign. The evaluation was focused on both traffic diversion and vehicle speed.

CHAPTER 3 TEST SPEED MONITORING DISPLAY AT THE CR-215 SITE

3.1 Test Plan

In testing the speed monitoring display at the Cr-215 site, the following features of the sign were considered: (1) Small non-flashing sign, (2) Big sign with no flashing, (3) Big sign with high flashing rate, (4) Big sign with low flashing rate, and (5) Warning sign with “Slowdown” message. By comparing the responses of motorists to the small and big signs, it can be demonstrated whether the big sign can be more effective in bringing down speed. With the comparison between the flashing and non-flashing signs, it was expected to see additional benefit from the flashing function since it would draw drivers’ attention to the speed message. By varying the flashing rate, it was possible to reveal motorists’ level of attraction to the flashing. By showing a warning message instead of displaying the measured speed, the difference between the messages on motorists’ compliance with the speed limit could be compared. In addition to these features for the speed sign on the speed monitoring display, two speed trailers were deployed 1,500 ft apart in a work zone. This scenario determined whether motorists continue to respond to the speed monitoring display after they’ve already seen one upstream. Figures 3.1, 3.2, and 3.3 present the small, big, and the sign with a warning message, respectively. Figure 3.4 shows the difference in dimensions between the small and big signs. Although the widths of these two signs are very similar, their heights are significantly different, 15.5 inches for the small and 23.25 inches for the big sign. The big sign is the largest feasible using the speed trailer purchased for this study. The small sign on the trailer borrowed from the City of Las Vegas can only display one size of number. The combination of the three features and the number of speed trailers comprised the test scenarios tested in this study. The scenarios are listed in Table 3.1.

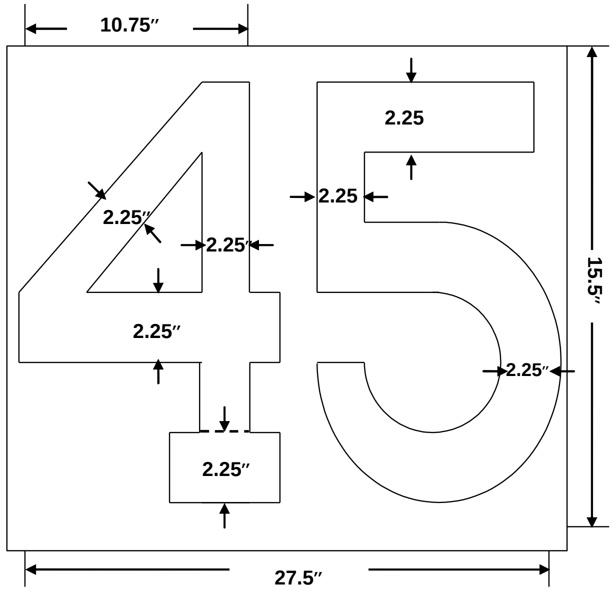
Table 3.1 Test Scenarios

Scenario	Location 1	Location 2	Dates with Data Available
1	No Tested Device	No Tested Device	1/9/07, 1/10/07, 1/11/07, 1/19/07
2	Small Sign	No	1/25/07, 1/26/07, 1/29/07, 1/30/07, 1/31/07, 2/1/07
3	Big Sign	Small Sign	3/2/07, 3/21/07, 3/22/07, 3/23/07
4	Big & Fast Flashing	Small Sign	3/5/07, 3/6/07, 3/7/07
5	Big & Slow Flashing	Small Sign	3/8/07, 3/9/07, 3/12/07, 3/13/07
6	“Slow Down”	Small Sign	3/27/2007*, 3/28/2007*, 3/29/2007*, 3/30/2007*

Figure 3.1 Small Sign

Figure 3.2 Big Sign with No Flashing

Figure 3.3 Warning Sign with Message "Slow down"



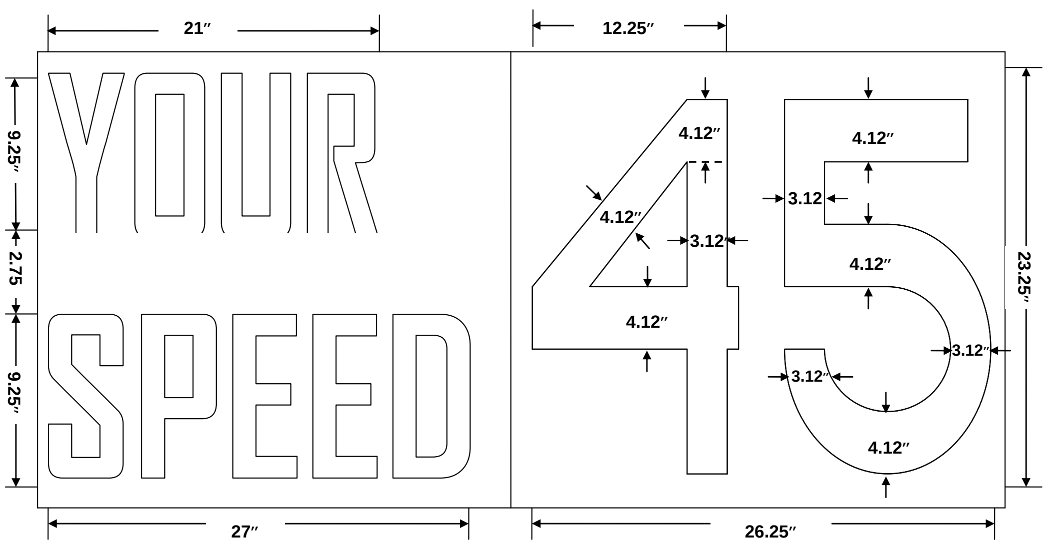


Figure 3.4 Size Measurements for the Small Sign (above) and Big Signs (below)

The test site was chosen on Northbound Cr-215 between Cheyenne Avenue and Lone Mountain Road, shown in Figure 3.5. This segment of road was a four-lane highway major arterial, two lanes in each direction, at the time when the test was conducted (see Figure 3.6). Construction as seen in Figure 3.7 was underway to convert this road segment to a freeway, a part of the beltway in the Las Vegas area. The Alexander Road overpass crosses this segment from east to west. Two northbound lanes were open in the work zone. Construction was underway on both sides of the two lanes. Concrete barriers were used to guide the traffic along most of the road segment where the test was conducted. There was no shoulder space between the edges of travel lanes and the barriers. The first speed trailer was set up under the bridge of the overpass facing the traffic traveling northbound. The shadow under the bridge improved motorists' ability to see the speed trailer's LED sign. The speed trailer with the small size sign was initially placed before the bridge, facing south. During the day, motorists had difficulty reading the speed displayed on the sign. The speed trailer was then moved to the shadow of the bridge. The second speed trailer was deployed about 2,000 feet downstream from the first. The road had a horizontal curve between these two speed trailers (Figures 3.5 and 3.6), so motorists could not see the second speed trailer from where they could see the first trailer. The roadway profile was an upgrade of 2 to 3 degrees running from about 1,000 feet upstream of the first speed trailer to the location where the second speed trailer was located (see Figure 3.6). Both speed trailers were placed on the right shoulder. The first speed trailer was located behind two segments of concrete barriers placed by the construction crew. The second speed trailer was placed on a shoulder where no construction was underway. The construction contractor placed two concrete barrier segments in the front of the speed trailer for safety.

A non-intrusive detector from Nu-Metrics, was used to collect traffic data to evaluate the speed trailer performance. Figure 3.6 illustrates the location of these Nu-metrics detector at the test site, and Figure 3.8 shows the detector with the metal plate and the plate cover. In the field, the cover was placed over the metal plate using industrial tape, which was also used to attach the plate and cover to the pavement surface. The battery life in the metal plate is about three weeks. Figure 3.9 shows the detector placement on the road. Usually, one person can install the detector on the road when traffic is light. The attractive feature of the detector is that it can measure the speed, occupancy, and length for each individual vehicle. This was needed for this study that looked at the behavior of motorists responding to speed monitoring displays in a disaggregate level. To capture the motorists' response to the speed trailer (e.g., change in speed), one detector was placed on each lane, about 200 feet downstream from the two speed trailers.

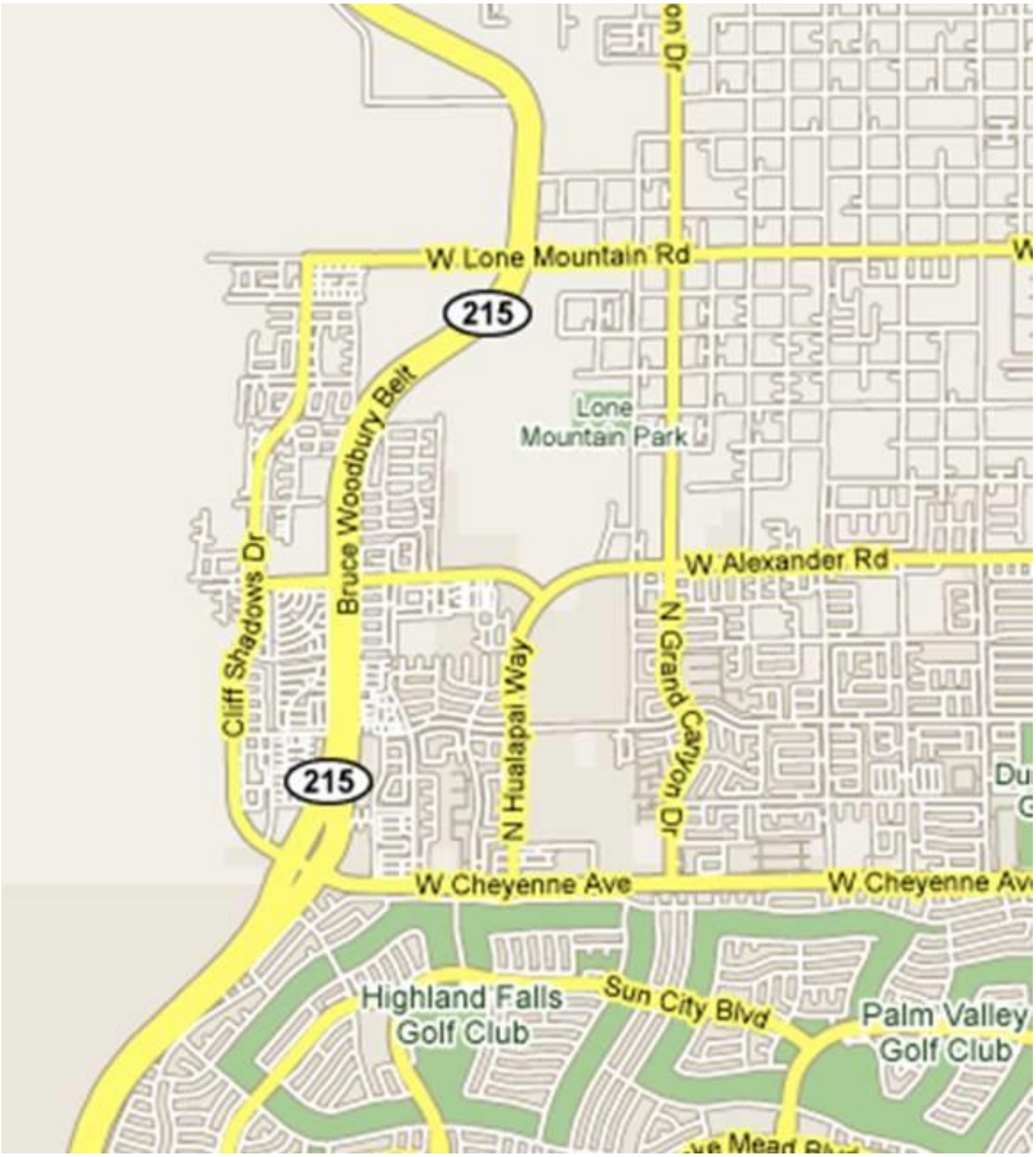


Figure 3.5 Location of the Chosen Work Zone on Cr-215 (Google Map)

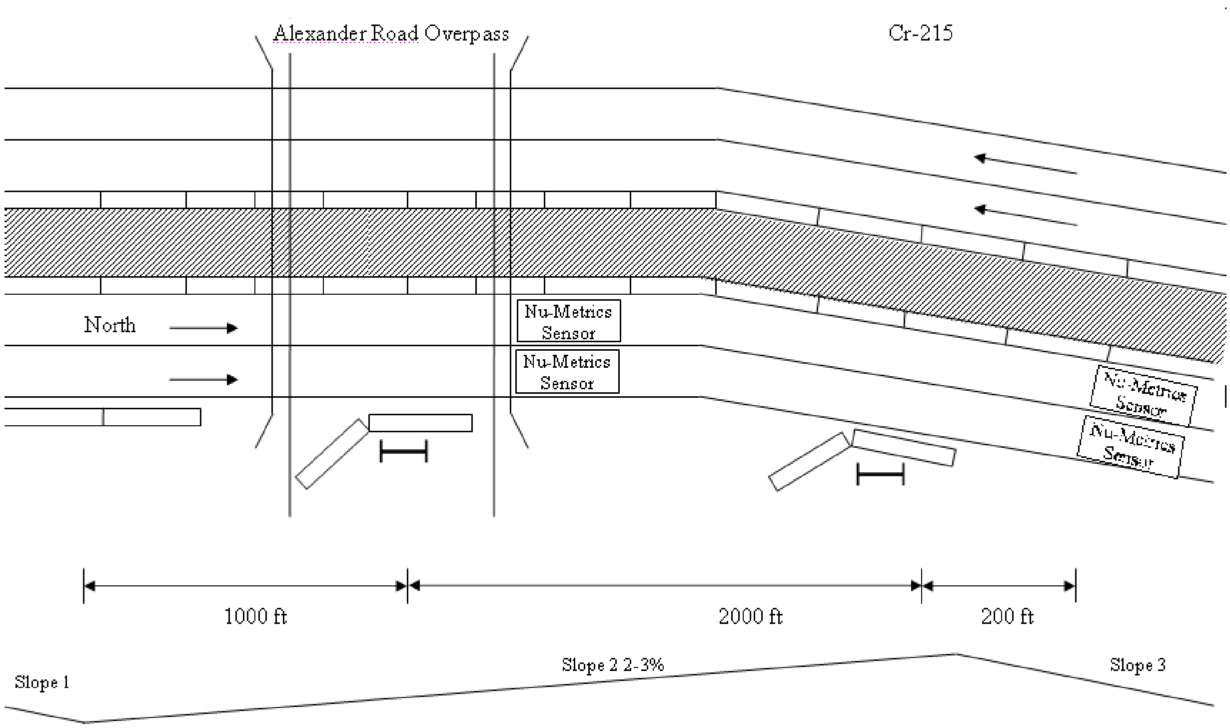


Figure 3.6 Layout of Speed Trailer and Detectors on the Test Site on Cr-215

Figure 3.7 The First Speed Trailer under the Alexander Road Overpass Bridge

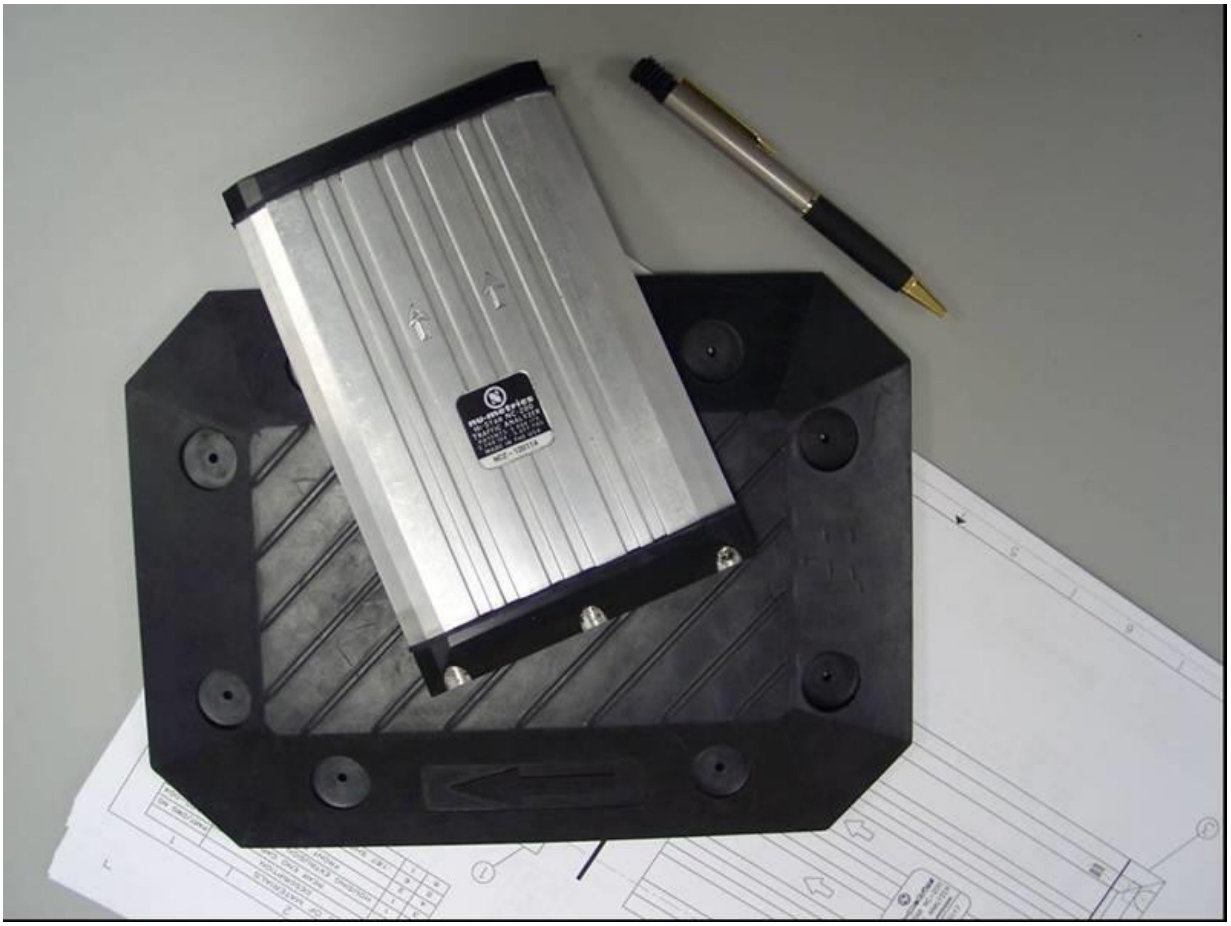


Figure 3.8 Nu-Metrics Detector

Figure 3.9 Nu-Metrics Detectors on the Road

3.2 Tests in the Field

Each scenario was tested at least five days for two hours, from 9:00 am to 11:00 am. Even though the speed trailers were stationed at the test location 24 hours a day, they were turned on for operation only during these two hours and turned off after 11:00 am when the test was completed. Regularly, one person drove a UNLV van to the site. After turning on the test speed trailer, the person would observe the test site conditions. Sometimes there might be construction activities on the shoulder that distracted the attention of motorists and thus slowed them down voluntarily. Concrete barriers under the bridge might have been removed for work on other road segments, and thus influenced the speeds of vehicles passing the test speed trailer under the bridge. Slow moving vehicles such as cement trucks for the road construction might pass the test site. Police activities might exist upstream or downstream of the work area that might control vehicle speeds through the work zone. All these activities were noted to assist with data analysis.

Even though a battery in Nu-Metrics detectors can last about three weeks, they were retrieved once a week. Since the tests for each scenario took about one week, the detectors were taken out right after the scenario tests were completed. When the detectors were taken back to school, which usually happened on Friday, they were placed back in the field on Sunday. Data stored in the detectors were downloaded immediately after the detectors were removed from the roadway. Due to technical problems, the data might not have been valid, so the tests for the scenario had to be repeated for a sufficient number of days to obtain valid data. At the beginning of the field test, Traffic Control Service, Inc. in Las Vegas provided free services for installing and retrieving the detectors. At the later stage of the test, the project research team performed installated and retrieved the detectors in the field. A Nu-Metrics consultant provided a one-time free service at the UNLV campus, to make sure the software to download the data was functioning appropriately. The consultant also visited the test site and provided valuable comments on installing the detectors.

Two incidents of vandalism happened during the project. When the test was being planned, two cameras were mounted on the Alexander Road overcrossing bridge, collecting traffic data to validating the data from Nu-Metrics. The wires and cables connecting the video digital recorders and the cameras were severed and removed. A solar panel on one of the speed trailers was stolen.

In addition, two fatal crashes happened at places within the work zone near the test site due to speeding. These two crashes confirmed the importance of controlling speeds in work zones.

The field tests were conducted from December 6, 2006 to March 30, 2007. Table 3.1 also lists the days that had valid data available for analysis.

3.3 Data Analysis

In the data analysis, the speed data were first analyzed by including all types of vehicles (passenger, single-unit trucks, and multi-unit trucks). Descriptions of the test results were provided based on the descriptive statistics, such as average speed, for different scenarios. Hypothesis tests were performed to compare the performance of different scenarios. Extensive analysis was conducted for vehicles operating in free flow conditions. Regression models for the likelihood of speeding (traveling faster than the speed limit) and vehicle speeds were developed. The relative performances of these scenarios in the right and left lanes were identified separately. To determine whether a vehicle was in free-flow condition, an innovative algorithm called the CUSUM was developed. When this algorithm was applied to the collected vehicle data, it was determined whether the vehicles operating through the test site were operating in platoon or free-flow conditions.

3.3.1 Profile of Speed Reduction and Speeding Rate

Based on the data collected for the scenarios in the days listed in Table 3.1, average speeds were derived for each scenario and provided in Table 3.2. It can be found from Table 3.2 that, when there was no speed trailer deployed at the test site under the bridge, the average speed for vehicles of all types in the left lane was 70.2 mph, in contrast to the speed limit of 45 mph. With the speed trailer equipped with different features, the average speeds were reduced by amounts varying from 4.7 mph to 8.8 mph. Among the three types of vehicles, passenger vehicles and single-unit trucks reduced their speeds more than the multi-unit trucks. For the vehicles of all types traveling in the right lane, it can be seen that they operated at 65.6 mph on average during the 'before' condition. This average is of course about 5.0 mph less than that in the left lane. This indicates that vehicles in left lane travel faster than those in right lane, which is consistent with field observations. It can also be found from Table 3.2 that the amount of speed reduction seems similar to that of traffic in the left lane. Among the three types of vehicles, multi-unit trucks traveled the slowest, and reduced speed slightly.

From Table 3.2 it can be seen that the average speed of all traffic at the second location was 69.2 mph and 60.0 mph for the left and right lanes, respectively, in the 'before' condition where there were no speed trailers deployed at the test site (neither under the bridge nor the location downstream). The average speed of traffic in the left lane at location #2 was similar to the speed in that lane at location #1 under the bridge; but it was not the same average speed as the right lane (65.6). The lower speed at the second location was probably caused by the 2-3% uphill slope between these two locations. It can also be seen that speeds were reduced at the second location by 5.9 mph (69.2-63.3) on the left lane and about 2.3 mph (60.0-57.7) in the right lane when there was a small sign at the first location, about 2,000 ft upstream from the second location. The speed reduction at the first location was 6.8 mph (70.2-63.4) in the left lane and 7.0 mph (65.6-58.6) in the right lane. These reductions at the first location declined by 0.9 (6.8-5.9) mph and 4.7 (7.0-2.3) mph over the 2,000 feet. This rate of speed reduction can be used to determine where additional speed trailers are needed.

Looking at the data in Table 3.2 for the left lane at the second location, especially for the data for the mix of all vehicle types, it can be seen that the average speeds for the four features (ranging from 57.2 mph to 59.9 mph) were less than that in the before conditions (69.2 mph). The reduction in speed was about 10 mph. The data for the right lane traffic show that there were also significant reductions in speed from 60.0 mph (the before condition) to a range from 51.8 mph to 55.3 mph. It appears that the motorists made additional speed reduction responding to the speed trailers that were tested with different features.

Table 3.3 provides the results for vehicles operating at excessive speeds. The results in Table 3.3 indicate that, on both the left and right lanes at the first location, about 97% of vehicles were operating over the 45 mph speed limit posted for the construction zone. The presence of speed trailers with various features reduced the traffic speeding percentage from 1% to 7%. When looking at the performance of the speed trailer to the speeding vehicles at the second location, Table 3.3 indicates that the percentage of speeding vehicles was 98.2 and 95.0 for the left and right lanes, respectively, when no speed trailer was deployed. When the small sign was tested 2,000 feet upstream of the first location, the speeding percentages dropped to 94.8 and 92.1 for the left and right lanes, respectively. With an additional speed trailer deployed at this location, the speeder percentages decreased to lower levels (91.4 for the left and 68.6 for the right lane).

The comparisons between the signs with different features and the before condition were made based on t-test. In this comparison, all three types of vehicles were considered, regardless of whether they were operating in free-flow condition or not.

According to a t-test for the means of speeds in the before (μ_1) and after (μ_2) conditions, the null hypothesis was that there was no mean difference between these two conditions, written as:

$$H_0 : \mu_1 - \mu_2 = 0 \tag{3.1}$$

The alternative hypothesis was that the speed was reduced, increased, or stayed the same. The alternative hypothesis for slowing down traffic is:

$$H_1 : \mu_1 - \mu_2 < 0\,. \tag{3.2}$$

The t-test statistic can be written as

$$S_e = \left(\mu_1 - \mu_2\right) \Big/ \sqrt{S_1^2/n_1 + S_2^2/n_2} \tag{3.3}$$

where n_1 and n_2 represent the sample sizes for the speeds in the before and after conditions, respectively; and S_1^2 and S_2^2 are the corresponding speed sample variances. In this study, the level of significance of 0.05 was used to determine whether the null hypothesis is accepted. The average speeds between scenarios were compared with different features of the speed trailer, where μ_1 and μ_2 represented speeds in two different scenarios. The null hypothesis is that the mean speeds of these two samples from two different scenarios are the same. The alternative hypothesis is that the mean speeds are not equal.

Table 3.4 lists the results of the comparisons between different features of the speed trailer deployed at the first location based on hypothesis tests when all types of vehicles were considered together. It can be seen from the upper part of the table that the speeds of vehicles in the before condition were significantly higher than those when the speed trailer was deployed with different features. In other words, the speed trailers tested with all different displaying features reduced speed significantly. In Table 3.4, the labels in the row for “Big” are all “<” and the label for the cell corresponding to the “Small” row and the “Big” column is “>”. The label “<” implies that the speed trailer with non flashing big sign reduced speed more than all the other features tested in this study. The three “<”’s in the row of “Small” indicates that the speed trailer with the smaller sign reduced more speed than the speed monitoring displays with the flashing features and the “Slow Down” message did. The label for the cell corresponding to the row of “Big & Fast Flash” and the column of “Big & Slow Flash” is “>”,indicating that the big sign with slow flashing performed better than with fast flashing in reducing traffic speed. The labels in the “Slow Down” column are all “<”, except for comparing with the ‘before’ condition, which means that the “Slow Down” feature did not outperform any other features.

As far as the traffic on the right lane at the first location is concerned, the results at the bottom of the table indicate a similar performance pattern between different features of speed trailers. One major difference was that the “Big & Fast Flash” feature outperformed the “Big & Slow Flash” feature to bring down speeds. Another difference was that the “Slow Down” feature reduced speed more than the big sign with flashing. It performed just as well as the small sign. These observations imply that fast flashing and “Slow Down” may not be well recognized by the traffic on the left lane. Vehicles on left lane ran faster than those on the right lane, so may not have seen the signs as well. They were farther from the signs than those on the right lane, and their view may also have been blocked by vehicles in the right lane.

Table 3.2 Comparison of Average Speeds

		1st Location						2nd Location					
		Before Condition	Small	Big	Big & Fast Flash	Big & Slow Flash	Slow Down	Before Condition	Small*	Big**	Big & Fast Flash **	Big & Slow Flash **	Slow Down **
Left Lane	All	70.2	63.4	61.3	65.4	64.4	65.4	69.2	63.3	57.2	59.9	58.6	N/A
		Diff	6.7	8.8	4.7	5.8	4.7	Diff	5.8	11.9	9.3	10.5	N/A
	Passen-ger	69.3	62.1	60.9	64.9	63.1	64.4	68.3	63.9	57.3	59.4	57.6	N/A
		Diff	7.1	8.4	4.3	6.1	4.8	Diff	4.4	11.0	8.9	10.6	N/A
	Single Unit	74.3	67.6	65.7	69.1	69.1	70.5	73.4	68.0	59.9	63.1	62.3	N/A
		Diff	6.6	8.5	5.1	5.1	3.8	Diff	5.3	13.4	10.2	11.1	N/A
	Multi-Unit	60.3	59.3	55.3	57.4	57.7	59.1	59.8	56.2	51.7	55.6	56.3	N/A
		Diff	1.0	5.0	2.9	2.6	1.2	Diff	3.5	8.0	4.2	3.4	N/A
	Free Flow	69.9	63.3	61.9	65.0	64.9	66.3	69.2	62.6	57.1	59.7	58.4	N/A
		Diff	6.6	7.9	4.9	4.9	3.5	Diff	6.5	12.0	9.4	10.7	N/A
Right Lane	All	65.6	58.6	57.6	59.9	61.0	58.7	60.0	57.7	52.9	53.6	55.3	51.8
		Diff	7.0	7.9	5.6	4.5	6.8	Diff	2.2	7.1	6.4	4.6	8.2
	Car	64.7	58.0	57.3	59.7	60.3	58.2	60.5	58.0	53.2	54.0	54.9	51.9
		Diff	6.7	7.4	5.0	4.4	*6.5*	Diff	2.5	7.2	6.5	5.6	8.6
	Single Unit	69.5	61.0	60.1	62.5	63.3	61.7	61.8	59.0	53.4	53.8	55.1	52.7
		Diff	8.4	9.4	6.9	6.1	7.7	Diff	2.7	8.4	8.0	6.6	9.1
	Multi-Unit	59.6	56.1	54.3	55.6	57.0	54.5	53.4	53.2	49.6	50.2	50.8	49.2
		Diff	3.5	5.3	4.0	2.6	5.1	Diff	0.1	3.7	3.1	2.5	4.1
	Free Flow	65.8	59.1	58.3	60.6	61.5	59.3	60.4	57.7	46.2	53.7	55.3	52.4
		Diff	6.6	7.4	5.1	4.2	6.4	Diff	2.6	14.2	6.6	5.0	8.0

* A speed monitoring display with a small sign at the first location and no speed monitoring display at the second location

** A speed monitoring display with the features indicated at the first location and a speed monitoring display with a small sign at the second location

N/A indicates no speed data collected for the scenario due to detector failure.

Table 3.3 Excessive Speeding Vehicles Rate and Sample Size of Free Flow Vehicles

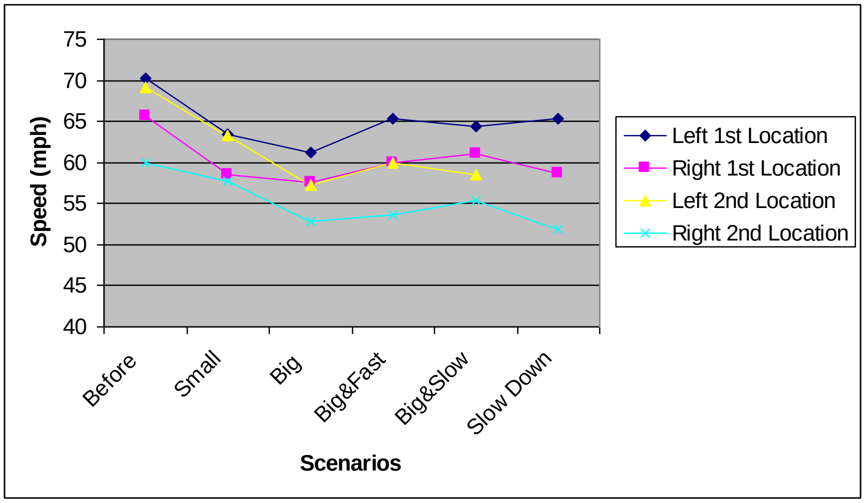
		1st Location						2nd Location					
		Before Condition	Small	Big	Big & Fast Flash	Big & Slow Flash	Slow Down	Before Condition	Small	Big	Big & Fast Flash	Big & Slow Flash	Slow Down
Speeding %	Left Lane	97.5	93.8	92.4	95.8	96.4	95.9	98.2	94.8	91.4	93.0	91.4	N/A
	Right Lane	97.0	91.9	90.3	93.4	93.8	92.4	95.0	92.1	68.6	88.1	91.1	84.3

Table 3.4 Hypothesis Test Result of All Vehicle Types at the First Location

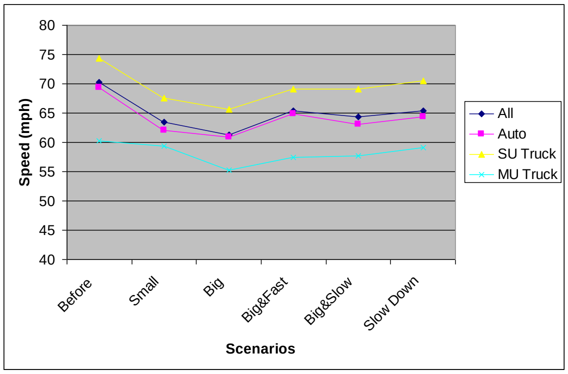
		Small	Big	Big & Fast Flash	Big & Slow Flash	Slow Down
Left Lane	Before Condition	>	>	>	>	>
	Small		>	<	<	<
	Big			<	<	<
	Big & Fast Flash				>	<
	Big & Slow Flash					<
	Slow Down					
Right Lane	Before Condition	>	>	>	>	>
	Small		>	<	<	=
	Big			<	<	<
	Big & Fast Flash				<	>
	Big & Slow Flash					>
	Slow Down					

Note: ">", "<", and "=" indicate that the mean speed in the condition described by the row title is greater or less than, or equal to that in the condition in the column title. For example, the 'small' sign condition had a higher mean speed than the 'big' sign.

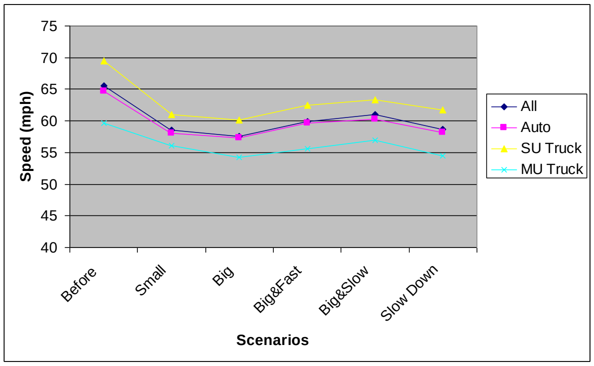
Figure 3.10 displays the speeds for three types of vehicles under different scenarios. The chart at the top of Figure 3.10 shows speed aggregates of all three types of vehicles: passenger car, single unit truck, and multi-unit truck. Average speeds under the tested scenarios with the presence of speed trailer were lower than the average speed under the before condition for the traffic at the left and right lanes and at both the first and second locations. The non-flashing big sign scenario had the lowest speeds compared to other scenarios, the non-flashing small sign scenario comes in second, followed by the scenario of big signs with flashing features and a warning message. The vehicle speeds in the left lane were higher than those in the right lane for both speed trailer locations. Looking at the speeds at the left lane, when there was a speed trailer deployed at the second location, speeds were further reduced. The same observation was found for the right lane. From the charts for the three different vehicle types in the left lane, shown in the left middle and left bottom of Figure 4, single unit trucks operated at higher speeds than the other two vehicle types, while the speeds of multi-unit trucks were the lowest. Under a warning sign, the speeds in the left lane at the first location tended to be higher than those in scenarios that displayed flashing features, different from the case in both the left and right lanes at the second location. Figure 3.11 displays the 85 percentile of speeds and the speeding percentages for these scenarios tested. Similar patterns to Figure 3.10 can be observed in Figure 3.11.



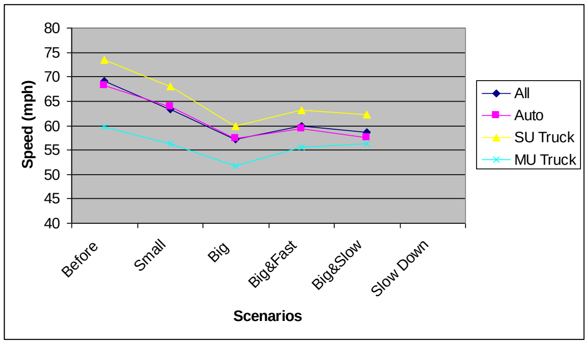
Overall speed profile



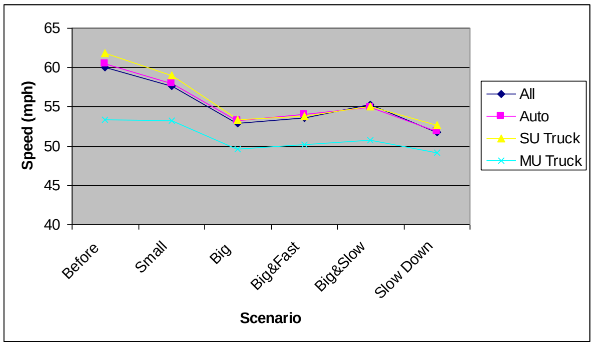
Speed profile on left lane at the 1st location



Speed profile on right lane at the 1st location

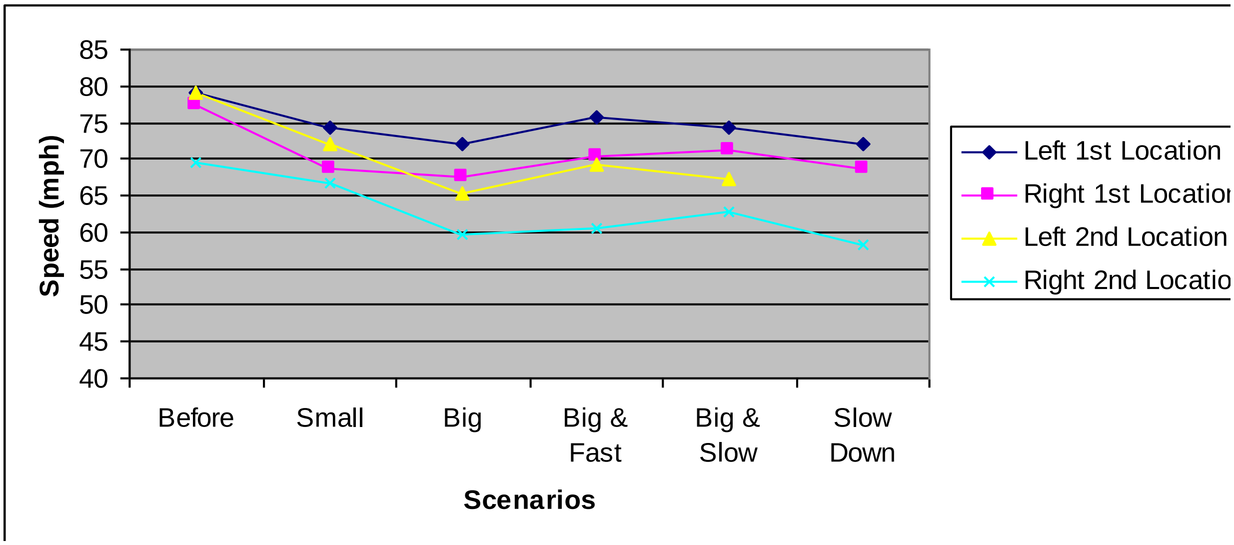


Speed profile on left lane at the 2nd location

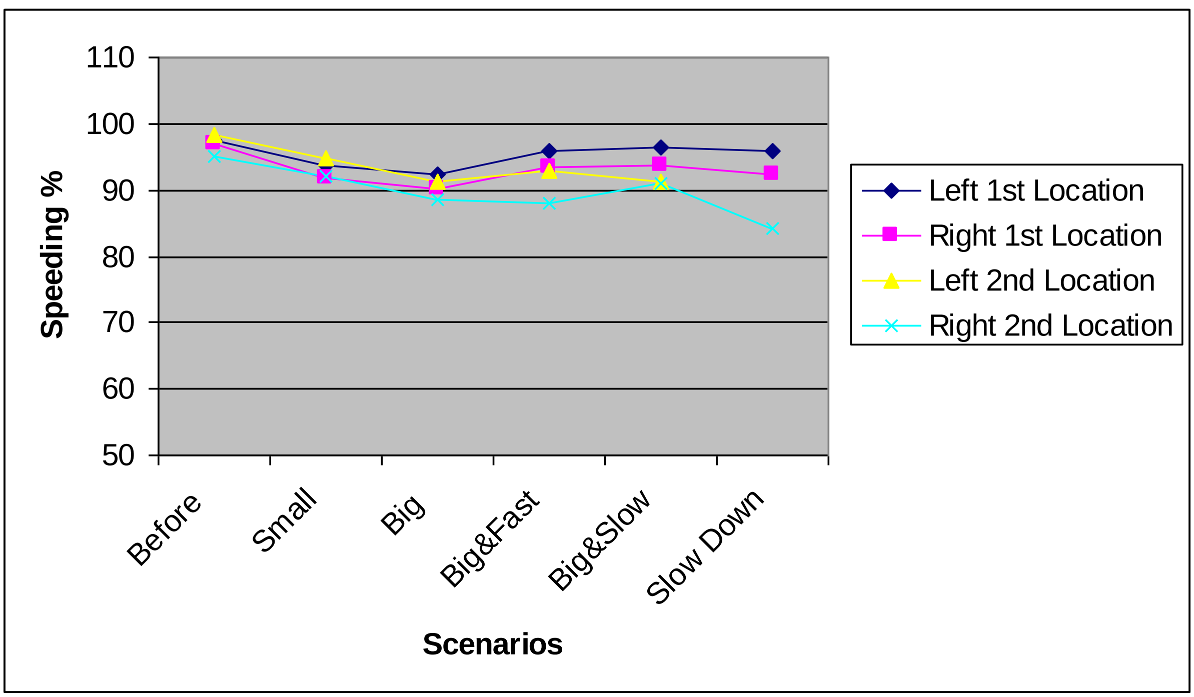


Speed profile on right lane at the 2nd location

Figure 3.10 Speed Profiles at the Cr-215 Site



85 Percentile Speed



Speeding Rate

Figure 3.11 85 Percentile Speed and Speeding Rate

3.3.2 Analysis for Vehicles Operating at Free-Flow Condition

If analyzing vehicles operating at both the free flow and platoon conditions together, the behaviors of those vehicles under free flow conditions would be clouded. It is important to investigate the vehicles under free flow conditions since their response to the speed monitoring display represents real reactions to the speed control devices. The behaviors of vehicles in platoon were influenced by the vehicles close to each other, and may not be their true response if they faced such speed control devices alone. That is why vehicles in free flow conditions were investigated in several previous studies.

Identifying vehicles in free-flow condition

CUSUM algorithm

To apply the CUSUM algorithm, the headways between vehicles observed sequentially at a location in a lane can be represented as y_1, y_2, … Among these headways, those of y_1, y_2, …, y_{t_0-1} can be assumed for vehicles in platoon, following a probability density function (p.d.f.) P_{θ_0}. The remaining headways y_{t_0}, y_{t_0+1}, … can be assumed for the vehicles operating in the free flow conditions before the next platoons, and their p.d.f.'s can be written as P_{θ_1}. In these two p.d.f.'s, the parameters θ_0 and θ_1 are assumed different, and the probability density function change at t_0 ($t_0 \geq 1$). In this study, P_{θ_0} was calibrated as the lognormal distribution, and P_{θ_1} was the exponential distribution.

Given the headways y_1, y_2, … observed sequentially, for a given headway y_k at time k, there are two hypotheses about whether it is from the same platoon as y_{k-1} or in free flow conditions. The likelihood for the headway y_k to be in a platoon and free flow conditions can be expressed as $P_{\theta_0}(y_k)$ and $P_{\theta_1}(y_k)$, respectively. The log-likelihood ratio between these two likelihoods, $s_k = \log[P_{\theta_0}(y_k)/P_{\theta_1}(y_k)]$, is positive when y_k comes from the same platoon. As shown in Figure 3.10, the cumulative sum of the log-likelihood ratio $S_k = \sum_{j=1}^{k} s_j$ increases continuously with the headways continuously coming from the same platoon, and decreases after headways from a free flow condition are observed. A substantial change in the difference between the cumulative sum of the log-likelihood ratio for the current time period and the minimum cumulative sum up to the current time period indicates a change in the state in which vehicles are operating. This difference can be written as:

$$g_k = \max_{0 \le j \le k} S_j - S_k . \tag{3.4}$$

If g_k is higher than a pre-defined threshold h, then y_k can be viewed as in free flow conditions.

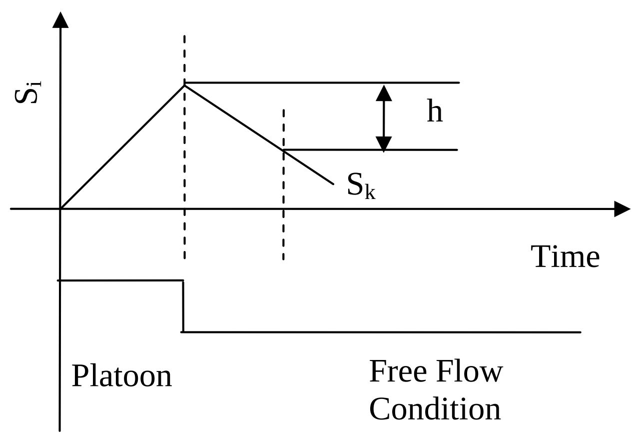


Figure 3.12 The CUSUM Algorithm Diagram

To distinguish vehicles operating in free flow conditions from those operating in platoons, a computer program was written to execute the CUSUM algorithm on the headway data of different lanes at these two locations sequentially. It can be seen from the methodology on the CUSUM algorithm that it is necessary to know the probability distributions of headways in free flow and platoon conditions, and the threshold for the difference between the cumulative sum at current time and the maximum cumulative sum (i.e., g_k). To develop the probability distributions of headways, traffic at the first location of the test site was recorded using a digital video for two hours from 9:00 am to 11:00 am (the same time period that the tests were conducted) on April 5, 2007. During the recording, no speed trailer was deployed. The recorded video was downloaded into a computer and run to determine headways between vehicles by reading the timestamps displayed on the computer screen. Whether a vehicle was operating in free flow conditions could be observed from the video based on its vehicle-following behaviors. Thus, the headway could be labeled as in free flow conditions or platoon, correspondingly. As a result, sufficient headway data as listed in Table 3.5 were collected.

Table 3.5 Headway Probability Density Distributions

	Category	Number of Headways	Probability Density Distribution Parameters
Left	Within Platoon	353	$\sigma = 0.64685$, $\mu = 0.67917$
	Free Flow Condition	176	$\lambda = 0.02783$
Right	Within Platoon	379	$\sigma = 0.62532$, $\mu = 0.96413$
	Free Flow Condition	243	$\lambda = 0.0405$

Based on the results of fitting probability density distributions, the following distributions were found fitting the data very well: generalized Pareto, lognormal, exponential, Weibull, beta, and gamma. Among these distributions, exponential and lognormal distributions were selected for the headways in the free flow conditions and platoons, respectively, since those two distributions were used in previous studies on headways. Some studies showed that the distribution for headways in platoon may differ when the platoon size is different. This complex issue was left for future studies. Basically, these two probability density functions can be expressed as:

$$\text{Exponential distribution: } f\left(x\right) = \lambda \exp\left(\lambda x\right) \tag{3.5}$$

$$\text{Lognormal distribution: } f\left(x\right) = \exp\left[-\frac{1}{2}\left(\frac{\ln x - \mu}{\sigma}\right)^2\right] \Big/ \left(x\sigma\sqrt{2\pi}\right) \tag{3.6}$$

The parameters in the fitted distributions are also listed in Table 3.5.

The threshold for the difference between the cumulative sum and maximum cumulative sum was determined through an iteration process. The process starts with any given value for the threshold. For each value of the threshold, it was counted how many vehicles classified as operating in free flow conditions were re-categorized as operating in platoon (f-p) and vice versus (p-f). It was observed that these two numbers stabilized at a value after a certain number of iterations. Table 3.6 lists the f-p and p-f data for the headways for the left and right lanes, separately. Apparently, the thresholds for left and right lanes were determined to be 0.1 and 0.0125, respectively.

Figure 3.6 Process for Finding the Threshold for the CUSUM Algorithm

Left Lane				Right Lane			
Threshold	**p-f**	**f-p**	**Total**	**Threshold**	**p-f**	**f-p**	**Total**
1	3	29	32	1	2	78	80
0.9	3	27	30	9	2	70	72
0.8	3	21	24	0.8	2	64	66
0.7	3	18	21	0.7	2	60	62
0.6	5	15	20	0.6	2	49	51
0.5	5	11	16	0.5	4	43	47
0.4	11	8	19	0.4	5	36	41
0.35	13	5	18	0.35	7	36	43
0.3	13	5	18	0.3	10	27	37
0.25	14	4	18	0.25	12	27	39
0.2	15	4	19	0.2	14	24	38
0.1	21	2	23	0.1	17	18	35
0.05	22	1	23	0.05	21	17	38
0.01	22	1	23	0.025	24	15	39
				0.0125	28	15	43
				0.01	28	15	43
				0.005	28	15	43
				0.001	28	15	43

The whole numbers represent the count of changes from clarifying vehicles to be operating in platoon condition to free flow condition, or vice versa.

Disaggregate modeling of vehicle responses

Regression models were developed to model the probability for a vehicle to be speeding under different scenarios and the relative impact of the scenarios on vehicle speed. The scenarios *at the first location* included in the models were (1) Small, (2) Big, (3) Big-Fast flashing, (4) Big-Slow flashing, (5) Slowdown message, and (6) Before conditions. The types of vehicles distinguished in the models were: (1) Passenger, (2) Multi-unit truck, and (3) Single Unit truck. The probability for a vehicle *n* to be speeding can be written as:

$$P_n(1) = e^{U_{1n}} \Big/ \left(e^{U_{1n}} + e^{U_{0n}}\right), \tag{3.7}$$

where U_{1n} and U_{0n} represents the "utility" for a vehicle to be speeding and not speeding, respectively. Because there are only two outcomes for a vehicle, speeding or not speeding, the probability for a vehicle *n* not to be speeding can be expressed as:

$$P_n(0) = 1 - P_n(1) \tag{3.8}$$

The two "utilities" can be related to the scenarios and types of vehicles, which can be represented as a vector of variables $\boldsymbol{x}_{in}$. Then, these "utilities" can be written as:

$$U_{in} = \beta' \boldsymbol{x}_{in} + \varepsilon_{in}. \tag{3.9}$$

In this study, $\boldsymbol{x}_{in}$ consists of interaction variables between scenarios and type of vehicles. These interaction variables as can be seen in the following tables are denoted as: Small Car, Small T, Small T+1, Big Car, Big T, Big T+1, BigF Car, BigF T, BigF T+1, BigS Car, BigS T, BigS T+1, Warning Car, Warning T, Warning T+1, Before Car, Before T, and Before T+1. "T" denotes a single unit vehicle while "T+1" means a multi-unit vehicle. With these interaction variables, different scenarios' impact on a particular vehicle type and the impact of a certain scenario on different types of vehicles can be identified.

For the vehicles in free flow conditions, their speeds as responses under different scenarios were evaluated based on the following model:

$$SP_n = \beta' \boldsymbol{x}_n + \varepsilon_n, \; n = 1, \cdots, M \tag{3.10}$$

where S_n represents the speed for vehicle *n*, $\boldsymbol{x}_{in}$ is the same set of variables denoting the interactions between scenarios and vehicle type. *M* is the total number of vehicles that passed through the test site under different scenarios.

The results listed in Table 3.7 are for the left lane at the first location; the right lane results are listed in Table 3.8. The results of the likelihood ratio tests in these two tables indicate that these two outcome models were justified statistically. The R-square values of the two linear regression models for speeds are low. Since the purpose of the modeling was to reveal the relative performance of the scenarios for different vehicles, the estimation accuracy as reflected by R-square values became secondary in this study.

From Table 3.7 it can be seen that the variables for passenger vehicles under the non-flashing small and big signs have negative coefficients. The coefficient for the passenger vehicles in the before condition is zero. The comparison between the two negative coefficients and the zero value implies that the two scenarios reduced the likelihood of speeding for passenger vehicles. These two negative coefficients are also not significantly different from each other. This indicates that these two different sizes of signs with no flashing features performed equally well to reduce the likelihood of passenger vehicles speeding. There are no coefficients shown in the table for the flashing features impact on the passenger vehicles, suggesting that flashing features did not reduce the likelihood of passenger vehicles speeding.

Multi-unit trucks' coefficients for the before condition is negative. Since the single unit trucks in the before condition were the base in the modeling, the multi-unit trucks were less likely to be speeding than the single unit trucks in the before condition. The coefficients for the multi-unit trucks under the tested scenarios - small sign with no flashing, big sign with no flashing, and warning sign, are all negative and significant. These negative coefficients are not significantly different than the before condition (-1.573742), suggesting that none of the three signs reduced the likelihood of multi-unit vehicles speeding. The coefficients for flashing big signs for multi-unit trucks are not presented in the table because they are not significant and implies that flashing was not effective in reducing the speeding likelihood for multi-unit trucks either.

For single unit trucks, only the coefficients for the non-flashing small and big signs are negative. Since the single unit trucks in the before condition was the base used in the modeling, with a coefficient of zero, non-flashing small and big signs did reduce the speeding likelihood of single unit trucks. These two coefficients are the same statistically and tells us that these two signs performed equally well to reduce the likelihood of speeding for single unit trucks. There are no coefficients significant for the big sign with flashing features for single unit truck, implying that the flashing feature made no difference in reducing the likelihood of speeding for the single-unit trucks.

The relative performance of the scenarios to reduce vehicle speeds can be analyzed by comparing the coefficients of the scenarios and vehicle types in Table 3.7. The constant in the model is 28.88462. This number, plus the speed limit 45 mph for the test site, reflects the average speeds for single unit trucks though the tests with no speed trailer deployed. This situation was the base in modeling. For passenger vehicles, the coefficients for the five scenarios are negative and significantly smaller (ranging from -8 to -11, i.e., 8 or 11 mph) than that for the before condition (-3.906269). This indicates that passenger vehicles operated at a significantly lower speed under the tested scenarios than in the before condition. The coefficients among the scenarios for the passenger vehicles are the same statistically, telling us that the passenger vehicles responded to these scenarios in a similar fashion. The multi-unit trucks' coefficients from the tested scenarios and the before condition are negative, and are all on the same level. This result indicates that the tested scenarios didn't significantly bring down speeds of multi-unit trucks in the left lane. For single unit trucks, coefficients for all the tested scenarios were negative, so these scenarios did reduce speeds for single unit trucks.

In summary, only two scenarios, i.e., the non-flashing small and big signs, significantly reduced the likelihood of speeding for both passenger vehicles and single unit trucks in the left lane. Warning signs reduced the speeding likelihood for the multi-unit trucks, but not the other two vehicle types. The flashing feature did not reduce the speeding likelihood. Multi-unit trucks were operated already at speeds close to the speed limits and thus were not influenced to further reduce speed. All the tested scenarios, including those with the flashing feature, significantly reduced speed for passenger vehicles and single unit trucks, but not the multi-unit trucks. This suggests that the flashing feature actually was effective in reducing speeds, so long as it was seen by drivers, although the flashing feature's likelihood to reduce speed was not as significant as the other scenarios.

Table 3.7 Modeling Results for Left Lane at Location 1

Left Lane Likelihood Model at Location 1

BINARY	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
Small Car	-.6881046	.1862982	-3.69	0.000	-1.053242	-.3229669
Small T1+	-1.403169	.4166719	-3.37	0.001	-2.219831	-.586507
Small T1	-.6350619	.280654	-2.26	0.024	-1.185134	-.08499
Big Car	-.6883335	.2093321	-3.29	0.001	-1.098617	-.2780502
Big T1+	-1.567472	.3292556	-4.76	0.000	-2.212801	-.9221429
Big T1	-1.273559	.2726598	-4.67	0.000	-1.807963	-.7391559
Warning T1+	-1.870658	.3242222	-5.77	0.000	-2.506122	-1.235194
Before T1+	-1.573742	.3955292	-3.98	0.000	-2.348965	-.7985185
const	3.464592	.1121457	30.89	0.000	3.24479	3.684393

Log likelihood = -915.82032
Number of obs = 4860
LR chi2(8) = 68.37
Prob > chi2 = 0.0000

Left Lane Regression Model at Location 1

SPEEDRED	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
Small Car	-11.68193	.9227946	-12.66	0.000	-13.49103	-9.872833
Small T1+	-15.86849	1.655881	-9.58	0.000	-19.11476	-12.62221
Small T1	-6.044894	1.067027	-5.67	0.000	-8.136752	-3.953037
Big Car	-11.82082	.956739	-12.36	0.000	-13.69646	-9.94518
Big T1+	-19.15635	1.440494	-13.30	0.000	-21.98038	-16.33233
Big T1	-8.370649	1.185379	-7.06	0.000	-10.69453	-6.046769
BigF Car	-9.239241	.9879401	-9.35	0.000	-11.17605	-7.30243
BigF T1+	-16.85604	2.078384	-8.11	0.000	-20.93062	-12.78147
BigF T1	-4.910931	1.345003	-3.65	0.000	-7.547749	-2.274114
BigS Car	-9.062205	.9822455	-9.23	0.000	-10.98785	-7.136558
BigS T1+	-16.66871	1.462078	-11.40	0.000	-19.53504	-13.80237
BigS T1	-3.648901	1.265884	-2.88	0.004	-6.130608	-1.167194
Warning Car	-8.097794	.9708068	-8.34	0.000	-10.00102	-6.194572
Warning T1+	-17.61189	1.530857	-11.50	0.000	-20.61306	-14.61071
Warning T1	-2.143683	1.163502	-1.84	0.065	-4.424674	.1373084
Before Car	-3.906269	.972798	-4.02	0.000	-5.813395	-1.999143
Before T1+	-16.85183	1.665974	-10.12	0.000	-20.11789	-13.58576
Const	28.88462	.8346991	34.60	0.000	27.24823	30.521

Number of obs = 4860
F(17, 4842) = 39.68
Prob > F = 0.0000
R-squared = 0.1223
Adj R-squared = 0.1192

The results in Table 3.8 for the speeding likelihood model show all negative coefficients for the passenger vehicles and the single unit trucks in the right lane for all five tested scenarios, all on the same level, while the two in the before condition are zero. This indicates that all five scenarios were equally effective in reducing the speeding likelihood for these two vehicle types in the right lane. For multi-unit trucks, the coefficients are the same level for all tested scenarios and the before condition, suggesting that these scenarios did not reduce the speeding likelihood for multi-unit trucks in the right lane.

Table 3 indicates that the coefficients for the speed of the passenger vehicles and multi-unit trucks under all five tested scenarios are negative and smaller than those in the before condition telling us that these five scenarios were effective in bringing down speeds for these two types of vehicles. Potentially, the non-flashing big sign was more effective for the multi-unit trucks in reducing their speeds than other scenarios, including the small sign. The coefficient for the single unit trucks in the before condition is zero, while in the other scenarios it was negative and on the same level, indicating that these five scenarios were equally effective in reducing the speed of single unit trucks in the right lane as well.

Using the analysis for just the right lane, all five of these scenarios reduced the speeding likelihood for all types of vehicles and reduced their speed correspondingly in the right lane. All five performed equally well in both reducing speeding likelihood and reducing speed, except that the no-flashing big sign was more effective in bringing down speed for multi-unit trucks in the right lane.

Comparing the results from the left and right lanes, it clearly shows different performance of the scenarios in the right and left lanes. Only the non-flashing small and big signs were effective at reducing speeding likelihood for the passenger vehicles and single unit trucks in the left lane, while in the right lane, all five scenarios were effective for these two vehicles types. No scenario was effectively reduced speeding likelihood for multi-unit trucks. This might be due to speed signs visibility issues particular to the multi-unit trucks. All the tested scenarios effectively terms reduced speed, in both the left and right lanes. The non-flashing big-sign performed better than other scenarios, including the small sign at right lane, in bringing down speed for multi-unit trucks. The flashing signs and warning signs performed just as well as the non-flashing big sign in most scenarios.

Table 3.8 Modeling Results for Right Lane at Location 1

Right Lane Likelihood Model at Location 1

BINARY	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
Small Car	-1.473691	.2668662	-5.52	0.000	-1.996739	-.9506423
Small T1+	-1.773162	.3215341	-5.51	0.000	-2.403357	-1.142967
Small T1	-1.244079	.3104206	-4.01	0.000	-1.852492	-.6356655
Big Car	-1.525425	.2780944	-5.49	0.000	-2.07048	-.9803705
Big T+1	-2.143174	.3317882	-6.46	0.000	-2.793467	-1.492881
Big T1	-1.615429	.3203918	-5.04	0.000	-2.243385	-.9874722
BigF Car	-1.103402	.3034523	-3.64	0.000	-1.698158	-.5086463
BigF T+1	-1.72196	.3975149	-4.33	0.000	-2.501075	-.9428453
BigF T1	-1.180363	.3815511	-3.09	0.002	-1.928189	-.4325365
BigS Car	-.7583685	.3165131	-2.40	0.017	-1.378723	-.1380143
BigS T+1	-1.927577	.3416597	-5.64	0.000	-2.597218	-1.257937
BigS T1	-1.258324	.3517057	-3.58	0.000	-1.947655	-.5689941
Warning Car	-1.205231	.2912159	-4.14	0.000	-1.776004	-.6344583
Warning T+1	-1.999661	.3473489	-5.76	0.000	-2.680453	-1.31887
Warning T1	-1.330481	.3250662	-4.09	0.000	-1.967599	-.6933633
Before T+1	-1.368415	.3658798	-3.74	0.000	-2.085526	-.6513039
Const	3.888413	.2381016	16.33	0.000	3.421743	4.355084

Log likelihood = -1579.7076
Number of obs = 6467
LR chi2(16) = 91.64
Prob > chi2 = 0.0000

Right Lane Regression Model at Location 1

SPEEDRED	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
Small Car	-11.54809	.7454372	-15.49	0.000	-13.0094	-10.08679
Small T1+	-14.4203	.996927	-14.46	0.000	-16.37461	-12.466
Small T1	-7.685086	.8554727	-8.98	0.000	-9.362097	-6.008076
Big Car	-11.7634	.7899917	-14.89	0.000	-13.31205	-10.21476
Big T1+	-17.23484	1.134715	-15.19	0.000	-19.45926	-15.01042
Big T1	-8.46649	.9576978	-8.84	0.000	-10.3439	-6.589084
BigF Car	-9.079383	.8153221	-11.14	0.000	-10.67768	-7.481081
BigF T1+	-14.56958	1.273662	-11.44	0.000	-17.06638	-12.07279
BigF T1	-7.473157	1.042806	-7.17	0.000	-9.517403	-5.428911
BigS Car	-7.763106	.7998955	-9.71	0.000	-9.331166	-6.195045
BigS T1+	-14.24879	1.119622	-12.73	0.000	-16.44362	-12.05396
BigS T1	-6.765218	.9784345	-6.91	0.000	-8.683274	-4.847161
Warning Car	-11.06096	.794895	-13.91	0.000	-12.61922	-9.502704
Warning T+1	-15.94696	1.165204	-13.69	0.000	-18.23115	-13.66278
Warning T1	-7.769419	.9146868	-8.49	0.000	-9.562509	-5.97633
Before Car	-4.287821	.7969979	-5.38	0.000	-5.850201	-2.72544
Before T+1	-11.34827	1.049651	-10.81	0.000	-13.40593	-9.290603
Const	25.09295	.6436339	38.99	0.000	23.83121	26.35468

Number of obs = 6467
F(17, 6449) = 39.19
Prob > F = 0.0000
R-squared = 0.0936
Adj R-squared = 0.0912

3.3.3 Benefit and Cost Analysis

The objective of the benefit and cost analysis was to determine the characteristics of work zones that can receive benefits from using the speeding monitoring display on principal arterials like the one on Cr-215. Thus, the benefit and cost were calculated for individual work zone projects.

The benefit from the reduction of accidents was estimated based on costs that would be saved for these accidents not happening. According to Stuster et al. (1998), "…a 1 km/h change in speed can expect to result in a 3% change in the number of crashes." Thus, if the total change in speed is expressed as Δ_v (mph), the change in the number of crashes can be estimated as:

$$\Delta_{crash} = \frac{\Delta_v}{0.6213} \times 0.03 \times N_{crash} \tag{3.11}$$

where N_{crash} denotes the total number of crashes estimated to happen in work zone area. In this study, Δ_v was the speed reduction caused by using speed trailers tested in work zones. In addition, only two categories of crashes were considered: fatal and non-fatal. If needed, more categories of crashes can be adopted. With the total number of crashes estimated for these two categories of crashes, the number of crashes that can be avoided due to the speed reduction can be calculated using the equation:

$$\Delta_{fatal} = \frac{\Delta_v}{0.6213} 0.03 \times N_{fatal} \tag{3.12}$$

$$\Delta_{non-fatal} = \frac{\Delta_v}{0.6213} 0.03 \times N_{non-fatal} \tag{3.13}$$

Since crash rate is known (at least on a national level) for different categories of crashes, the total number of crashes in these categories can be derived for a road segment in a work zone as:

$$N_{fatal} = r_{fatal} VMT \tag{3.14}$$

$$N_{non-fatal} = r_{non-fatal} VMT \tag{3.15}$$

$$N_{crash} = N_{fatal} + N_{non-fatal} \tag{3.16}$$

where r_{fatal} and r_{fatal} are crash rates for fatal and non-fatal crashes, respectively; r_{fatal} and $r_{non-fatal}$ denotes the crash rates for these two categories of crashes, and VMT represents the vehicle miles traveled by the vehicles through the work zone. From Sinha and Labi (2007), it was found that the fatality and non-fatality rates for a principal arterial are 1.3 and 124.69 per 100 million *VMT*, respectively.

For a work zone with traffic volume of AADT, the *VMT* can be estimated as:

$$VMT = AADT \times L \times D \tag{3.17}$$

where L denotes the distance over which vehicles keep their reduced speeds. Here L may not be the length of the entire work zone since vehicles may pick up their speed later after they pass a speed trailer. In this study, the result indicated that the vehicles reduced their speeds when they passed the speed trailer and kept the reduced speed traveling through the entire work zone. Thus, the length of work zone was used in the calculation. The term D represents the duration of a work zone. For this test site on Cr-215, the value of AADT in 2006 was found to be 138,000.

If the unit costs for these two categories of crashes are available, the total cost saving (denoted as B for benefit) due to avoiding the occurrence of these crashes can be estimated as:

$$B = c_{fatal}\Delta_{fatal} + c_{non-fatal}\Delta_{non-fatal} \tag{3.18}$$

where c_{fatal} and $c_{non-fatal}$ represent the unit costs for these two categories of crashes, respectively. From Forrest et al. (2005), it was found that the unit costs for the crashes with severity level of property damage, injury and fatality for 2002 in Nevada were \$3,500 , \$24,700 , and \$2,432,000, respectively. Then, the unit cost for the fatality is \$2,432,000, while that for the non-fatality crashes was derived as the average of the other two unit costs, which gives \$14,100.

The costs for deploying speed trailer in a work zone consist of capital cost (C) for purchasing speed trailers and maintenance (M):

$$T_c = C + M \tag{3.19}$$

The costs that are regularly incurred for a sophisticated speed control system such as planning, design, and operation were not considered in this study because a speed trailer is a relatively simple technology. If more than one speed trailer is used, C is the total cost for purchasing all the speed trailers:

$$C = m \times c \tag{3.20}$$

where m is the number of speed trailers, and c denotes the cost for purchasing one speed trailer. This capital cost can be annualized as:

$$C_a = C \frac{i(1+i)^n}{(1+i)^n - 1} \tag{3.21}$$

where i represents the interest rate and n is the life cycle of speed trailer. In the calculation in this study, the interest rate was assumed to be 8%, a number popularly used in previous studies (Falcocchio et al. 2000). The life cycle of a speed trailer was assumed to be 10 years. This percentage can be varied for different technologies. Because the duration of a work zone may be shorter than a year, the annualized capital cost was converted to a daily based value:

$$C_d = C_a / 365 \tag{3.22}$$

Then, the capital cost for a work zone project shorter than a year can be derived as:

$$C_p = C_d \times D \tag{3.23}$$

Maintenance cost M is estimated as 50% of the capital cost:

$$M = 0.5 \times c \text{ or} \tag{3.24}$$

$$M_d = 0.5 \times C_d \tag{3.25}$$

each of which is for the total maintenance cost for the entire life duration of speed trailer or the daily based maintenance cost, respectively. The maintenance cost for a work zone project can then be written as:

$$M_p = M_a \times D \tag{3.26}$$

The total cost for a project can be calculated as:

$$T_p = C_p + M_p \tag{3.27}$$

Given the benefit (B) and cost (T_p) estimated above, the benefit and cost ratio can be derived as B/T_p. Since both the benefit and cost have an element of duration, the impact of this element on the benefit and cost ratio is canceled. As a result, only one characteristic of a work zone is a variable in this function. Based on this function, the length of a work zone that can make this ratio greater than one can be derived.

Figure 3.11 shows the relationship between the work zone length and the benefit and cost ratio. It can be determined from the figure that a work zone that can make the benefit and cost even must be 0.4 mile (2,112ft).

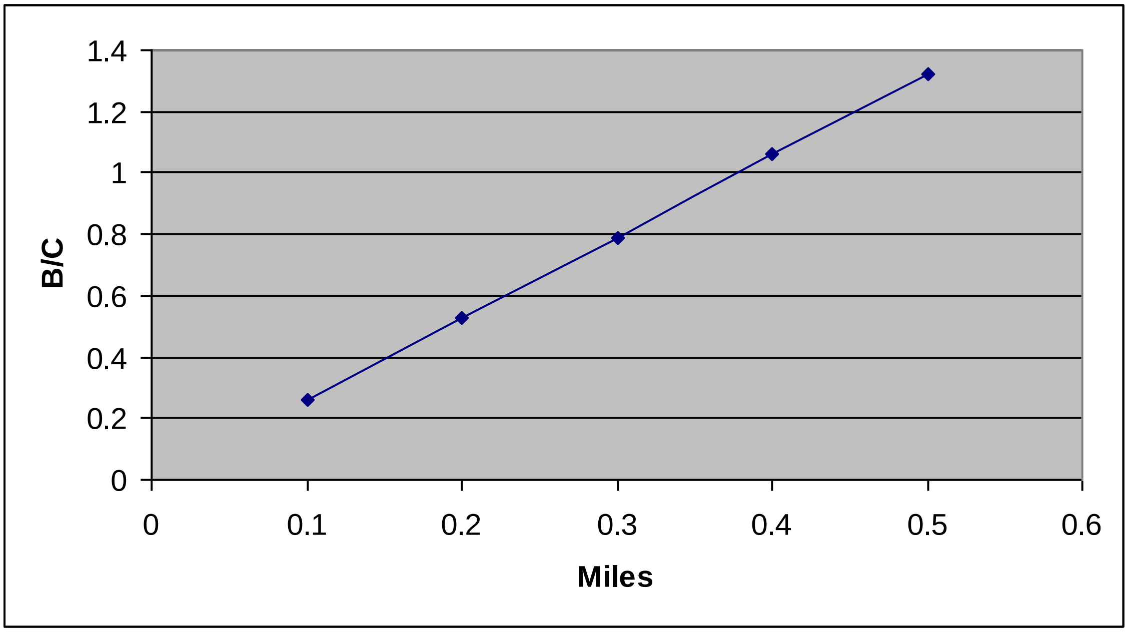


Figure 3.11 Relationship between Benefit and Cost Ratio and Work Zone Length

CHAPTER 4 TESTING SPEED MONITORING DISPLAY ON I-15

4.1 Testing Plan

There were five scenarios tested on I-15 for the speed monitoring display, which are shown in Table 4.1.

Table 4.1 Test Scenarios and Days with Valid Data for Analysis

Scenario	Location 1 (at LP22)	Location 2 (at LP 2)	Days Data Available	Lane
1	Small Sign, No Flashing	No Speed Monitoring Display	02-02-07, 02-06-07	4
2	Big Sign, No Flashing	No Speed Monitoring Display	12-26-06, 12-28-06, 12-29-06, 01-02-07, 01-03-07, 01-05-07, 01-08-07	3
3	Big Sign, Fast Flashing	No Speed Monitoring Display	01-11-07, 01-12-07, 01-16-07	3
4	Big sign, Slow Flashing	No Speed Monitoring Display	01-18-07, 01-19-07, 01-26-07	3
5	Big Sign, No Flashing	Small/big sign, No Flashing	02-07-07, 02-08-07, 02-09-07	4

The warning sign tested on Cr-215 was not included on I-15 since the schedule was very tight compared to that on Cr-215. In addition, the small sign tested on I-15 was different from that on Cr-215. On Cr-215, the small sign was borrowed from the City of Las Vegas, while I-15 used the one on the speed trailer purchased for this study.

The test site chosen was on Northbound I-15 between Tropicana Avenue and Flamingo Road. The work zone was a road widening project in which construction in the median was to add one traveling lane in each direction. When the test was conducted at the beginning, in late December 2006, there were three lanes open at the test site. During early March 2007, when the small sign and the two speed trailers scenarios (Scenarios 1 and 5 in Table 4.1) were tested, the construction work in the median was completed and the closed lane in the median was open. As a result, the road geometrics at the test site were changed from three lanes to four lanes open to traffic during the rest of the test period.

In the field test, the speed trailers were set up on the median shoulder, not the preferred right hand side, because there was no space on the right hand side shoulder for a speed trailer. This was different from the test on Cr-215 where the speed trailers were set up on the right hand shoulder. This location may influence the effectiveness of the speed trailer because motorists anticipate roadway information more on the right hand side than the other side. Instead of stationing the speed trailer behind the concrete barriers during the whole months of the test on Cr-215, the speed trailers on I-15 were set up once the tests were conducted for about two hours for each test. When testing was not being performed, the speed trailers were stored behind the concrete barrier in the median. This storage place was very close to their test set up location. They were towed to the test location and set up each time testing was conducted. This set-up process took ten to thirty minutes to complete, depending on whether speed sign adjustments were needed.

Instead of using the intrusive detector Nu-Metrics on Cr-215, a non-intrusive, vision detection technology was used to collect performance measures to evaluate the speed monitoring display. Cameras were mounted on light poles up and downstream of the test speed trailer. Videos of traffic operating through the test site were recorded during a test. They were processed in-house to obtain traffic data for evaluation. By using this non-intrusive technology, traffic was not disrupted when the cameras were mounted. Four cameras were mounted (see Figure 4.1), the first on light pole #18, labeled LP18 in the figure, far upstream of the speed trailer. This camera captured traffic conditions before drivers actually saw the speed trailer. The speed trailer and this camera were far enough apart that motorists couldn’t see the trailer. The second camera was mounted on light pole #22, labeled LP22 in the figure. It covered 200-300 ft before the speed trailer. The radar gun on the speed trailer can measure speeds for vehicles operating 500 feet from the speed trailer. This camera was planned to capture motorists’ response, allowing for perception-reaction time, after seeing the speed trailer. The third camera was set up on light pole #23, labeled LP23, and covered motorists immediately passing the speed trailer. Both the second and third cameras were intended to capture the whole response process immediately after they saw the test speed trailer. The fourth camera was mounted about 1,500 feet downstream from the speed trailer. At this site, traffic conditions after motorists have seen the speed trailer for a significant distance can be recorded.

Mounting in the field, shown in Figure 4.2, was a camera attached to a plastic pole which was then bonded to the light pole. A power cord and a communication wire line were connected to the camera at the top and ran down to connect to a digital video recorder (DVR) and a pair of batteries wired in parallel on the ground. Heights of the cameras to the ground were measured while mounting and recorded to calibrate the video processor. An NDOT District 1 maintenance crew helped mount and dismount the cameras for the entire study. During the tests, the angles of the cameras were changed several times when strong winds affected the view of the desired area on the ground. In this case, the NDOT maintenance crew was summoned for quick fixes. A student with an electronic engineering background went up to the top of the pole with a maintenance worker in a cabin of a crane truck to mount the camera. The student used a cell phone to communicate with researchers on the ground to set appropriate camera angles.

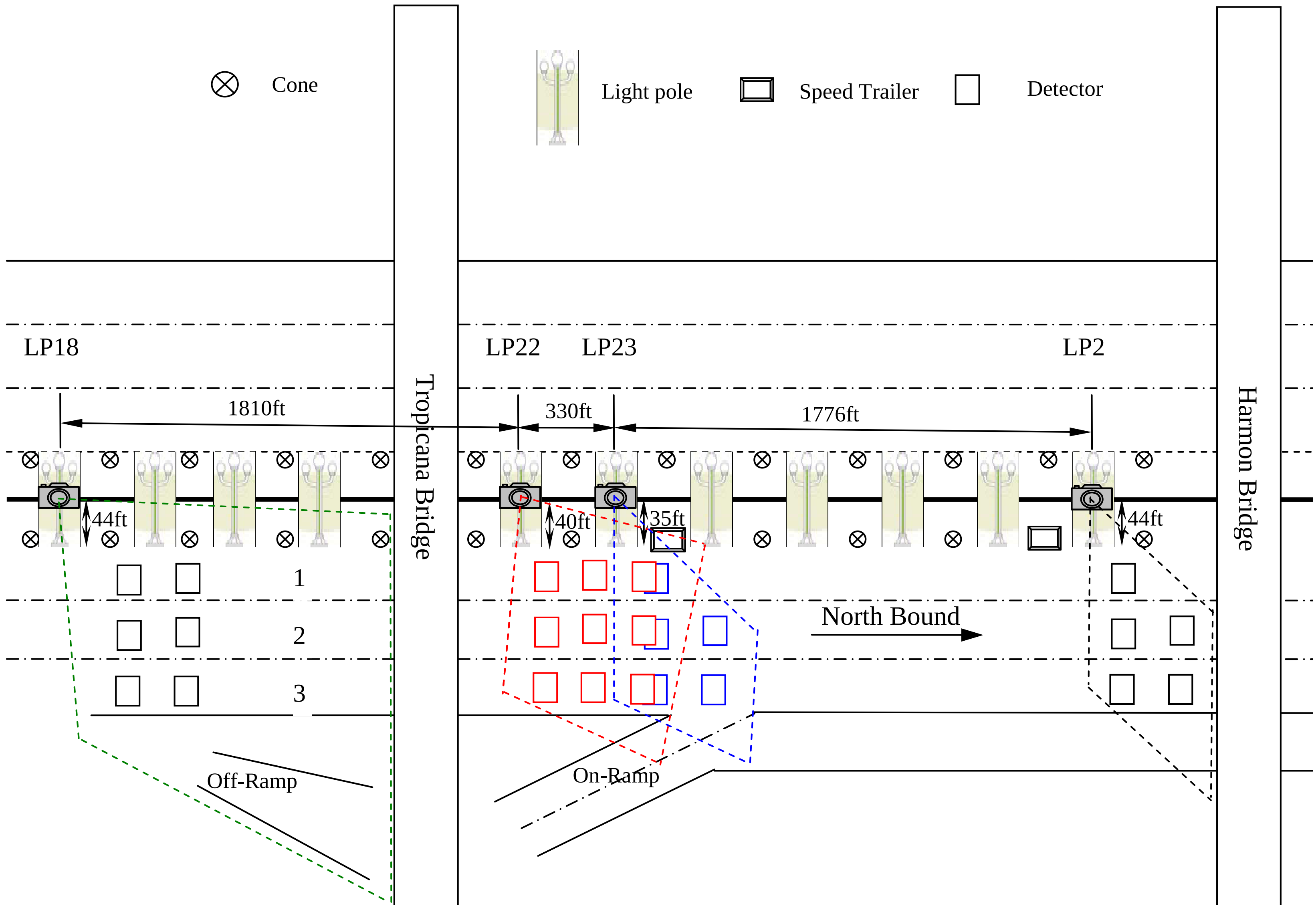


Figure 4.1 Camera Layout on the Test Site

Figure 4.2 Camera Mounted on Light Pole 23 on I-15

4.2 Field Test

With the cameras mounted on the four light poles and the speed trailers stationed at specific places in the work zone, tests were conducted for the four scenarios one after another. Table 4.1 lists the days the test was performed. For each test, a UNLV TRC van was used to carry the needed equipment, devices and tools to the site. At least two people had to be present because the batteries were very heavy to lift over the concrete barriers to connect to the power cord. Usually, the first camera was connected first, followed by the other three in sequence. After connecting the cameras, the speed trailer was moved from the storage area to the testing location. The work zone area in the median, where the speed trailer was stationed, was wide enough to allow the van to turn around and tow the trailer to the test location. When the tests for the two speed trailers scenario were performed, another speed trailer borrowed from the City of Las Vegas was towed directly from the UNLV campus to the testing site. In this case, at least three people were needed on site.

Although the field tests were performed for several months, there were many days of data that could not be used. The geometrics (especially lane closures) of the roadway where the test equipment (particularly the cameras) was deployed, changed in unpredictable ways. One major reason was the research team's lack of advance notice of the work zone's traffic control plan for any particular day. Those changes in the roadway geometrics was not ideal for the study on some days, thus, those days of data had to be excluded from the analysis.

4.3 Data Processing

The videos recorded during the tests were processed using Autoscope, a video image-processing product. The videos recorded on the digital video recorders had to be downloaded into video image files in a computer so Autoscope could derive the traffic operational data (i.e., speed and flow rate.) This downloading process was performed in real-time, which means that the downloading was operating only when the videos were played. This requires the same amount of time to download the data as the time used to record the video. Another issue was a limitation of the image software, videos recorded over about three hours each day had to be broken into pieces only as long as 15 minutes. A large amount of storage space was also needed for the downloaded video streams. To make space available on a PC, these downloaded video streams were copied to DVDs. This video file manipulation process was very time consuming.

Another major task was to calibrate the Autoscope so the derived traffic data was accurate. Figure 4.3 shows a digital image and the calibration dialogue box used in the calibration. More about using Autoscope to derive traffic data is presented in Appendix A. In a standard procedure, calibrating the Autoscope requires the determination of real-world distances between each of the calibration lines positioned on an image. The two major inputs are the height a camera was mounted and the crosslane (lane width) distance. They were measured in the field and recorded for this study. Three types of detectors can be created using Autoscope: presence, speed, and count. Figure 4.4 shows the presence detector (the solid line along pavement markers), and Figure 4.5 presents the speed (the loops) and count detectors (the bars across the road). As shown in Figure 4.6, these detectors can be connected to perform detection of vehicles based on conditions specified by users through using logic functions. The calibration was to compare the traffic data (e.g., speed) measured from Autoscope and the actual data. In this study, two approaches were taken for the calibration. One was to compare the speeds from Autoscope and those from a radar gun installed in the speed trailer. The radar gun's measured speeds and the speed trailer's display were also recorded and stored in the speed trailer. Since the recorded speed data were for vehicles on any of traveling lanes in the range of the radar gun, and no identifiers exist in the stored data indicating the lane in which a vehicle's speed was measured, these speed data only provide a rough profile of speeds for the vehicles traveled at the location 500 feet upstream of the speed trailer (the range of radar gun). The second calibration approach was to compare speeds for identified vehicles. In this approach, a separate trip was taken to a site close to the place where the first camera was mounted. Two radar guns from the Transportation Research Center of UNLV were used to measure selected vehicles. These selected vehicles had outstanding features (primarily trucks) that could be easily identified visually from the videos taken by the first camera. Three researchers were stationed in a van. Two operated the radar guns and read the speeds measured, while the third one wrote down the speeds as they were announced. At the same time speeds were measured using radar guns, videos of the traffic were taken. Back in-house, the recorded videos were replayed to identify the vehicles corresponding to the radar gun speeds. The speeds were read for the identified vehicles displayed on the screen in Autoscope. The speeds measured these two different ways were compared. It was concluded that they were very close, and good enough to provide traffic data with satisfactory accuracy.

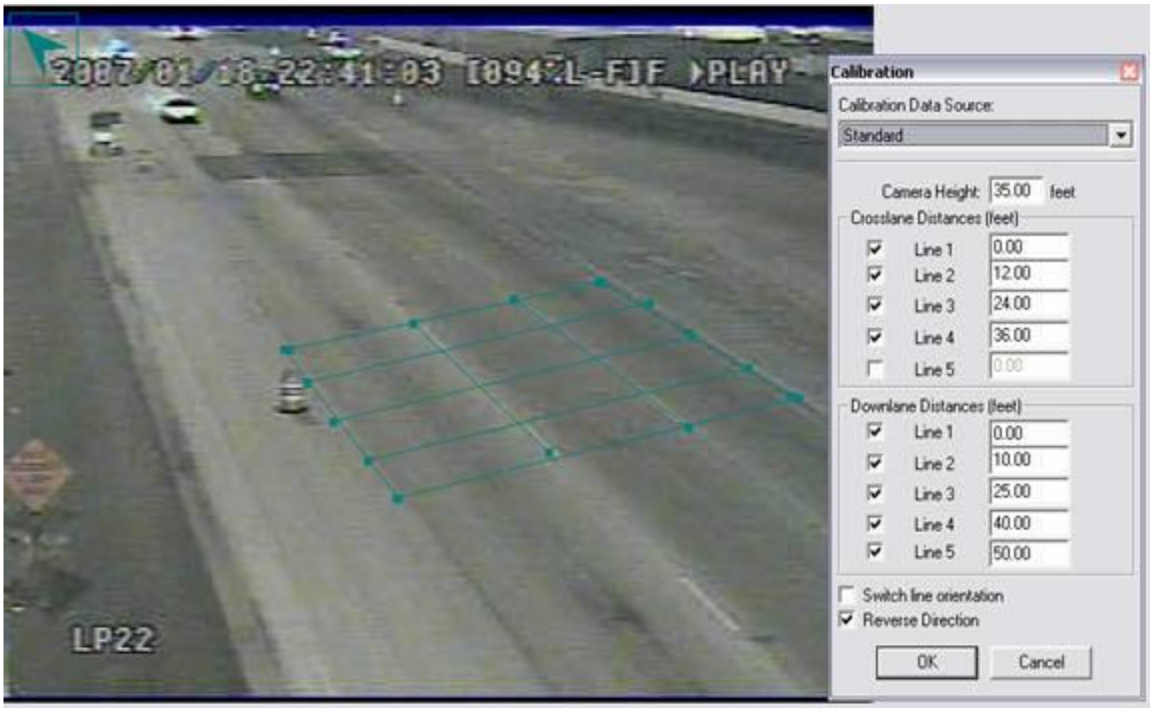


Figure 4.3 Calibration of Autoscope

Figure 4.4 Presence Detectors

Figure 4.5 Speed Detector

Figure 4.6 Boolean Detector Function

While calibrating the Autoscope, the accuracy of the traffic data was found to suffer from three technical problems. First, vehicle headlights were very bright at night and could trigger the vehicle detection when vehicles were not actually yet within an Autoscope speed loop (see Figure 4.7). Two vehicles operating very close with bright headlights could be detected as one single vehicle such as a truck. Second, trucks with trailers tended to be detected as separate small vehicles. Third, trucks on one lane blocked the view of vehicles on the other lane (see Figure 4.8). This is a typical occlusion problem in vision detection. To solve the headlight problem, different contrast ratios in Autoscope were tried. The one with the best results, i.e., Contrast Level 4, was chosen in this study. To mitigate the second problem, a computer program was written to correct the ‘truck’ vehicle classification for vehicles operating on an adjacent lane.

Four metrics were used to address these three problems:

1. Actual Vehicles: number of vehicles that passed a location, seen from the videos.
2. Correct Detection: number of vehicles detected correctly
3. Missed Detection: number of vehicles undetected
4. False Detection: number of vehicles counted even when no vehicles were present on the video. This could be due to the following circumstances: vehicle head lights in the same lane, head lights of vehicles in other lanes, occlusion, etc.

The relationships between these metrics are:

1. Actual Vehicles = Correct Detection + Missed Detection
2. Detected Vehicles = Actual Vehicles + False detection

The results of vehicle detection when Contrast = 0 and Contrast = +4 are shown in Tables 4.2 and 4.3, respectively. It can be seen from the tables that false detections are suppressed considerably when contrast = +4.

After calibration, the videos were processed using Autoscope. Figure 4.9 presents an example of the traffic speed data over the space covered by the four videos. Even with the great effort spent calibrating Autoscope, the quality of the traffic data was still questionable, particularly for vehicles on right side lanes.

Figure 4.7 Headlight Problem

Figure 4.8 Truck Double Counting

Table 4.2 Large Truck (>39ft) Counts for Video from Camera on Light Pole #22, Contrast +0 in Video Processing

	Lane 1		Lane 2		Lane 3	
Actual Vehicles	0	Container	1	Container	0	Container
	1	Truck with empty carriage	2	Truck with empty carriage	1	Truck with empty carriage
	5	Truck with one trailer	22	Truck with one trailer	12	Truck with one trailer
	0	Truck with two trailers	2	Truck with two trailers	2	Truck with two trailers
Total	**6**		**27**		**15**	
Correct Detection	0	Container	1	Container	0	Container
	0	Truck with empty carriage	1	Truck with empty carriage	0	Truck with empty carriage
	3	Truck with one trailer	17	Truck with one trailer	12	Truck with one trailer
	0	Truck with two trailers	2	Truck with two trailers	2	Truck with two trailers
Sub-total	**3**		**21**		**14**	
Missed Detection	0	Container	0	Container	0	Container
	1	Truck with empty carriage	1	Truck with empty carriage	1	Truck with empty carriage
	2	Truck with one trailer	5	Truck with one trailer	0	Truck with one trailer
	0	Truck with two trailers	0	Truck with two trailers	0	Truck with two trailers
Sub-total	**3**		**6**		**1**	
False Detection	1	Same lane by light	2	Same lane by light	0	Same lane by light
	1	Car in central lane	5	Car in central lane	0	Car in central lane
	1	Unknown	1	Unknown	0	Unknown
Sub-total	**3**		**8**		**0**	

Note: Video data was collected from 22:40 pm to 23:00 pm in January 15, 2007

Table 4.3 Big-Size Truck (>39ft) Counts for Video from Camera on Light Pole #22, Contrast +4 in Video Processing

	Lane 1		Lane 2		Lane 3	
Actual Vehicles	0	Container	1	Container	0	Container
	1	Truck with empty carriage	2	Truck with empty carriage	1	Truck with empty carriage
	5	Truck with one Trailer	22	Truck with one Trailer	12	Truck with one Trailer
	0	Truck with two trailers	2	Truck with two trailers	2	Truck with two trailers
Total	**6**		**27**		**15**	
Correct Detection	0	Container	1	Container	0	Container
	0	Truck with empty carriage	1	Truck with empty carriage	0	Truck with empty carriage
	3	Truck with one Trailer	15	Truck with one Trailer	12	Truck with one Trailer
	0	Truck with two trailers	2	Truck with two trailers	2	Truck with two trailers
Sub-total	**3**		**19**		**14**	
Missed Detection	0	Container	0	Container	0	Container
	1	Truck with empty carriage	1	Truck with empty carriage	1	Truck with empty carriage
	2	Truck with one Trailer	7	Truck with one Trailer	0	Truck with one Trailer
	0	Truck with two trailers	0	Truck with two trailers	0	Truck with two trailers
Sub-total	**3**		**8**		**1**	
False Detections	1	Same lane by light	0	Same lane by light	0	Same lane by light
	1	Car in central lane	1	Car in central lane	0	Car in central lane
	0	Unknown	1	Unknown	0	Unknown
Sub-total	**2**		**2**		**0**	

Note: Video data was collected from 22:40 pm to 23:00 pm in January 15, 2007

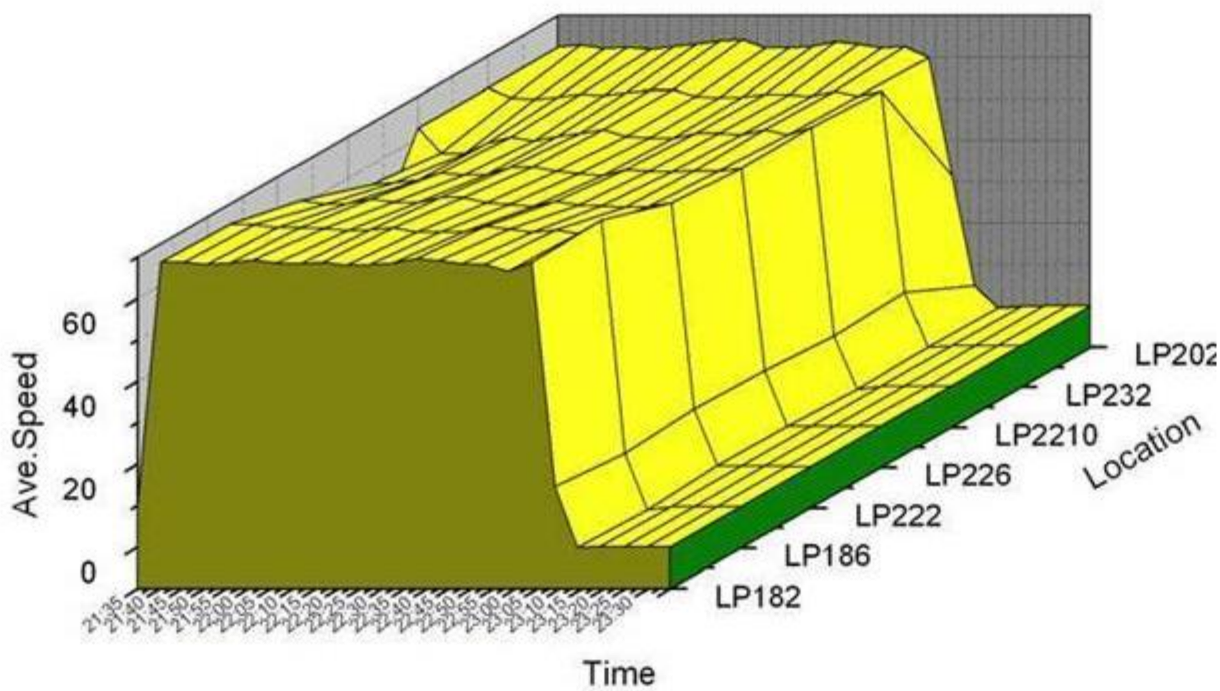


Figure 4.9 An Example of Speed Data for Traffic in the Second Lane over Several Data Collection Locations on February 11, 2007

4.4. Data Analysis for the Test on I-15

4.4.1 Profile of Speed Reduction

In the analysis, the small sign with no flashing scenario was not considered because there were four lanes open to the traffic when this scenario was tested. When testing the other three scenarios on the big sign, only three lanes were available. It appears that the one lane difference in geometric condition made the speed profile over space dramatically different. Therefore, this scenario was not included in the analysis. As a result, only the features for the big sign (no flashing, flashing with different flashing rates) were evaluated together.

Table 4.4 shows the average speeds of the vehicles at the left most lane (Lane #1), closest to the speed trailers tested in this study. The speeds were calculated by including all the vehicles, regardless of whether they were operating in the free flow or bunching conditions. From this table it can be seen that all the tested scenarios brought down speeds at the location where a speed trailer was deployed. The amount of speed reduced ranged from 8 mph to 16 mph. At the second location downstream about 2,000 feet after the first speed trailer, the speeds can either go up like the flashing big sign an non-flashing small sign scenarios or continued to go down like the non-flashing big sign scenario. In most of the cases, the speeds either stayed the same or continued to slow down. Although the geometric conditions for testing the small sign were changed from three lanes open to four lanes open to traffic, the speed reduction at the first location was significantly more than those in other scenarios.

Table 4.4 Speeds With Both Free Flow and Bunching Vehicles

	Upstream Speed Trailer	**1st Location After Speed Trailer**		**2nd Location After Speed Trailer**	
Big Sign with no Flashing	61.04	Mean: 52.18		61.80	
		Diff: 8.856		-0.76	
		>		<	
Big Sign with Fast Flashing	63.50	51.98		54.54	
		11.51		8.95	
		>		>	
Big Sign with Slow Flashing	65.78	55.78		56.75	
		10.00		9.03	
		>		>	
Small Sign with no Flashing	63.68	46.73		45.75	
		16.95		17.92	
		>		>	

Note that “>” and “<” indicates that the speed at the upstream location is bigger or smaller than those at the first or second locations downstream the speed trailer, respectively.

4.4.2 Analysis for Vehicles in Free Flow Condition

Following the same procedure used for Cr-215 to determine whether a vehicle is in free flow condition, each vehicle operating through the test site was identified whether they were in free flow condition or bunching condition. The parameters for the headway probability density distributions were estimated and presented in Table 4.5.

Table 4.5 Parameters Estimated for Probability Density Functions of the Headways in Free Flow and Bunching Conditions

Left	FF*	Exponential: λ =0.12446	h*** = 0.037
	Bunching**	Lognormal: σ =0.50115, μ =0.53435	
Middle	FF	Exponential: λ =0.14037	h = 0.016
	Bunching	Lognormal: σ =0.51208, μ =0.65866	
Right	FF	Exponential: λ =0.12678	h = 0.018
	Bunching	Lognormal: σ =0.4988, μ =0.67908	

*: FF = free flow condition, **: Bunching = bunching condition, ***: h = threshold for the decision function in the CUSUM algorithm

Table 4.6, in conjunction with Figure 4.10, displays the speeds of the vehicles that were operating in free flow conditions in all the lanes. Figure 4.10 displays the speeds of the vehicles that were operating in free flow conditions in all the three lanes. From the chart at the top of Figure 7 it can be seen that vehicles at the location before the speed trailer (LP18) operated at different speeds under different scenarios. They all dropped their speeds at the location immediately after the speed trailer (LP22). Under some scenarios including the one with a speed trailer deployed at the second location, they picked up their speeds later (LP2). Note that there was no valid data for the two speed trailer scenario in the left most lane. This pattern of speed reduction in the left most lane can also be found in the middle and right lanes.

It is important to observe that the speed trailers set up at the second location did not demonstrate a positive impact on the vehicles. The speeds in the middle and right lanes actually went up even when there were one or two speed trailers. Note that the average speeds at these two lanes at the first location had been far lower than the speed limit (55 mph.) The speed trailer at the second location may not be effective anymore.

Table 4.5 Operating Speeds Considering Only the Speeding Vehicles

		Left			Middle			Right		
		Upstream Speed Trailer	1st Location After Speed Trailer	2nd Location After Speed Trailer	Upstream Speed Trailer	1st Location After Speed Trailer	2nd Location After Speed Trailer	Upstream Speed Trailer	1st Location After Speed Trailer	2nd Location After Speed Trailer
Big	Mean	61.23439	53.574572	61.7693	61.7823	51.904967	56.9317	59.495338	51.57055	55.1381
	Diff		7.6598179	-0.5349		9.8773296	4.85058		7.924784	4.35725
BigF	Mean	63.30523	54.942584	57.2566	65.83582	59.391042	56.3157	62.660163	53.70329	54.207
	Diff		8.3626468	6.04865		6.4447831	9.52014		8.95687	8.45319
BigS	Mean	66.34527	57.83211	58.9359	69.72751	62.26062	56.8986	61.311379	57.79028	55.0812
	Diff		8.5131596	7.40935		7.4668933	12.8289		3.521103	6.23019
Small	Mean	63.38744	48.894072	44.4669	67.86836	51.207775	61.1297	61.52003	48.91618	56.9093
	Diff		14.493369	18.9205		16.660582	6.73866		12.60385	4.61074
Two Trailers	Mean	70.324	54.966887	N/A	70.54637	51.835052	62.1437	67.312398	46.48128	57.0594
	Diff		15.357113	N/A		18.711323	8.40265		20.83111	10.253

The difference, denoted as “diff”, was derived by subtracting the speed at the first or second location downstream from the upstream speed trailer.

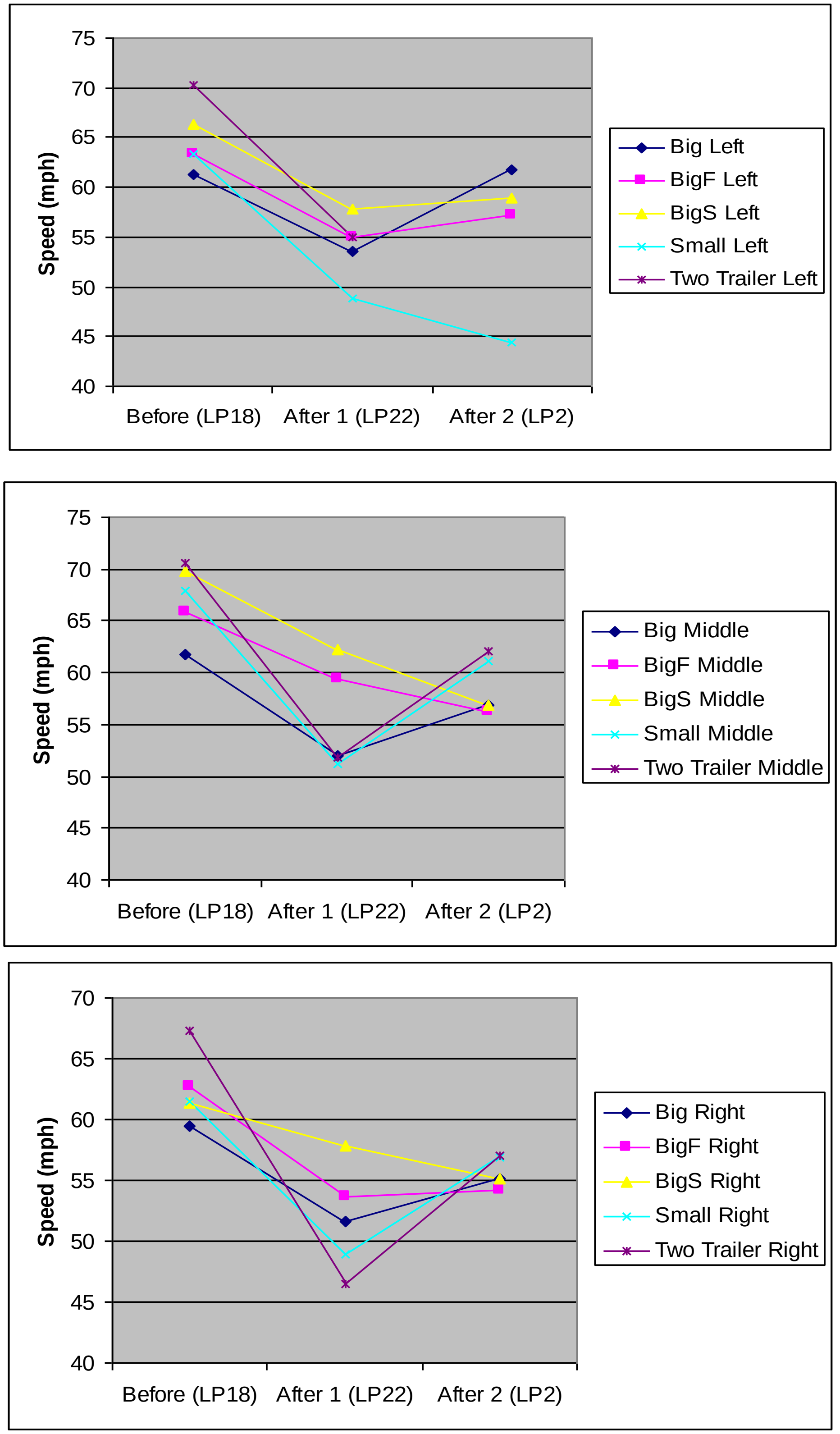


Figure 4.10 Speed Patterns at Three Locations for Five Scenarios Tested

Vehicle Speeding Likelihood Model for the I-15 Site

In the analysis using regression models, three scenarios were considered: (1) Big sign (Big), (2) Big sign with fast flashing rate (BigF), and (3) Big sign with slow flashing rate (BigS). The non-flashing small sign and the two speed trailer scenarios were not included in the modeling because the geometric conditions of the work zone were changed when it was tested. Two vehicle types were included: (1) Passenger vehicle and (2) Truck. Trucks were not further classified into single-unit and multi-unit trucks as the analysis done for Cr-215 because these classifications of trucks, derived from the videos using Autoscope, were not reliable.

In the development of the vehicle speeding likelihood model, the dependent variable is defined as the speed reduction ratio:

$$\frac{\overline{u_j} - u_i}{\overline{u_j}} = r_i \tag{4.1}$$

where $\bar{u}_j$ denotes the average speed at the before location for test scenario j, and u_i represents speed for vehicle i. By using the ratio as shown in the equation, different average speeds for the before conditions of different scenarios can be taken into account. In the analysis for Cr-215, the location from which the speed data were collected for the before condition was the same as that where the speed data for each scenario were collected. There was only one set of data for the before condition that other scenarios can all be compared with. For I-15, there was one before condition for each test and scenario because the location from which the speed data was collected was upstream of the tested speed trailers and was not the same as the place where the speed data were collected downstream from the speed trailers. Since speeds were reduced in all the tested scenarios, the values of the speed reduction ratio are always positive.

The results from the modeling are listed in Table 4.7. In the modeling, the scenario of trucks under the non-flashing big sign was used as the base. It can be seen from the table that the three coefficients for passenger vehicles, each for a different scenario, are positive, which means that the speeding likelihood for passenger vehicles is greater than for trucks going past the big non-flashing sign. This observation is consistent with our intuitive because passenger vehicles usually operate faster than trucks. Among these three coefficients, that for the big non-flashing sign has the smallest value, which indicates that the big non-flashing sign performed better than flashing signs in lowering speeding likelihood. For the trucks operating through these three scenarios, the coefficient for the big non-flashing sign is the smallest (i.e., zero). It indicates that the non-flashing sign performed the best in reducing the speeding likelihood for trucks as well. In a word, the flashing big signs were not effective reducing the likelihood of speeding across all vehicle types.

Vehicle Speed Model for the I-15 Tests

Like the modeling for speeding, the scenario of trucks under the non-flashing big sign was used as the base. The constant in Table 4.7 represents the average speed reduction ratio for this scenario. It is positive and thus indicates that it reduced the truck speeds. This constant is also bigger than the absolute value of any other coefficients, implying that these scenarios all brought down vehicle speeds. The slow-flashing big sign scenario for passenger vehicles has a smaller coefficient than other scenarios, suggesting that the slow-flashing big sign reduced more speed than the fast-flashing big sign or the non-flashing sign. For trucks, the big sign with no flashing had more speed reduction than the other two speed signs with flashing.

Based on the interpretation of the above results on speeding likelihood and speed reduction, the non-flashing big sign can be more effective in bringing down speeding likelihood, but may not reduce actual speeds. The speed signs with slow flashing can reduce speed for passenger vehicles more than the non-flashing sign.

Table 4.7 Modeling Results for Left Most Lane

Logit estimates

BINARY	Coef.	Std. Err.	z	P>|z|	[95% Conf.	Interval]
Big Car	.386414	.0624514	6.19	0.000	.2640115	.5088165
BigF Car	1.055939	.0777161	13.59	0.000	.9036181	1.20826
BigF Truck	.2971568	.1029407	2.89	0.004	.0953967	.4989168
BigS Car	2.079414	.1244133	16.71	0.000	1.835569	2.32326
BigS Truck	1.958828	.1565719	12.51	0.000	1.651953	2.265704
Const	.2276551	.0558943	4.07	0.000	.1181043	.3372059

Number of obs = 11043
LR chi2(5) = 643.30
Prob > chi2 = 0.0000
Log likelihood = -6457.7554
Pseudo R2 = 0.0474

DepVal3	Coef.	Std. Err.	t	P>|t|	[95% Conf.	Interval]
Big Car	-.0264357	.0048488	-5.45	0.000	-.0359402	-.0169312
BigF Car	-.037794	.0056046	-6.74	0.000	-.0487799	-.0268081
BigF Truck	-.0215465	.0079003	-2.73	0.006	-.0370325	-.0060604
BigS Car	-.0112007	.0066603	-1.68	0.093	-.0242561	.0018546
BigS Truck	-.0134985	.0082031	-1.65	0.100	-.029578	.002581
Const	.0843835	.0043732	19.30	0.000	.0758112	.0929558

Number of obs = 11043
F(5, 11037) = 11.12
Prob > F = 0.0000
R-squared = 0.0050
Adj R-squared = 0.0046

4.4.3 Cost and Benefit Analysis

In calculating the benefit and cost ratio for the speed trailer tested on the I-15 site, the following are the differences from Cr-215:

First, different crash rates were used because Cr-215 is a principal arterial, while I-15 is an Interstate highway. For an Interstate highway, the crash rates are 0.56 and 46.56 crashes per 100 MVMT for fatal and non-fatal, respectively.

Second, a different AADT value was used. The AADT on I-15 was 229,000. This difference implies that there could be more benefit for deployment of a speed trailer. The benefit and cost ratio might be higher on I-15 than on Cr-215.

Third, the average speed reduction on I-15 was 8 mph, while on Cr-215 it was 6 mph.

Figure 4.11 shows the relationship between benefit and cost. The work zone where the benefit and cost transition from <1 to >1 occurs, is about 0.4 mile (about 2,112 ft) longer than the length of the 5 mile-long work zone on I-15. Even though more traffic reduced speed, incurring more benefit, crash rates on Interstates are lower than those on Cr-215, reducing the benefit. As a result, the critical work zone length on I-15 is longer than that on Cr-215.

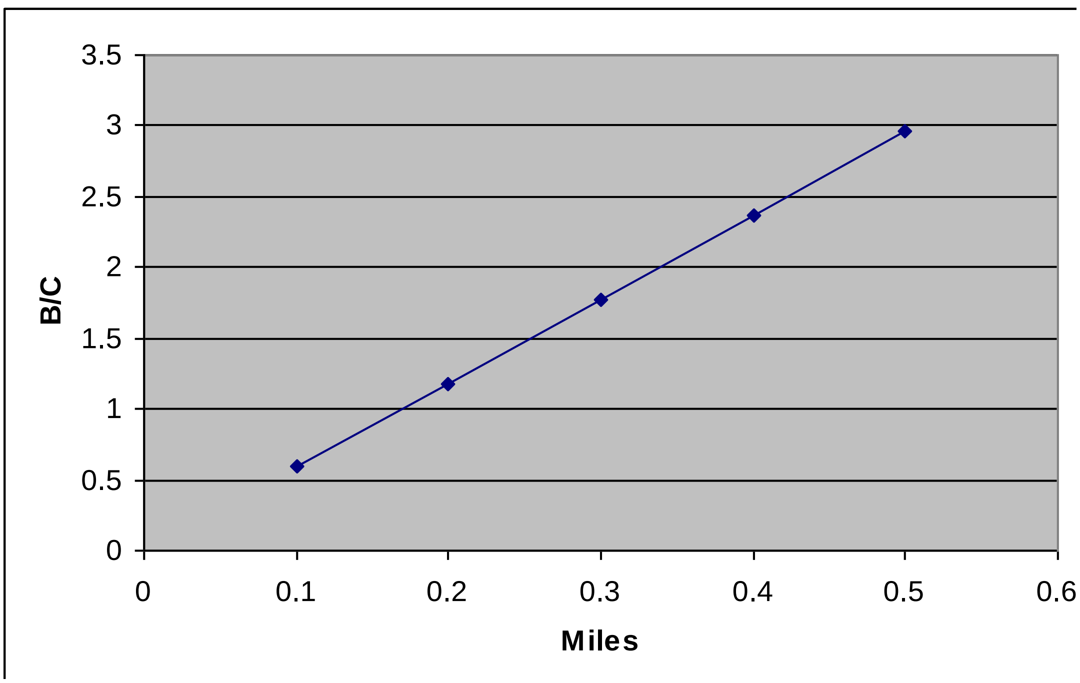


Figure 4.11 Relationship between Work Zone length and Benefit / Cost Ratio for Speed Monitoring Display on I-15

4.5 Findings, Conclusion, Recommendation and Implementation Guidelines

Findings

1. The speed trailers tested in this study, regardless of features such as size, flashing, and message content, all reduced the speed of vehicles operating over the speed limit. On Cr-215, the multi-unit trucks on the left lane did not reduce speed since their speeds were already close to the speed limit. In addition, their sight to the tested speed trailers may have been blocked by vehicles on the right lane.
2. The big sign performed better than the small sign for multi-unit trucks in the right lane on the Cr-215 site. It had the same performance as the small sign for other types of vehicles. Because the test site settings for the small and big signs on I-15 were different, no comparison was made between their performances.
3. The big sign with the lower flashing rate performed better than the big non-flashing sign in the left most lane on I-15 to reduce speed. On the Cr-215 site, the non-flashing and flashing big signs performed equally well in reducing speed. It was noticed that the tests on Cr-215 were all day time, while those on I-15 were during the night. The flashing may be more attractive during night time than day time. During the tests, it was the background of the speed signs that flashed, due to restrictions of the speed trailer purchased for this study. This flashing pattern may not make the flashing stand out as much as the other forms of flashing, such as flashing speeds.
4. The second speed trailers continued reducing speeds of motorist further after the significant reduction at the first location on Cr-215. This effect was not observed on I-15. Apparently, the speeds at the second location on Cr-215 were still far above the speed limit in the work zone and there is still the potential for motorists to reduce speed. On I-15, the speeds at the second locations were already below the speed limit and motorists may not want to reduce their speeds further.
5. The benefit and cost analyses for Cr-215 and I-15 indicate that work zones longer than 2,000 feet can produce more benefit from speed control than the cost for purchasing and operating speed trailers.

Conclusions

1. Speed trailers can significantly reduce operating speeds on freeway and principal arterials.
2. The size and features of the sign did affect the performance of speed trailers. The displays should be enhanced and used in the right place and right time.
3. The additional speed trailer can be very effective in reducing vehicle speeds when speed reduction at the first location is not sufficient.
4. Speed trailer use is very cost effective in reducing speed on both freeway and principal arterials.

Recommendations

1. It is recommended that speed trailers be used in work zones to reduce operating speeds.
2. It is reasonable to require the use of speed trailers in construction contracts.

Implementation Guidelines

Like any traffic signs, visibility could be an issue to speed trailers. When testing on Cr-215, the speed sign was not visible when it was facing south toward the sun during midday. The visibility was improved after it was moved under the overpass bridge.

The flashing was not significantly effective on Cr-215 when the tests were conducted in the day time, but was obviously more effective on I-15 when the test was conducted during the night. This may suggest that flashing be used during the night rather than the day.

Speed trailers can be set up on either the right or left shoulder of a roadway. Vehicles in left lanes tend to travel faster than those in the right lanes; consequently, speed trailers will likely be more effective if they are placed on the left side of multi-lane highways. Since the right side is the location motorists expect road sign messages, a speed trailer can be set up on the right hand shoulder. In this case, the line of sight for the vehicles in the left lanes may be blocked by the vehicles on the right lane, particularly where there are many trucks in the right lane. To correct the problem, a speed trailer can be set up on the left shoulder. On multilane highways, the best solution is to use two speed trailers. When there are more than two lanes in each direction, like the test site on I-15, the visibility issue could be a problem. Overhead locations would be better if there are more than three lanes, or if truck volume is high.

A speed trailer deployed in work zones has to be protected if it is placed on a shoulder. In this study, the speed trailers on Cr-215 were set up behind concrete barrier rail.

Two speed trailers can be used in a work zone about 1,500 feet apart. The vehicle speeds at the upstream speed trailer need to be evaluated. The second speed trailer would be used when there is a potential to reduce speed at the second location.

The sign should be as big as practicable. The higher the roadway speed, the bigger the sign needed. The size of the speed sign tested in this study on I-15 seems small. It should be bigger.

Flashing for night time work is recommended. The flashing feature tested was effective on I-15. On Cr-215, the flashing feature did not produce better performance. One possible reason is the way of flashing measured speeds on speed trailers may influence the sign's ability to attract drivers' attention. It suggests that the flashing should be made as attractive as possible. For example, instead of flashing the background on a speed sign, it may be better to flash the measured speed. The color and brightness of the light can also be changed.

CHAPTER 5 TESTING AUTOMATIC WORK ZONE INFORMATION SYSTEM IN WORK ZONES

5.1 Test Plan

In this study, the following work zones were investigated as candidates for testing the automatic work zone information system.

- I-15 North Bound diverting at Tropicana Avenue to Dean Martin Drive and back at Flamingo Road. (see Figure 5.1)
- I-15 North Bound diverting at Tropicana Avenue. to Frank Sinatra Drive and back at Flamingo Road. (see Figure 5.1)
- Paradise Road between Flamingo Road and Harmon Avenue. (see Figure 5.2)
- Charleston Boulevard between Campbell Drive and Rancho Drive. (see Figure 5.3)
- US93 / I-515 Sound Wall Project from Las Vegas Boulevard to Charleston Boulevard (see Figure 5.4)
- Blue Diamond Road from Lindell Road to Decatur Boulevard (see Figure 5.5)
- I-15 South bound diverting at Blue Diamond Road to Dean Martin Drive, Valley View Boulevard, Southern Highland Parkway, back at St. Rose Parkway.
- Henderson Spaghetti (see Figure 5.6)

To determine whether a work zone is appropriate for the testing, contacts with the contractors, resident engineers, or NDOT professional staffs were made. Field trips were made to each of candidate work zones. Possible layout of the system at each of these work zones was discussed with the responsible persons. For the work zone on I-15, more than one possibility of diverting traffic to local roads was investigated. Travel time data were collected by taking several test drives on the possible detours, which are shown on Figure 5.1. An application for a permit with a detailed traffic control plan was submitted to Clark County, but was declined because it would divert a significant volume of large trucks to local roads.

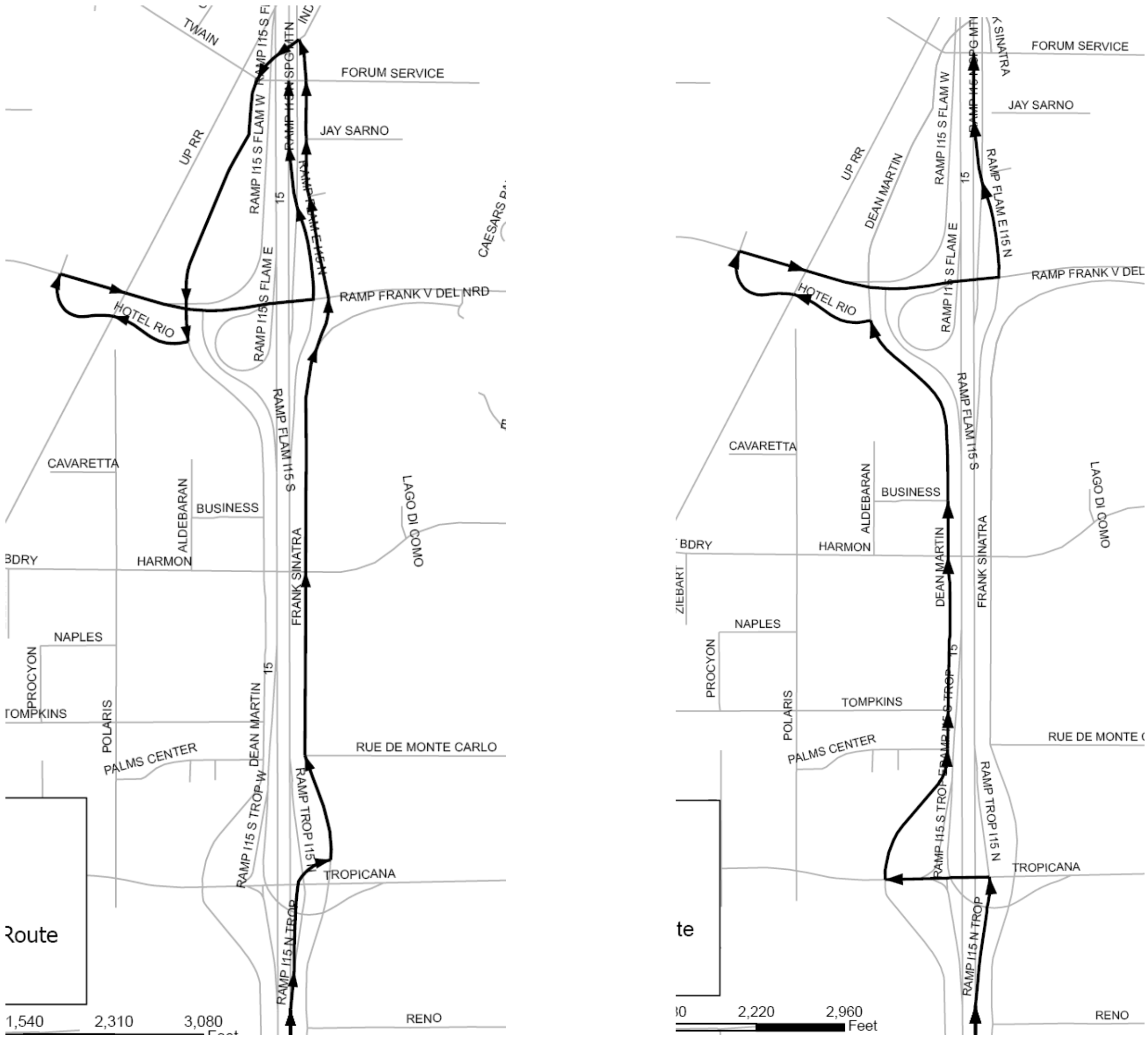


Figure 5.1 (left) I-15 North Bound Diverting at Tropicana Avenue to Frank Sinatra Drive and back at Flamingo Road, (right) I-15 North Bound Diverting at Tropicana Avenue to Dean Martin Drive and back at Flamingo Road

After considering and rejecting five other sites for various reasons, the location on I-515 close to the Henderson Spaghetti was chosen. Figure 5.6 shows this location on a map and the exit in a photograph.

Figure 5.2 Paradise between Flamingo Road and Harmon Avenue (Google Map)

Figure 5.3 Charleston Boulevard between Campbell Drive and Rancho Drive (Google Map)

Figure 5.4 US93/I515 Sound Wall Project from Las Vegas Boulevard to Charleston Boulevard (Google Map)

Figure 5.5 Blue Diamond Road from Lindell Road to Decatur Boulevard (Google Map)

Figure 5.6 Henderson Spaghetti and the Location for the Automatic Work Zone Information System at the Russell Road Exit (Google Map)

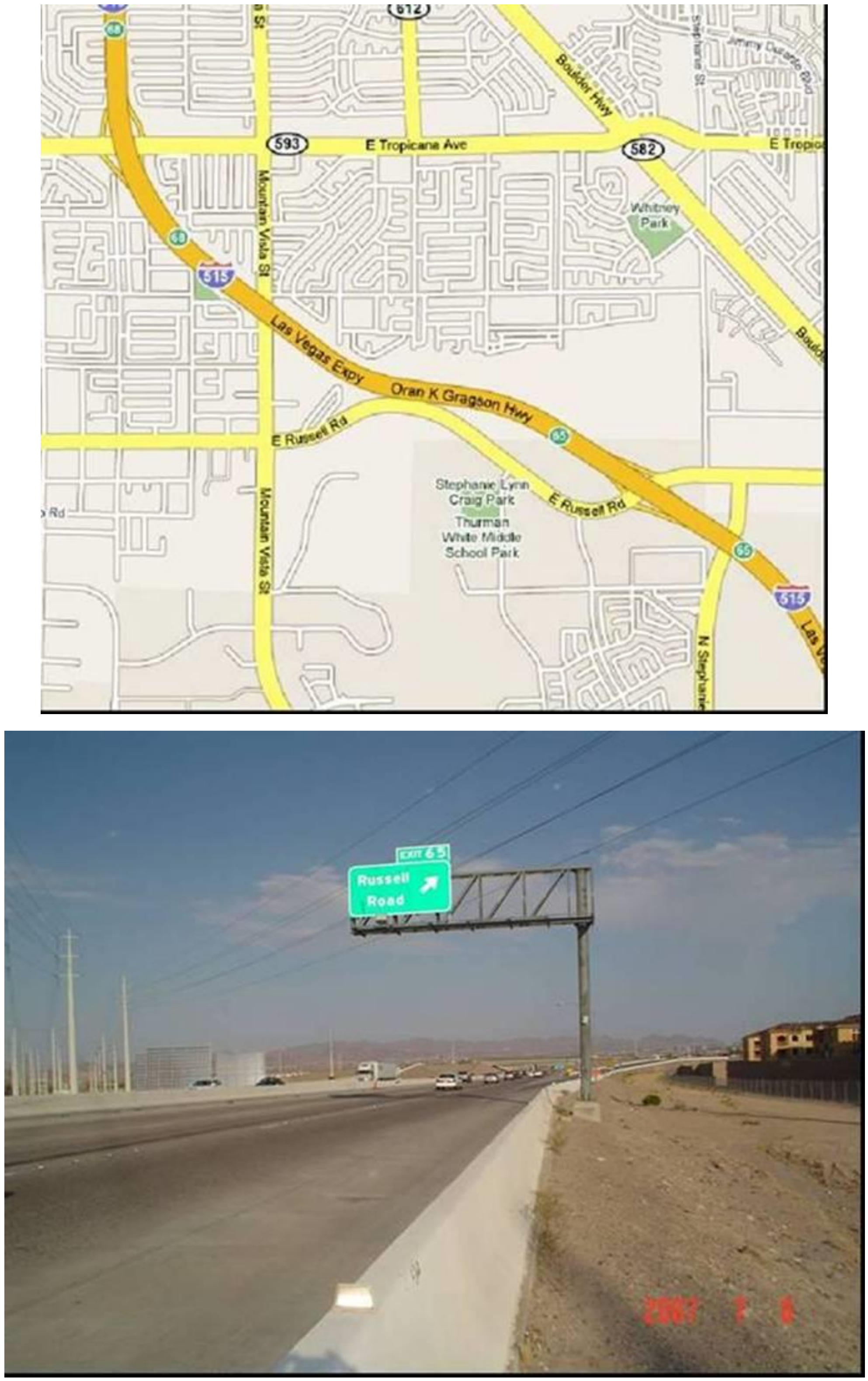


Figure 5.7 The Russell Road Exit on Southbound I-515, upper shows Map (Google Map) and bottom a Picture

5.2 Automated Work Zone Information System Field Test

Similar to the Automated Work Zone Information System developed and tested in other states, the system developed for the test at the site on I-515 was located upstream of a work zone. Instead of developing a complicated system to conduct the test, the system only consisted of a changeable message sign. Figure 5.8 shows that the changeable message sign was located upstream of the exit at Russell Road. The detection of congestion was accomplished by human observation stationed downstream of the changeable message sign. Periodic reporting on traffic conditions downstream was used to determine which messages to display on the changeable message sign. Cameras 1 and 3 were installed on two utility poles and were meant to collect traffic data to evaluate changes of traffic flow on the main road and off ramp, respectively. The test was conducted by evaluating the response of motorists to different messages displayed on the changeable message sign.

As a matter of the fact, the setting in Figure 5.8 was part of a complete queue detection system, not for congestion in a work zone, but for possible queue back up from the off ramp onto the freeway mainline during football games at the Sam Boyd Stadium. This queue detection system is shown in Figure 5.9. Cameras 2 and 3, each coupled with a vision detection device called Autoscope for detecting the progression of congestion from the off ramp to the freeway. Two radio frequency antennas were installed, one on each luminary pole for Cameras 2 and 3, respectively. These antennas transmitted the traffic information from the video detection equipment to a computer connected to the changeable message sign. The computer processed the data from the detection and determined the appropriate messages to be displayed on the changeable message sign based on a predetermined decision-making logic. Appendix B presents the development of this queue detection system.

Testing the system for the work zone, immediately downstream of the location where the system was deployed, was initiated with very little notice. The system could not be modified to accommodate the detection of the possible congestion from the work zone. With the cameras available at site, they were immediately ready to be used to record traffic and evaluate changes of traffic patterns responding to different messages displayed on the changeable message sign.

The detection of congestion was accomplished by human observation stationed downstream from the changeable message sign. Camera 3 which was designed to collect traffic data for detecting queue was used to collect traffic data to see whether there was any significant traffic diversion at the off ramp.

The test was conducted on August 18, 2007, from 1:20 pm to 3:45 pm. During this time period, there was no congestion observed. To test the system, different messages were displayed for three different time periods: Blank from 1:20 pm to 2:00 pm, “Drive Safely” from 2:00 pm to 2:45 pm, and “Congestion Ahead” from 2:50 pm to 3: 45 pm.

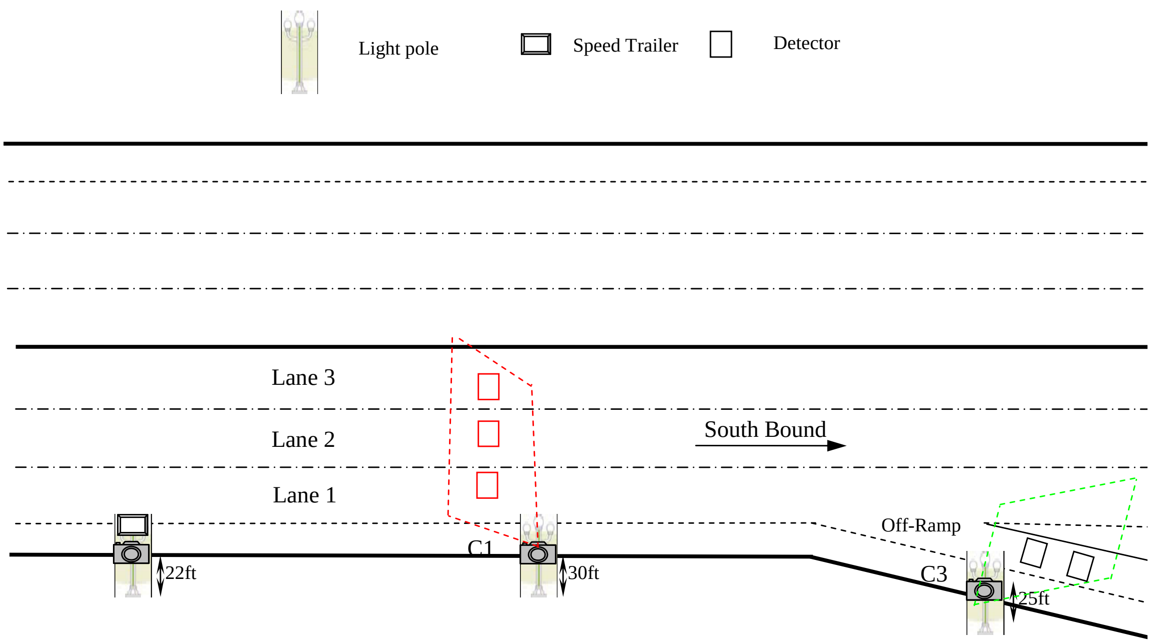


Figure 5.8 Simplified Automatic Work Zone Information System for Testing on I-515

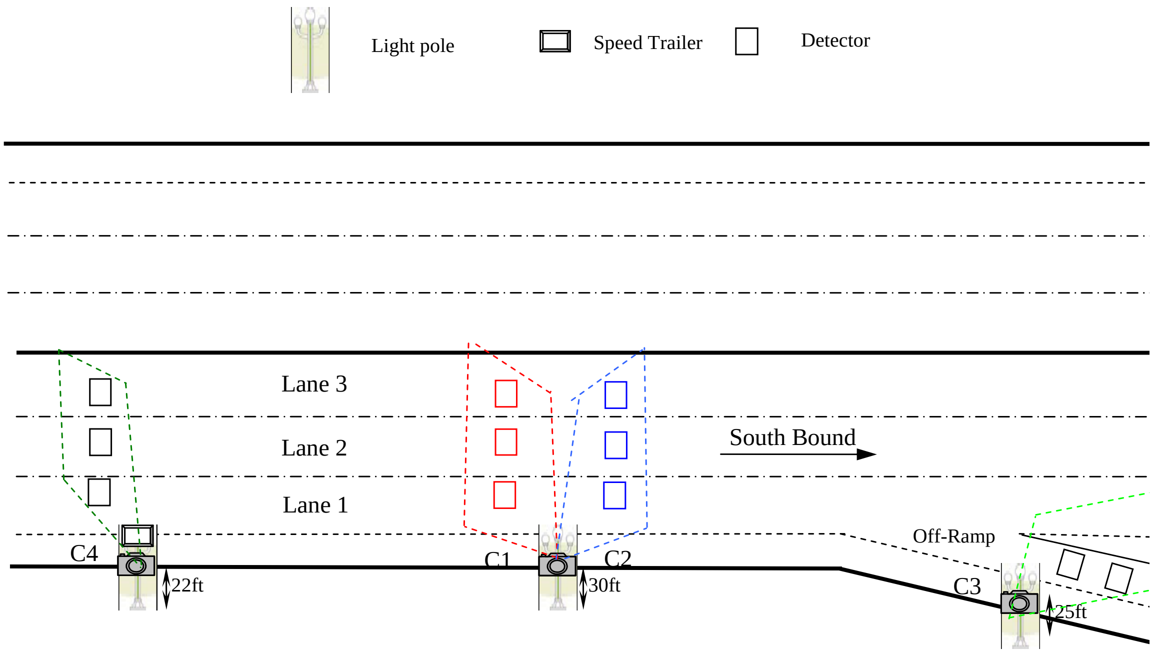


Figure 5.9 Automatic Work Zone Information System and the Setting for Evaluation

5.3 Data Analysis

Diversion: As described above, the traffic count data collected from the off ramp was used to test whether there was significant traffic diversion for different messages shown on the changeable message sign. Table 5.1 lists the results for the three time periods, each with a different message. The traffic counts were the average traffic counts during 5 minute time intervals. It can be seen from the table that there was no significant difference between the average traffic counts during these three time periods.

Table 5.1 Traffic Diversion at the Russell Avenue Exit

	Duration	Message Displayed	Average Traffic Count (veh/5min)	Traffic Count Standard Deviation
13:20 pm - 14:00 pm	40 min	Blank	9.2	1.3
14:00 pm - 14:50 pm	50 min	Drive Safely	9.7	1.4
14:50 pm - 15:45 pm	55 min	Congestion Ahead	10.2	1.7

The speeds from Camera 1 are presented in Table 5.2 and displayed in Figure 5.10. Apparently, the lowest speed was in the right lane (Lane #1) and the highest on the left lane (Lane #3). This is a speed pattern over those lanes consistent with intuition. These speeds were compared to see the impacts of different signs. Table 5.3 lists the results from hypothesis tests. It shows that the speeds in Lane 3 during the time period with message "Congestion Ahead" were significantly lower than those in the other time periods. This result indicates that the changeable message sign was very effective in controlling speed for a work zone.

Table 5.2 Speed Data at Camera 1

	Lane 1	Lane 2	Lane 3
No Message	61.93	66.17	76.23
Drive Safely	62.33	65.74	77.42
Congestion Ahead	61.31	64.99	76.05

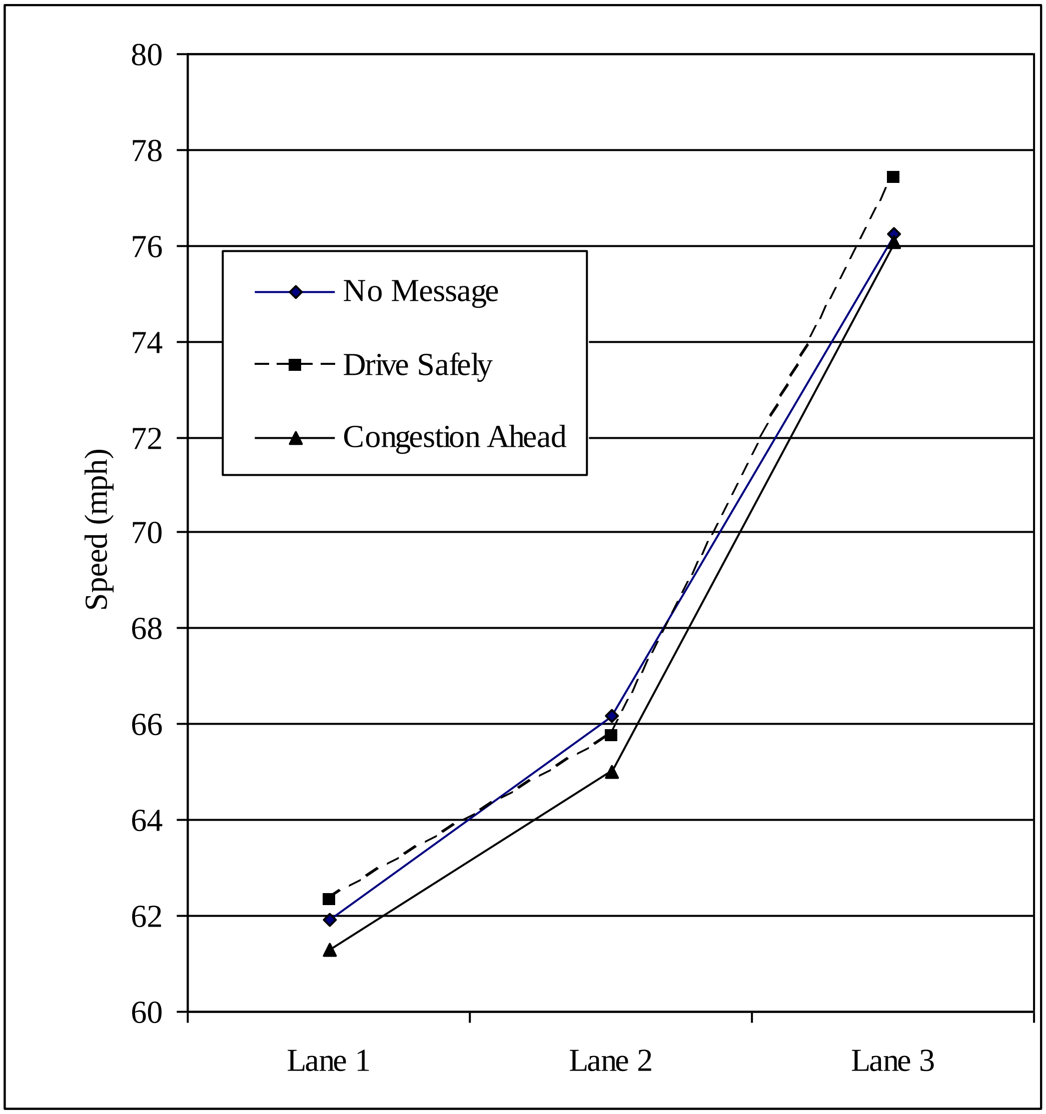


Figure 5.10 Changes of Speeds at the Camera 1 Location

Table 5.3 Results of Hypothesis Test for the Speeds from Camera 1

	Drive Safely		
	Lane 1	**Lane 2**	**Lane 3**
No Message	same	same	same
Congestion Ahead	same	same	reduce

5.4 Benefit and Cost Analysis

The methodology used in the cost and benefit analysis for the automatic work zone information system was basically the same as the one used for the speed monitoring display. The benefits calculated were safety related due to reduced speed. Since the automatic work zone information system included more components than the speed trailer, derivation of the system costs involved more calculations.

The system components included in the calculation were: changeable message sign, cameras, vision detection processor, and radio frequency. One changeable message sign and one radio frequency were counted, while two vision detection processors and two cameras were included. The unit costs for changeable message sign, camera, vision detection processor and radio frequency were $50,000, $400, $4,000, and $300, respectively. The capital cost was calculated as $59,100. Their life spans were assumed the same at 10 years. Then the annualized cost could be calculated as $8,808 at 8% interest rate. This annualized cost can be used to derive the daily based capital cost C_d.

Installation cost was the cost to set up the system for each work zone project, denoted as C_{inst}. The installation included mounting and dismounting cameras and radio frequency, and system integration in the field. Mounting cameras and radio frequency would take three hours with one ITS-related technician and one maintenance crew consisting of one supervisor and three workers. Dismounting these cameras and radio frequency took another one hour. Integrating the system to make the whole system work as expected took two more hours in the field. The annual salaries for both the ITS technician and the supervisor of the maintenance crew were calculated at $60,000**,** and the salary for the three maintenance workers was estimated at $40,000. The fringe benefit rate was assumed to be 30%. Then, the cost for setting up and dismounting the system C_{inst} was calculated at $1,503.

It is also assumed that the ITS technician should be available for operating the system during half of the duration of a work zone project. The cost for this part of work comprised the operation cost $C_{opr} = h \times D$, where h is the technician's hourly rate.

The maintenance cost was estimated as the half of the capital cost, which can be written as:

$$M_p = 0.5 \times C_d \,. \tag{5.1}$$

The total cost for a work zone project can be derived as:

$$T_p = C_d \times D + C_{inst} + h \times D + 0.5 \times C_d \times D \,. \tag{5.2}$$

It can be seen from the equation that only the installation cost is not a function of the duration of a work zone.

In calculating the benefit, the AADT for the test site was taken as 124,667, an average of the AADT taken at three locations on I-515: Flamingo Road, Tropicana Avenue, and Russell Road. The speed reduction is 0.5 mph for one lane only. The crash rates were those for Interstates which are the same as those used for the test of speed trailer on I-15.

Figure 5.11 shows the relationship between the duration and length of work zone that makes the benefit and cost even. The tradeoff between the duration and length of a work zone is because the installation cost for this system is a constant. It can be seen from the figure that the required work zone duration to make the system beneficial decreases as the length of the work zone is increased. This is reasonable because it is the duration and length that determine the amount of vehicle miles traveled to receive the benefits of speed reduction. Given that the system has a large installation cost, there is a tradeoff between the duration and the length of a work zone to make the system effective financially. If most work zones range one to three miles, they have to last months to generate sufficient benefit to cover the system costs, which may be very restrictive in reality. This may raise a concern for the application of such a system in work zones.

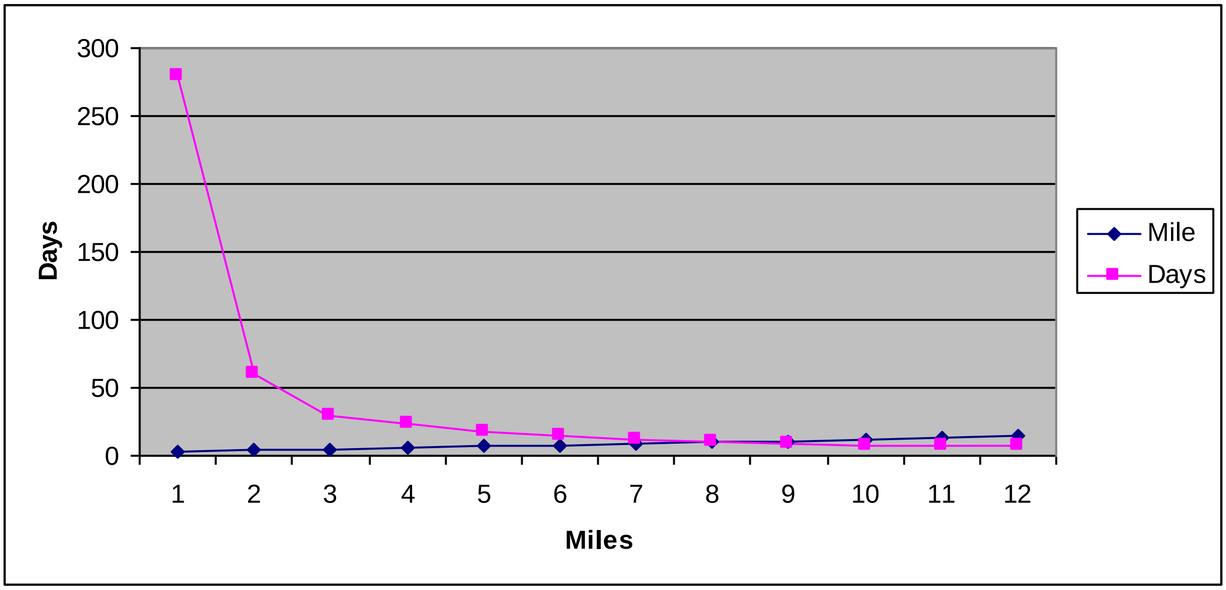


Figure 5.11 Conditions for the Automatic Work Zone Information System to be Beneficial

5.5 Findings, Conclusions, Recommendations, and Implementations

Findings

1. There was no significant diversion responding to the message on congestion in the test work zone; however, there was no congestion in the work zone area. There have been studies on the diversion effect on Automatic Work Zone Information Systems, but findings were mixed. Findings on diversion in this study are not conclusive.
2. Motorists responded to congestion message by reducing speeds in the lane closest to the changeable message sign. This finding can be found in other studies that evaluated the effectiveness of Automatic Work Zone Information Systems.
3. There are situations for the Automatic Work Zone Information Systems to be cost effective. The scale of work zones that can be cost effective could be quite limited compared to that for the speed trailer. The issue is the cost to set up the system in the field, requiring careful evaluation of the costs and benefits of the system for controlling speed in work zones.

Conclusions

1. Automatic Work Zone Information Systems were effective in a limited scale compared to a speed trailer.

Recommendations

1. It is recommended that the automatic work zone information system be installed in work zones on state highway systems. Whether the automatic work zone information system is cost effective for a specific work zone should be evaluated on a case by case basis.

Implementation Guidelines

1. Installing the system needs skilled electronics technicians and their cost should be included in the cost and benefit analysis. The technicians should be very knowledgeable about technologies related to the automatic work zone information systems.
2. The wireless communications adopted in this study require line-of-sight. For work zones where line-of-sight does not exist, additional communication devices such as radio frequency are needed for transmitting the data.
3. The lifecycles of the system components may be different, which implies that some components may wear out easily. For example, the wire connecting the cameras to Autoscope processor may not work well after several uses. Trouble-shooting this type of problem may also take time.
4. Vandalism could be an issue when the system is installed in a place that is accessible by the public. In the implementation on I-515, the antenna was displaced after the initial installation, and such a distortion to the antenna indicated possible vandalism. When a similar system was installed on Tropicana Avenue close to Las Vegas Boulevard, the research team placed the wires higher on a light pole, making them too high for vandals.
5. Coordination with contractors of the work zone is important in identifying the location of recurring congestion. If needed, the locations of detectors and the changeable message sign

should be moved to cover the congestion areas that may change due to changes in work zone activities or locations.

6. If the congestion location changes frequently, a separate cost and benefit analysis should be conducted to calculate the benefit of the automatic work information systems for those work zones.

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APPENDIX A

Parameters for Presence Detector, Speed Detector, Counting Detector, and Detection Function

PRESENCE DETECTOR PARAMETERS

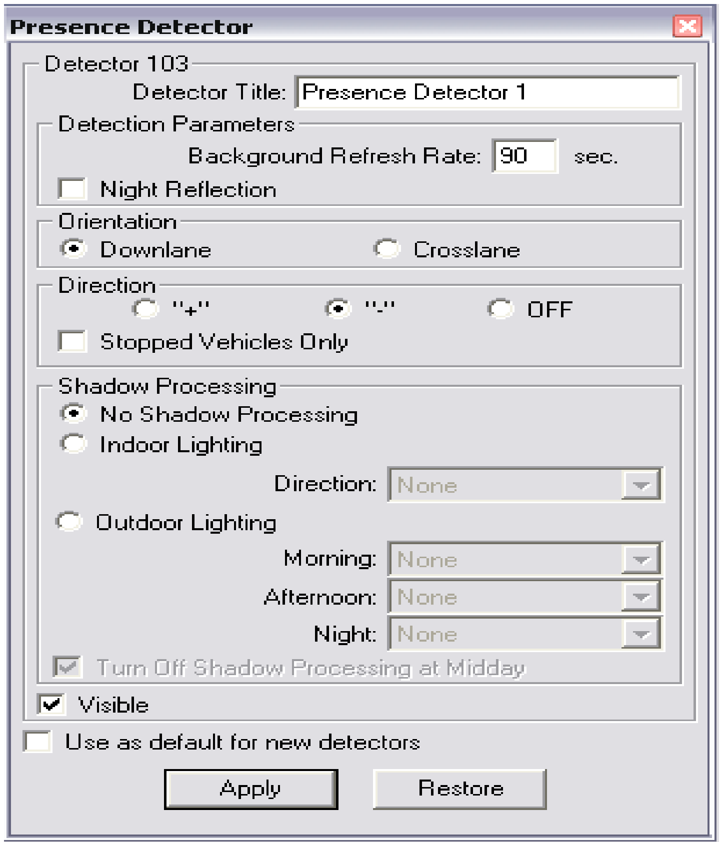


Figure A1 Presence Detector Configuration

Detector ID number: Identifies the detector number.

Detector Title: Uniquely identifies this detector for future reference.

Detection Parameters. Specifies detection conditions.

- **Background Refresh Rate (**seconds). Specifies the guaranteed minimum time (for safety) an object may remain stationary before the Machine Vision Processor begins to consider it as background. For freeway applications, 30 to 60 seconds. For intersection applications, 20 to 600 seconds.

- **Night Reflection.** Specifies whether the Machine Vision Processor compensates for roadway reflections that cause false detections. If this feature is not selected, light projected from a vehicle's headlights may turn ON a detector if the beam is sufficiently dense. The detector may then measure the vehicle length as both the beam plus the vehicle itself.

Orientation: Defines whether the Presence detector is a Crosslane or Downlane detector.

- **Downlane:** If the Presence detector is parallel to the lane, specifies a Downlane detector.
- **Crosslane:** If the Presence detector is perpendicular to the lane, specifies a Crosslane detector.

Direction: Defines in which direction to detect traffic. Direction cannot be specified until the field of view is calibrated.

- **+ or -.** Creates a directional Presence detector.
- **OFF.** Turns detector directionality off.
- **Stopped Vehicles Only.** Creates a Presence detector that detects only vehicles that stop under the detector.

Shadow Processing: Enables additional detection processing to prevent false vehicle detections caused by the shadows cast by vehicles in adjacent lanes.

- **No Shadow Processing:** Turns off shadow processing. Select if shadows do not pose detection problems.
- **Indoor Lighting:** Prevents false detections caused by shadows cast by vehicles in adjacent lanes when indoor lighting is used and there is no movement of the sun through the sky to change the shadow direction (such as in a tunnel).
- **Outdoor Lighting:** Prevents false vehicle detections caused by shadows cast by vehicles in adjacent lanes. When you edit this parameter, the software shows a Sun icon. The movement of the sun through the sky is taken into account.

SPEED DETECTOR PARAMETERS

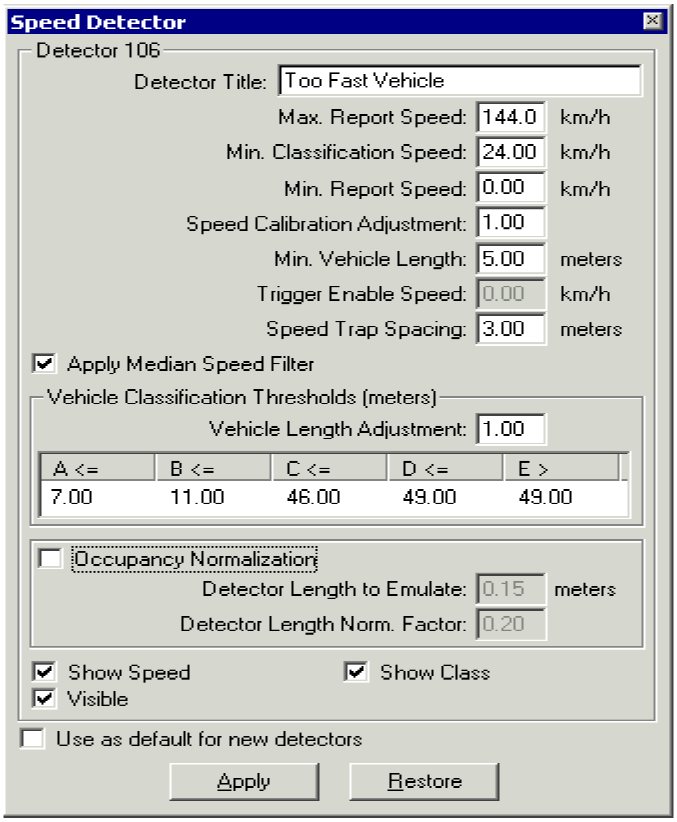


Figure A2 Speed Detector Configuration

Detector ID number. Identifies the detector number.

Detector Title: Uniquely identifies this detector for future reference.

Max. Report Speed: Specifies the highest speed the detector reports.

Min. Classification Speed: Specifies the lowest speed a vehicle may travel and still be measured and classified.

Min. Report Speed: Specifies the lowest speed the detector reports.

Speed Calibration Adjustment: Specifies a speed measurement adjustment factor that compensates for traffic traveling at different road surface heights, such as over and under bridges. In the field of view, higher elevation traffic appears to move faster than lower elevation traffic traveling at the same speed. The measured speed is multiplied by the speed measurement adjustment factor to get a new adjusted reported speed.

Min. Vehicle Length: If the value in the option is not zero, then the minimum call placed by the detector is the minimum length times the measured speed. This option prevents the occurrence of very short detector actuations.

Trigger Enable Speed: The Speed detector allows you to use one detector or a combination of detectors to act as a lane discriminator (to avoid crosslane occlusion) when connected to a Speed detector. Typically, downlane Presence detectors are used as lane discriminators.

Speed Trap Spacing: Specifies a spacing distance that is used only when detector outputs are required to simulate the output of two inductive loops. The measured vehicle speed and the spacing distance are used to calculate the delay between two output pulses.

Apply Median Speed Filter: When selected, reports only the median speed of the current measured speed and the last four valid speeds measured (five total). This filter is particularly useful in freeway applications where the speeds of closely following vehicles are very similar. It also removes outlier values.

Vehicle Classification Thresholds: Defines the threshold values for vehicle classification.

- **Vehicle Length Adjustment:** Specifies multiplication factor to adjust how lengths are viewed.
- **A through E.** Defines minimum, maximum, and intermediate vehicle lengths for five categories.

Occupancy Normalization. Enables the Machine Vision Processor to correct Speed detector occupancy (ON time) for comparison with other types of visual detection sensors, such as inductive loops.

- **Detector Length to Emulate:** Specifies length of emulated detection zone.
- **Detector Length Norm. Factor:** Corrects any biases found in the occupancy outputs (such as constantly 10% high).

Show Speed. Shows measured speed on video display.

Show Class. Shows vehicle classification on video display.

Visible. When checked, this causes the overlay graphics for the Speed detectors to be visible on the video that is output by the Machine Vision Processor. When unchecked, the overlay graphics for the Speed detectors are not visible on the video that is output by the Machine Vision Processor.

Use as default for new detectors. Each time when a new detector of this type is created, the selections made in this dialog are applied to the new detector as defaults.

COUNT DETECTOR PARAMETERS

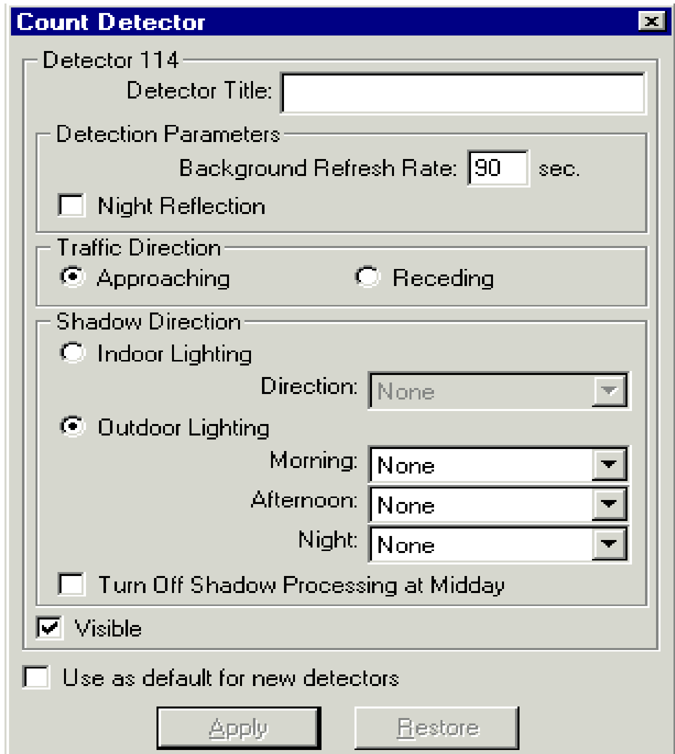


Figure A3 Count Detector Configuration

Detector ID number. Identifies the detector number.

Detector Title: Uniquely identifies this detector for future reference.

Detection Parameters. Specifies detection conditions.

- **Background Refresh Rate** (seconds). Specifies the guaranteed minimum time (for safety) an object may remain stationary before the Machine Vision Processor begins to consider it background.
- **Night Reflection**. Specifies whether the Machine Vision Processor compensates for roadway reflections that cause false detections.

Traffic Direction. Specifies whether traffic is moving towards, or away from, the Machine Vision Processor:

- **Approaching.** Defines traffic as moving towards the Machine Vision Processor.
- **Receding.** Defines traffic as moving away from the Machine Vision Processor.

Shadow Direction. Prevents false vehicle detections caused by shadows cast by vehicles in adjacent lanes. When you edit this parameter, the software shows a Sun icon.

- **Indoor Lighting.** Prevents false detections caused by shadows cast by vehicles in adjacent lanes when indoor lighting is used and there is no movement of the sun through the sky to change the shadow direction (such as in a tunnel).
- **Direction.** Specifies where shadows appear on the image.
- **Outdoor Lighting.** Prevents false vehicle detections caused by shadows cast by vehicles in adjacent lanes. When you edit this parameter, the software shows a Sun icon. The movement of the sun through the sky is taken into account.
- **Morning.** Defines the list of possible directions from which the morning shadows approach the detector.
- **Afternoon.** Defines the list of possible directions from which the evening shadows approach the detector.
- **Night.** Defines the list of possible directions from which the night shadows approach the detector.

Turn Off Shadow Processing at Midday. Selects whether to stop processing shadows at midday, when shadows are normally at the lowest level. Midday is defined as the period when the sun is higher than a certain degree. The number of degrees (n) is based on the Latitude/Longitude settings for the detector file.

Visible. When checked, this shows the overlay graphics for the Count detectors on the video output by the Machine Vision Processor. When unchecked, the overlay graphics for the Count detectors are not visible on the video that is output by the Machine Vision Processor.

Use as default for new detectors. Each time you create a new detector of this type, the selections made in this dialog are applied to the new detector as defaults.

DETECTOR FUNCTION PARAMETERS

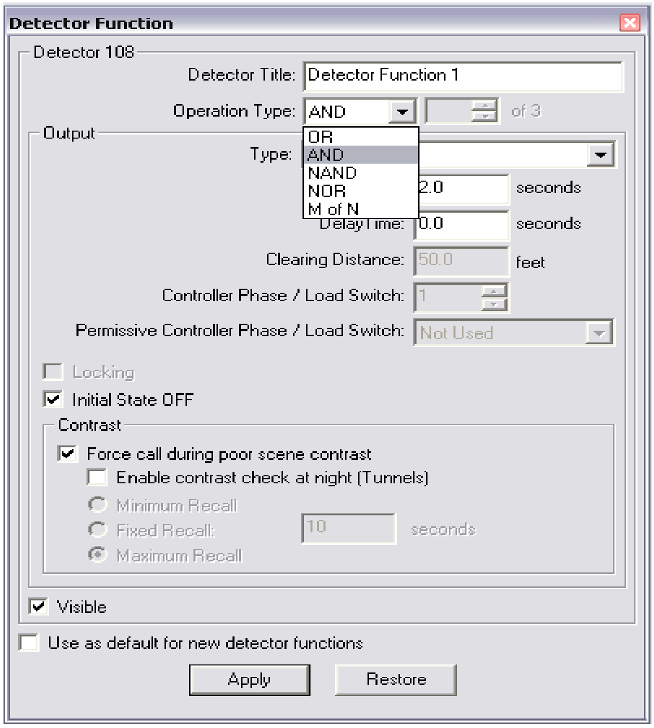


Figure A4 Boolean Detector Function Configuration

Detector ID number. Identifies the detector number.

Detector Title: Uniquely identifies this detector for future reference.

Operation Type. Combines separate detectors into one customized Detector Function. When the conditions set by the Boolean Operation selected, are present, the Detector Function turns ON.

- **OR.** When you select OR, the Detector Function turns ON when at least one of the member detectors of the Detector Function is ON.
- **AND.** When you select AND, the Detector Function turns ON only when all of the member detectors of the Detector Function are ON.
- **NAND.** When you select NAND, the Detector Function turns ON when at least one of the member detectors of the Detector Function are OFF.
- **NOR.** When select NOR, the Detector Function turns ON only when all of the member detectors of the Detector Function are OFF.
- **M of N.** When you select M of N, the Detector Function turns ON only when a defined number M, of the N member detectors, is ON.

Output. Output types are predefined to follow a certain course of action based on the controller phase input.

Locking. Sets an output call to last the duration of an input phase status.

Initial State OFF. When this flag is set, the startup state of the Detector Function and the state of any TS1 and/or TS2 outputs assigned to the detector are modified from the normal behavior.

Contrast. Defines an override for normal Detector Function when the scene contrast falls below a certain level.

Visible. When checked, this causes the overlay graphics for the Detector Functions to be visible on the video that is output by the Machine Vision Processor. When unchecked, the overlay graphics for the Detector Functions are not visible on the video that is output by the Machine Vision Processor.

Use as default for new detector functions. Each time a new detector of this type is created, the selections made in this dialog are applied to the new detector as defaults.

APPENDIX B

QUEUE DETECTION SYSTEM DEVELOPMENT

To better explain the implementation of the automatic work zone information system, the process to build the queue detection system that was also supported by NDOT is presented below.

Basically, the proposed system consists of the following components:

1. Camera Unit
2. Digital Video Recorder
3. Battery Power Supply Unit
4. Radio Frequency Transceiver Unit
5. Autoscope Interface Processor Unit
6. Changeable Message Sign Interface Processor
7. Logic for Determining Messages to be Displayed on Changeable Message Sign

The block diagram of the system with the components is shown in Figure B1. The actual snap shot of the components are shown in Figure B2. The location of the component in the field is found in Figure 5.9.

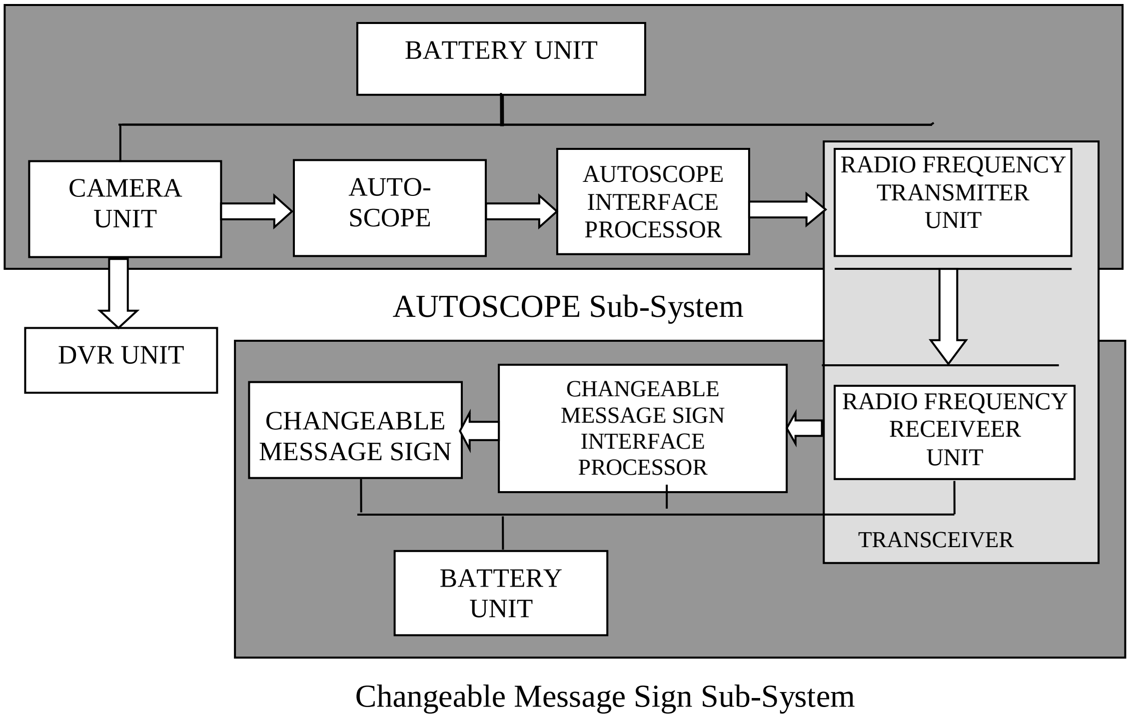


Figure B1 Block Diagram of the System

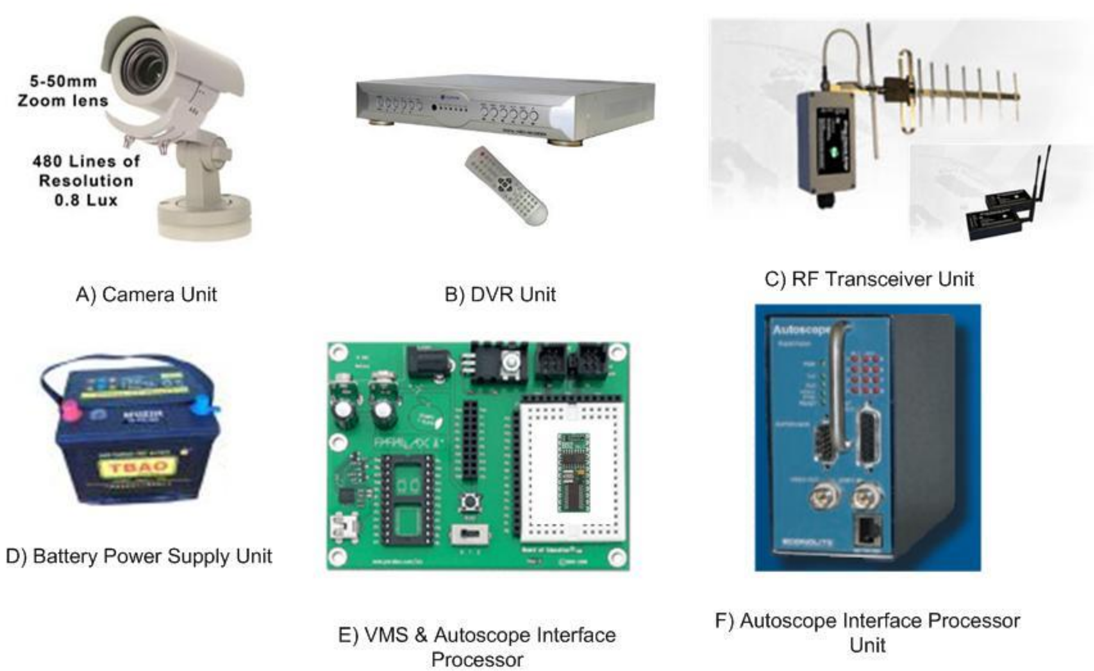


Figure B2 Snapshot of System Components

B.1 Camera Unit:

The camera unit selected for the queue detection system was based on the following criteria:

- Resolution
- Field of view
- Illumination
- Power supply and consumption
- Cost

The selected camera unit, PC219ZWPH High Resolution Weather Resistant 5-50mm Zoom Camera has the following specifications:

> *The wide range zoom vari-focal 5-50MM lens and 350 line, (480 lines HR model) 0.6 lux color camera combine to deliver a new level of performance, reliability, convenience and flexibility. DC driven auto-iris lens and built-in backlight compensation ensure fantastic video performance in almost all lighting conditions. Camera measures 6.1"H x 3.5"W x 7.87"D. (including integral sunshield/ rainhood). Runs on 12 volts DC and draws 130 milliamps.*

These specifications are listed in the table below:

Table B1 Specification of the PC219ZWPH High Resolution Weather Resistant 5-50mm Zoom Camera

Features	**Specifications**
Horizontal Resolution	480 Lines
Illumination	0.6 ~ 0.8 Lux/ F1.8
Image Sensor	1/3" CCD Sensor Interline
Power Requirements	12VDC
Power Consumption	320mA at 12V DC
Video Format	NTSC
Pixels	492 (V) × 771 (H)
Video Connection	BNC Female
S/N Ratio	48dB
Lens Type	5-50mm Zoom
Lens Control	Auto Iris DC Driven
Backlight	Built-in Backlight Compensation
Weight	27.87oz (790 grams)
(D) × (W) × (H)	7.64" × 3.5" × 7.52" (19.4cm × 8.9cm × 19.1cm)

There are cameras recommended by the vendor of Autoscope, the video image processor. The prices of the recommended cameras were more expensive than the one chosen for this study.

B.2 Digital Video Recorder

A digital video recorder (DVR) or personal video recorder (PVR) is a device that records video in a digital format to a disk drive or other medium. The DVR unit selected for our system was based on the following criteria:

- Resolution and frames per second recording capabilities
- Storage capacity for recordings
- Power supply and consumption

The selected DVR unit, Triplex Stand-Alone 4 CH DVR - CDR4060 has these specifications:

- High Resolution: 720 × 480
- Real Time Display: 120 frames/sec
- Recording Frame Rate: 30 frames/sec

- Hard Disk Drive: 80GB
- 4 Video Inputs
- Event Recording by Alarm Sensor or Video Motion Detection,
- Programmable Recording Speed,
- 1 CH Audio In & Out
- Built-in P/T/Z control, compatible with Pelco-D protocol

The specifications of the chosen DVR are listed in the table below.

Table B2 Specification of the Triplex Stand-Alone 4 CH DVR - CDR4060

Features	**Specifications**
TV System - NTSC	60 fields/sec
TV System - PAL	50 fields/sex
Resolution	NTSC 720x480
Video Inputs	4BNC, 1.0Vp-p Composite 75 ohms
Video Outputs	1.0Vp-p Composite 75ohms, 1 main monitor, 1 slave monitor
Real Time Display	120 frames/sec
Recording Speed	30 frames/sec, Programmable 1 to 30 frames/sec
Algorithm	MPEG
Recording	Schedule, Continuous, Event Recording by Motion detection and Alarm sensor
Hard Disk Drive	80 GB
Replay	Forward, backward (fast, normal, stop, pause)
Alarm In	4 inputs
Alarm Output	1 relay output
Power Consumption	Approx. 20W
Power Source	DC 12V 3A
Operating Temp.	41°F to 113°F
Humidity	10 to 90%
Dimension	13.66(W) × 10.35(D) × 2.05(H)
Weight	6 lbs.

B.3 Battery Power Supply Unit

The battery power supply unit for the DVR, Camera, Autoscope and the Processors consists of two 12V deep-cycle batteries connected in parallel or serial to provide sufficient operation voltage and current. An analysis of current requirement for the system was conducted and two batteries in parallel were determined to be sufficient to provide the power for the system. Our calculation estimated the two batteries would provide an un-interrupted power supply for 6 hours before needing to re-charge. Figure B14 shows the battery connections adopted in our implementation.

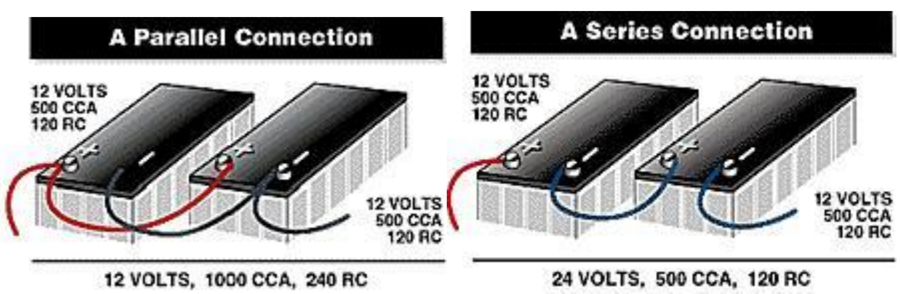


Figure B3 Two 12V Deep-Cycle Batteries Connected in Parallel or in Series to Provide Sufficient Operation Voltage and Current

The most important consideration in buying a deep cycle battery is the Ampere-Hour (AH) or Reserve Capacity (or Reserve Minutes) rating that will meet our requirements. Most deep cycle batteries are rated in discharge rates of 100 hours, 20 hours, or 8 hours. The higher the discharge, the lower the capacity due to the Peukert Effect and the internal resistance of the battery. Reserve Capacity (RC) is the number of minutes a fully charged battery at 80 F (26.7 C) is discharged at 25 amps before the voltage falls below 10.5 volts. By the parallel connection, the two battery system can last 240 minutes (four hours). To convert Reserve Capacity (RC) to Ampere-Hours at the 25 amp rate, multiple RC by 0.4167. More ampere-hours (or RC) are better in every case. Within a BCI group size, the battery with higher ampere-hours (or RC) will tend to have longer life and weigh more because of thicker plates containing more lead.

Specifications of the Exide Deep Cycle Battery are:

- Nautilus Gold Marine/RV
- 12 Volt
- 500 CCA; 625 CA;
- Length: 12"; Width: 6-13/16"; Height: 9 1/2"
- Lead/antimony construction - the right kind for cycling
- Negative and positive cast grid construction - increased recharge & discharge rates
- Enveloped polypropylene separators - for enhanced vibration resistance
- Twin stainless steel terminals connect quickly, resist corrosion and allow multiple attachments
- Rigid polypropylene case and cover - for longer life in the maritime environment
- MCA @ 32° Farenheight - 625
- Reserve Capacity - 180
- Amp Hour (20 Hour Rate) - 105

B.4 Radio Frequency Transceiver Unit

The Radio Frequency Transceiver unit for the system consists of the following components: 1) Radio Frequency Transmitter with yagi-pole antenna, and 2) Radio Frequency Receiver with yagi-pole antenna or base-station antenna. The Radio Frequency Module selected for the system was based on the communication range and power consumption. The Radio Frequency Module used in our system was the Digi XStream-PKG-R 900 MHz, manufactured by Maxstream, INC.

The Digi XStream-PKG-R 900 MHz (or 2.4 GHz) stand-alone Radio Frequency Modems provide outstanding range (up to 20 miles) in a low-cost wireless solution. The modem is coupled with a DIP- switchable RS-232 / RS-422 / RS-485 interface board.

No configuration is necessary for out-of-box Radio Frequency communications. The modem’s default configuration supports a wide range of data system applications. Advanced configurations can be implemented using simple AT or binary commands. Figure B4 shows the product specification of the Digi XStream-PKG-R 900 MHz stand-alone Radio Frequency Modem.

Product summary is:

- ISM 900 MHz or 2.4 GHz operating frequencies
- 100 mW (900 MHz) or 50 mW (2.4 GHz) power output (up to 20 mile range)
- RS-232/RS-485 interfacing built-in
- Commercial (0 – 70° C) or Industrial (-40 – 85° C) temperature ratings
- FCC/IC/ETSI/CE approved
- Advanced networking & low-power modes supported

Long Range Performance	
Indoor/Urban Range	Up to 1500’ (450 m)
Outdoor line-of-sight Range	Up to 7 miles (11 km) w/ 2.1 db dipole antenna
Outdoor line-of-sight Range	Up to 20 miles (32 km) w/ high-gain antenna
Receiver Sensitivity	-110 bBm (@9600 bps)

<table>
<tr><th colspan="4">XStream-PKG-R™</th></tr>
<tr><td rowspan="6">Power Requirement</td><td colspan="2">Power Supply Voltage</td><td>7-18 V</td></tr>
<tr><td rowspan="2">Receive Current</td><td>900 MHz</td><td>70 mA</td></tr>
<tr><td>24 GHz</td><td>90 mA</td></tr>
<tr><td rowspan="2">Transmit Current</td><td>900 MHz</td><td>170 mA</td></tr>
<tr><td>24 GHz</td><td>180 mA</td></tr>
<tr><td colspan="2">Power Down Current</td><td>< 1 mA</td></tr>
</table>

Figure B4 Specification of Digi XStream-PKG-R 900 MHz stand-alone Radio Frequency Modem

High-gain antennas offer the maximum range available for our MaxStream Radio Frequency module. The Yagi-antenna selected for our system is a 4 element, Gain (dBi) 8.1, frequency range (MHz) 902-928, etc. The specification and the picture of the antenna is given in Table B6 and Figure B16.

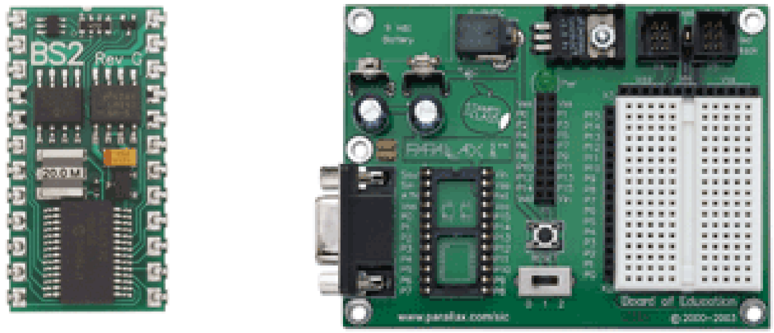
Table B3 Specification of 4-Element Yagi-Antenna

Specific Freq. (MHz)	896-980
Gain (dBd)	6
Maximum Power Input (Watts)	200
Product Narrative	4 element, 6 dB gain yagi. 1 piece unit construction with elements welded to boom. Feed System is enclosed in potted PVC radome for weatherability.
Type	4-Element Yagi
General Freq. (MHz)	896-980
Bandwidth @ Rated VSWR (MHz)	84
Gain (dbi)	8.15
H. Beamwidth	105 Deg.
Vert. Beamwidth	65 Deg.
Front to Back Ratio (dB)	16 dB
VSWR	1.5:1
Polarization	Vert./Horiz.
Lightning Port.	DC Ground
Size (H×W×D)	12”
Weight	0.68
Rated Wind Velocity	125

Figure B5 4 Element Yagi Antenna

B.5 Autoscope Interface Processor Unit

The Autoscope interface processor unit consists of a BASIC Stamp© processor that interfaces with the DB15 Autoscope. The BASIC Stamp is a microcontroller developed by Parallax, Inc. which is easily programmed using a form of the BASIC programming language. The BASIC Stamp runs on 5 to 15 volts DC. The BS2-IC consumes 8 mA in running mode and 100 µA in sleep mode, not including any circuitry on the I/O pins. The BS2-IC, a variant of BASIC Stamp (BASIC Stamp II), measures 1.2” (30 mm) L x 0.62” (16 mm) W x 0.35” (9 mm) D. The BASIC Stamp II Carrier Board measures 2.8” (71 mm) L x 3.1” (79 mm) W x 0.6” (15 mm) D. The BASIC Stamp II uses PIC16C57 Microchip Technology Inc. The BASIC Stamp modules work in 0 to 70° C temperatures with up to 70%, non-condensing humidity. After you write the code for your application, you simply connect the BASIC Stamp to the computer’s serial port or USB, provide power to the BASIC Stamp and press ALT-R (DOS version) or CTRL-R (Windows version) within the appropriate BASIC Stamp editor to download your program into the BASIC Stamp’s EEPROM. As soon as the program has been downloaded successfully, it begins executing its new program from the first line of code. Figure 5.17 shows the diagram of the Basic Stamp and the carrier board that houses the processor.



a) BASIC Stamp Module b) Carrier Board

Figure B6 Basic Stamp Module and Carrier Board with Serial Interface

Vehicle detection by video cameras is one of the most promising new technologies for traffic data collection for advanced traffic control and management.

Autoscope, a new vehicle detection system, can detect traffic in many locations (i.e., multiple spots) within the camera's field-of-view. These locations are specified by the user in a matter of minutes using interactive graphics and can be changed as often as desired. This flexible detection placement is achieved by placing detection lines along or across the roadway lanes on a TV monitor displaying the traffic scene. Therefore, these detection lines are not physically placed in the pavement but only on the TV monitor. Every time a car crosses these lines, a detection signal (presence or passage) is generated by the device.

Because of this design, Autoscope can be installed without disrupting traffic operations. Furthermore, it is not locked to a particular detection configuration. The detection configuration can be changed manually or dynamically (i.e., by software as a function of traffic conditions). Because of these features, this video detection system leads to advanced traffic surveillance and control applications.

Autoscope® RackVision is a machine vision vehicle detection technology. The RackVision vehicle detection system delivers the same high performance machine vision processing that is available in the Autoscope Solo Pro, a single unit system produced by the same manufacturer. The RackVision can be used with AIS black and white, color or CCTV cameras.

Autoscope RackVision™ has been designed to plug directly into standard US loop detector racks. It can be easily integrated into existing Autoscope Solo® communications installations. RackVision™ units can be networked together simply and automatically using built-in network and communications software and off-the-shelf Ethernet cables.

Autoscope RackVision™ has the following features:

- Single camera video detection processor card and TS1 I/O in a 2-slot width footprint.
- Provides basic vehicle detection, traffic data measurement, and incident detection.
- Plugs into existing standard US loop detector racks.
- Stores traffic data in non-volatile memory.
- Auto-selects NTSC or PAL video formats.
- Low power consumption.
- Self-test on power-up.
- Local language support.
- IP addressable into Autoscope Solo® network, using sophisticated networking at high data rates.
- LED indicates status for communications, valid video, data processing, and power.
- Detector I/O via front panel DB 15 connector.
- Optional video compression card.

It provides the following benefits:

- Cost-effective solutions for traffic management.
- Field proven accuracy.
- Easy to install and configure.
- Flexibility to meet a variety of detection and surveillance needs.
- Expanded application opportunities.
- Connect to existing black and white or color Autoscope AIS or CCTV cameras.
- Up to 6 RackVision units and a power supply can easily fit into a standard US loop amplifier rack.

- Optional enclosure for shelf mounting.

Its setup and operation are featured as:

- Simple mouse and keyboard operations: add, delete, or move up to 99 virtual detection zones. Customize detection to meet your requirements.
- Detection zones for count, presence, speed, and incident detection applications. Real-time polling or stored data include: volume, occupancy, speed, five vehicle classes, and other traffic data over selected time periods. Status of incident and other alarms are available.
- Local output support for speed and classification unavailable, unless connected to a Detector Port Master Module.
- Easily assign detector outputs to interface with existing traffic control equipment.
- Provides 8 outputs and 4 inputs via edge connector or front panel DB15 (Jumper selectable). This feature is used by our system to generate outputs to inform the changeable message sign for traffic congestion and incidents.

The specifications for the Autoscope RackVision are:

Communications

- D8-9 RS-232 for local PC communication
- One RJ-45 connector for RS-485 full-duplex network connection

Regulatory

- NEMA TS2 compliant
- CE EN 55022
- CE EN 61000-6-1
- FCC Part 15, Class A

Power

- 10-28 VDC
- <400 mA
- <650 mA

AIS Camera

- 22× continuous focus zoom lens
- Horizontal: 5” to 73” FOV
- Vertical: 5” to 58” FOV

Environmental
- -29°F to +165°F (-34°C to +74°C)
- 0-95% relative humidity

Video Input
- Composite 75Ω 1 Vpp, BNC connector
- Color: NTSC or PAL
- Black & White: CCIR or RS170

Output
- 1 Vpp, BNC connector
- NTSC or PAL
- Operational video compression

Dimensions and Weight
- 4.5” H × 2.25” W × 7” L (114 mm × 57 mm × 178 mm)
- 0.9 lb (0.04 kg)

Warranty
- Two-year warranty
- Extended warranty available (5-year warranty package)

Product Support
- Product support and training by team of factory-trained Autoscope technical support specialists

Autoscope Sub-System

The diagram of the sub-system that detects and transmits the information to the Radio Frequency base-station is shown in Figure B7. The sub-system consists of the following components: 1) Camera unit, 2) Power supply unit, 3) Autoscope Rackvision™, 4) Autoscope interface processor unit, and 5) Radio Frequency transmitter module. Flow chart of operation is presented in Figure B8.

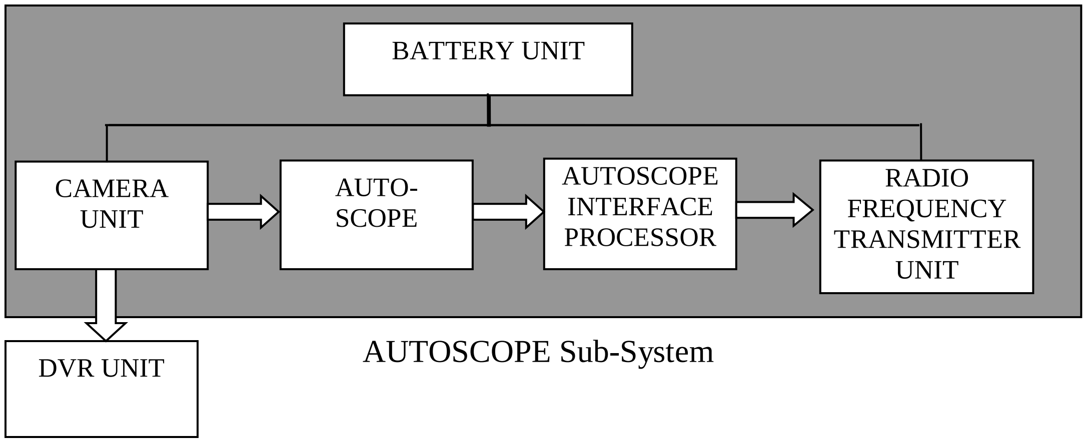


Figure B7 Autoscope Sub-System Block Diagram

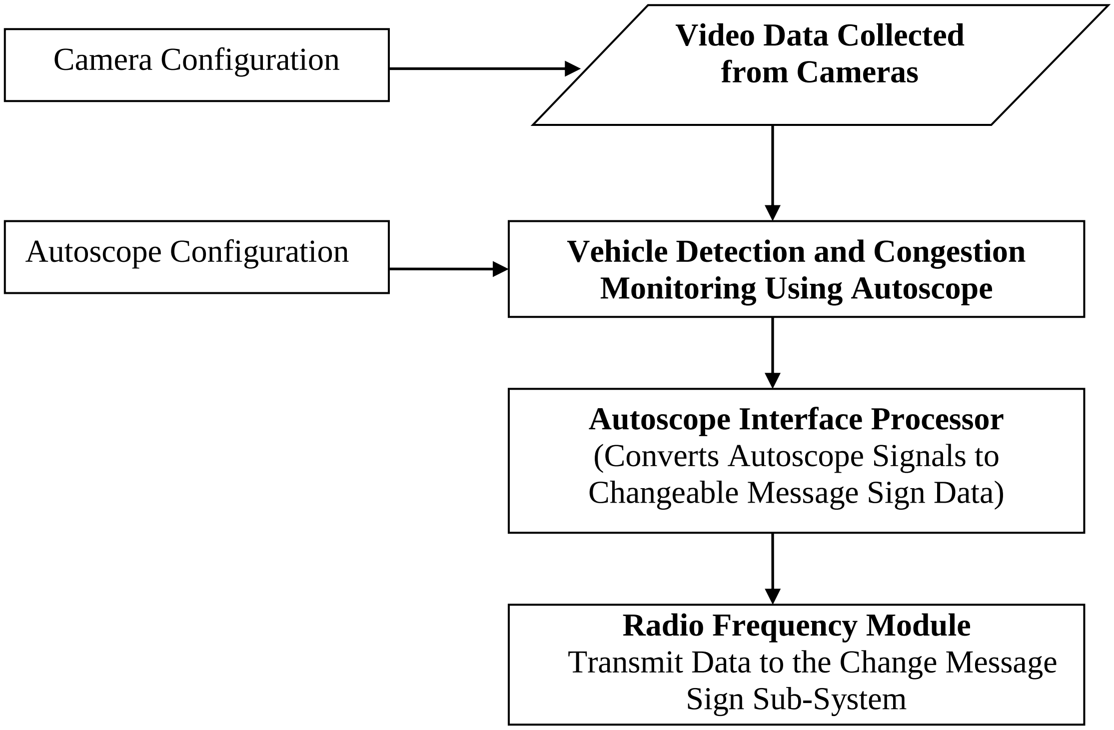
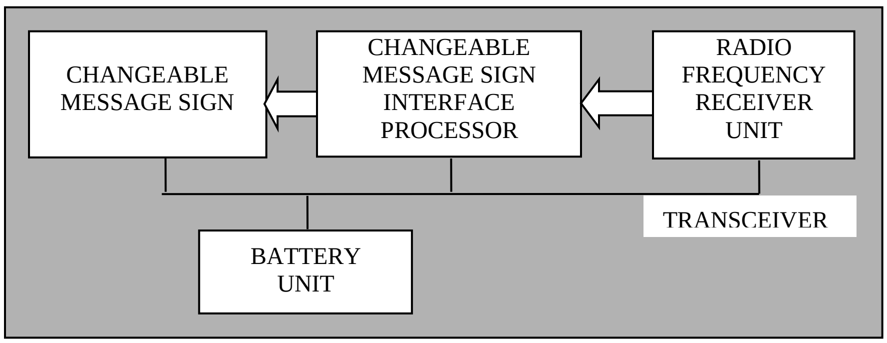


Figure B8 Autoscope Sub-System Operation Flow

B.6 Changeable Message Sign Interface Processor

The changeable message sign Interface Processor is also a BASIC Stamp, a microcontroller developed by Parallax, Inc. This microcontroller is easily programmed using a form of the BASIC programming language. The changeable message sign interface processor receives the signal transmitted from the Autoscope and displays the appropriate message on the Changeable Message Sign. The diagram of the sub-system is shown in Figure B9. Flow chart of operation is presented in Figure B10.



Changeable Message Sign Sub-System

Figure B9 Changeable Message Sign Sub-System Block Diagram

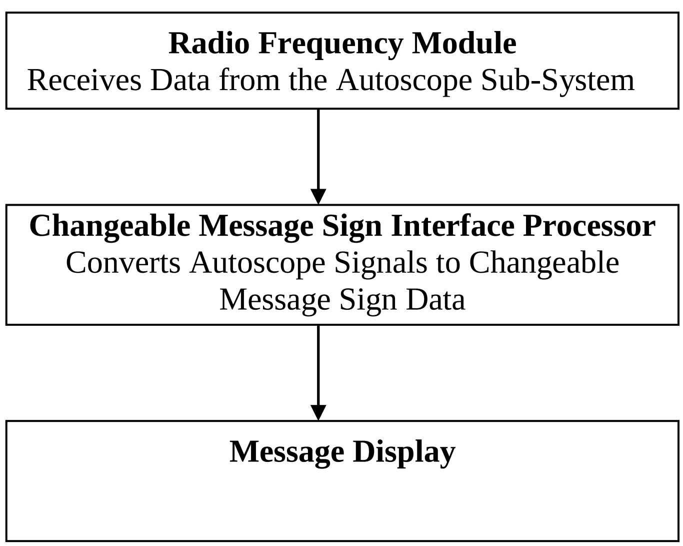


Figure B10 Changeable Message Sign Sub-System Operation Flow

B.7 Logic to Determine Messages for Changeable Message Sign

A logical argument was developed to determine the messages displayed on the changeable message signs based on the system components layout in the test site. The logic was coded in a computer program. This program was tested multiple times, working only in the last test, so was not available for use in the field tests.

Figure 4.11 presents the layout of the detectors for the queue detection system at a typical test site. It can be seen that there are three travel lanes and two vision detectors are assumed to be installed at locations 1 and 2. The vision detectors can provided traffic data for speed and presence which are denoted as (P_{11}, S_{11}), (P_{12}, S_{12}), (P_{13}, S_{13}), (P_{21}, S_{21}), (P_{22}, S_{22}), and (P_{23}, S_{23}). P_{ij} denotes presence detector at location *i* and lane *j*, while S_{ij} represents speed detector at location *i* and lane *j*. (P_{1j}, S_{1j}) is within the coverage of A1. (P_{2j}, S_{2j}) is within the coverage of A2. Coverage of A1 is downstream of A2.

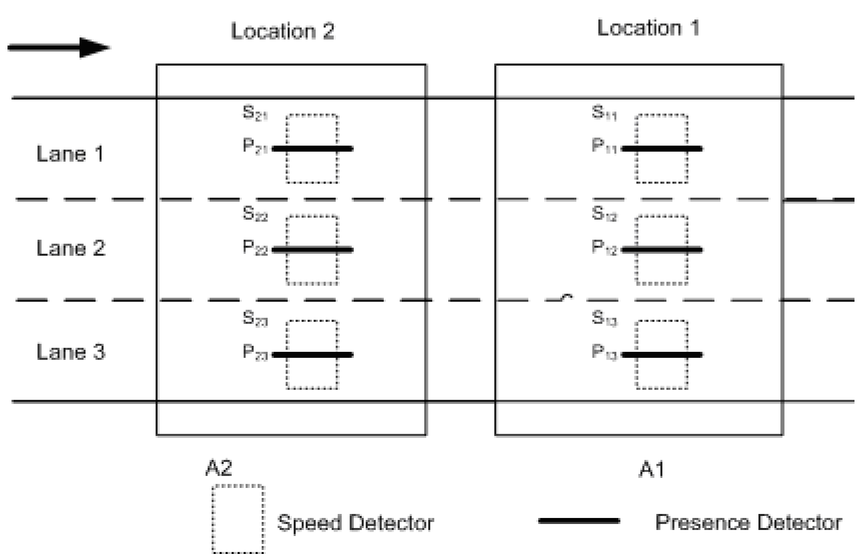


Figure B11 Presence and Speed Detectors within the Coverage of the Autoscope, a Vision Detection Product

The objective of the logic is to present different messages on a changeable message sign when a queue is not detected, or when a queue is detected and whether the queue back to back up locations 1 or 2. The messages to be displayed corresponding to these three conditions are listed in Table B4. The logic to determine that one of the three conditions occurs on the road is presented in Table B5 and Figure B12.

Table B4 Messages and the Corresponding Conditions

Condition	Message
No Queue Detected	Blank
Queue Reaches Location 1	CONGESTION AT 0.5 MILE AHEAD
Queue Reaches Location 2	CONGESTION AT 1.0 MILE AHEAD

Table B5 Logic to Present Message on a Changeable Message Sign

<table>
<tr><th></th><th></th><th>Congestion at 0.5 Mile ahead</th><th colspan="4">Congestion at 1.0 Mile Ahead</th></tr>
<tr><td rowspan="4">Location 1</td><td>P_{12}</td><td>1</td><td colspan="4">1</td></tr>
<tr><td>P_{13}</td><td>1</td><td colspan="4">1</td></tr>
<tr><td>S_{12}</td><td>$S_{12} \leq 5$ mph</td><td colspan="4">$S_{12} \leq 5$ mph</td></tr>
<tr><td>S_{13}</td><td>$S_{13} \leq 5$ mph</td><td colspan="4">$S_{13} \leq 5$ mph</td></tr>
<tr><td rowspan="6">Location 2</td><td>P_{21}</td><td rowspan="3">1 or 0</td><td>1</td><td>1</td><td>0</td><td>1</td></tr>
<tr><td>P_{22}</td><td>1</td><td>0</td><td>1</td><td>1</td></tr>
<tr><td>P_{23}</td><td>0</td><td>1</td><td>1</td><td>1</td></tr>
<tr><td>S_{21}</td><td>$P_{21}=1, S_{21} > 5$ mph</td><td>$S_{21} \leq 5$ mph</td><td>$S_{21} \leq 5$ mph</td><td></td><td>$S_{21} \leq 5$ mph</td></tr>
<tr><td>S_{22}</td><td>$P_{22}=1, S_{22} > 5$ mph</td><td>$S_{22} \leq 5$ mph</td><td></td><td>$S_{22} \leq 5$ mph</td><td>$S_{22} \leq 5$ mph</td></tr>
<tr><td>S_{23}</td><td>$P_{23}=1, S_{23} > 5$ mph</td><td></td><td>$S_{23} \leq 5$ mph</td><td>$S_{23} \leq 5$ mph</td><td>$S_{23} \leq 5$ mph</td></tr>
</table>

* 1 represents presence of vehicles and 0 represents non-presence of vehicles

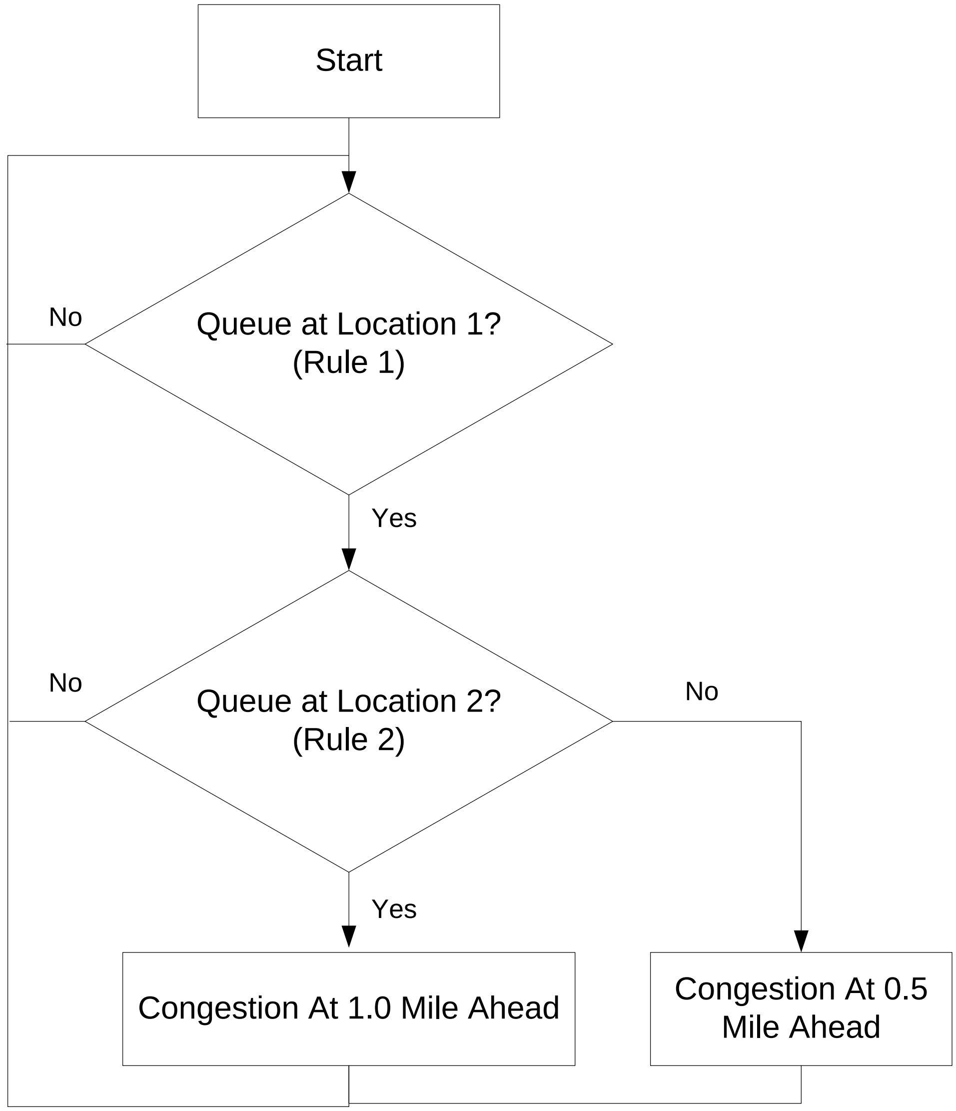


Figure B12 Control Logic for Displaying Messages on a Changeable Message Sign

In Figure B12, the rules are specified as follows:

Rule 1: (P_{12}=1 and $S_{12}\leq$5mph) and (P_{13}=1 and $S_{13}\leq$5mph);

Rule 2: (P_{21}=1 and $S_{21}\leq$5mph and P_{22}=1 and $S_{22}\leq$5mph)

Or (P_{22}=1 and $S_{22}\leq$5mph and P_{23}=1 and $S_{23}\leq$5mph)

Or (P_{21}=1 and $S_{21}\leq$5mph and P_{23}=1 and $S_{23}\leq$5mph)

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