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Report No. UT-08.04

EVALUATION OF ADVANCE WARNING SIGNAL INSTALLATION

Phase II: Long-term Monitoring

Prepared For:

Utah Department of Transportation
Research Division

Submitted by:

Brigham Young University
Department of Civil and Environmental Engineering

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Undergraduate Research Assistant

June 2008

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16. Abstract

A driver approaching a signalized intersection where the light has turned yellow must make a decision whether to stop or proceed. A signal that is properly designed will provide an opportunity for a safe and legal maneuver. As approach speeds increase, however, it becomes more difficult to execute a safe maneuver. One countermeasure that is used to help provide advance warning to drivers of an approaching intersection or the impending signal change at an approaching intersection is an advance warning signal (AWS) system. A number of AWS systems have been installed throughout the country. Four such systems were installed in the state of Utah in 2005. Since that time the effectiveness of these systems has been evaluated as a function of intersection safety. The metrics used for evaluation include crash data analysis, speed distribution analysis, and red-light running (RLR) analysis. The objective of this study is to evaluate and report the long-term effectiveness of the AWS systems installed in the state of Utah in June 2005, particularly at the intersection of Bangerter Highway and 13400 South. The results of the study indicate that overall the AWS system has generally had a positive impact on the community, with positive results noted in all areas of analysis. Given the nature of the study, however, it is difficult to quantify the extent of the overall impact as a function of only the AWS system.

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TABLE OF CONTENTS

LIST OF TABLES

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LIST OF FIGURES

Executive Summary

A driver approaching a signalized intersection where the light has turned yellow must make a decision whether to stop or proceed. A signal that is properly designed will provide an opportunity for a safe and legal maneuver. However, as the approach speed increases, choosing the correct option becomes more difficult for the driver. The driver may decide to proceed when the correct option is to stop, and run the red light; or the driver may decide to stop when the correct option is to proceed, which could cause a rear-end crash. Because of this, many high-speed signalized intersections have high rates of red-light running (RLR), conflicts, and crashes.

One countermeasure that is used at such intersections is the installation of a dynamic advance warning signal (AWS) system. This system consists of a sign and warning lights that are placed upstream of the intersection. The purpose of an AWS system is to warn drivers of, and provide information on, the impending signal change at an approaching intersection. The desired results include a reduction in RLR and a safer speed distribution, with the ultimate goal of improved safety at the intersection.

While many studies have addressed the question of the effectiveness of AWS systems, few have included data from more than six months after installation. In order to effectively evaluate AWS systems, it was necessary to gather information on the long-term effects of AWS systems and on the effect of AWS systems on crash rates.

Background and Objective

The subject of this report is a study of the effects of an AWS system at an intersection of Bangerter Highway in Riverton, UT. This system was installed by the Utah Department of Transportation (UDOT) in response to concerns about safety and abrupt stops by trucks which were damaging the pavement. The system consists of a blank-out overhead dynamic advance warning signal (BODAWS), flashers mounted next to the sign, and advance video detection. The system was installed at three intersections on Bangerter Highway (13400 South, 2700 West, and Redwood Road) and at one on S.R. 201 in Salt Lake County during June 2005. Data on speeds and RLR were collected at one of the intersections on Bangerter Highway (Bangerter Highway and 13400 South) before and after the installation using the SmartSensor Advance™ sensor with Digital Wave Radar™ technology. Crash data for the three intersections were collected from UDOT reports compiled from law-enforcement crash reporting forms. Crash data were also collected for a control intersection (Bangerter Highway and 12600 South) with the before and after data compiled and compared to determine the effects of the AWS.

The objective of this study is to determine the long-term effects of the BODAWS system on safety by analyzing long-term speed, RLR, and crash data.

AWS System Components

The AWS system consists of two major components: the AWS component, and the advanced detection (AD) component. The AWS component includes an electronic LED display that, when activated, displays the message “PREPARE TO STOP.” When it is not activated, the display is blank. The sign is accompanied by two flashers, which flash alternately when the sign is activated, and are dark when the sign is inactive. Because of the “blank out” nature of the signs, they have been referred to in previous research as “Blank-out overhead dynamic advance warning signal” (BODAWS) systems. The AD component consists of a video detection camera mounted on a light pole with one optical detection zone that covers all lanes of travel.

The operation of the AWS system involves the interaction of the AWS sign with the downstream signal. Specifically, the operation of the AWS system is defined by the amount of time before the start of the yellow interval that the AWS sign is activated. This amount of time is called the lead flash time or the time it takes a vehicle to travel from the last location where the AWS sign is legible to the stop bar. The lead flash time was initially set to be 6 seconds.

Preliminary results of the study showed that a high number of vehicles were running the red light at high speeds. It was theorized that the AWS system gave drivers enough time to accelerate through the intersection before or shortly after the light turned red. In an effort to mitigate this problem, the lead flash time was changed from 6 seconds to 5 seconds on April 21, 2006, then from 5 seconds to 4 seconds on May 23, 2006. The lead flash has remained constant at 4 seconds throughout the remainder of the study.

Data Collection

UDOT contracted with researchers at Brigham Young University (BYU) to evaluate the effectiveness of the AWS systems. A before-and-after crash study was conducted for the three AWS-equipped intersections and the control intersection. The 'before' period was June 8, 2003 to June 7, 2005. The 'after' period was June 8, 2005 to June 7, 2007. This was two years before and two years after AWS system installation.

A before-and-after speed and RLR study was conducted for the intersection with 13400 South (one of the locations where the AWS system was installed). The 'before' period for this analysis included April 27, 2005 to June 7, 2005. The 'after' period included data collected from June 8, 2005 to October 20, 2007. This was about six weeks before the installation of the AWS system and about two years and four months after. The 'after' period was divided into five periods to facilitate speed and RLR data analysis.

Study Results

Study results are provided for crash, speed, and RLR at the intersection.

Crash Results

The crash study focused on the frequency and rate of crashes related to the study intersections. Two years of 'before' data was compared to two years of 'after' data. The before-and-after crash frequencies for crashes involving only vehicles traveling on Bangerter Highway are summarized in Table ES-1.

Table ES-1. Before-and-After (Two-Year) Crash Frequencies for Crashes Only Involving Vehicles Traveling On Bangerter Highway

		Number of Crashes	
		Before	After
Redwood Road	Rear-end	16	19
	Right-angle	0	2
	Other	6	2
	Total	22	23
2700 West	Rear-end	14	13
	Right-angle	0	2
	Other	2	0
	Total	16	15
13400 South	Rear-end	15	9
	Right-angle	1	3
	Other	3	4
	Total	19	16
12600 South (control site)	Rear-end	13	19
	Right-angle	0	3
	Other	4	1
	Total	17	23

As illustrated in this table, the total Bangerter Highway-only crash frequency for the control intersection increased from 17 crashes before the installation of the AWS system to 23 crashes after installation. The frequency at the intersection with Redwood Road also increased but only slightly, from 22 crashes before to 23 crashes after. Bangerter Highway-only crash frequencies at the other AWS-equipped intersections decreased by a small amount. When considering specific crash types, a slight increase in right-angle crashes are noted along with a decrease in rear-end crashes. Rear-end crashes increased at the control site, while the right-angle crashes increased at the control site and at other sites along the southern end of Bangerter Highway. The trend in right-angle crashes does not, however, appear to be RLR related. Less than one crash per year at each of the AWS-equipped intersections was found to be attributed to RLR.

Because Bangerter Highway-only crash frequencies increased at Redwood Road and decreased at the other AWS-equipped intersections, and because of the relatively small magnitude of the changes, no strong conclusion can be made regarding the effect of the AWS system on total Bangerter Highway-only crashes. It does seem apparent, however, that the AWS systems did not cause a dramatic increase in total Bangerter Highway-only crash frequencies, as demonstrated by the fact that total Bangerter Highway-only crash frequency at the control intersection increased by 5 crashes, while the frequencies at the other intersections increased by 1 crash at the most, or decreased.

The before-and-after Bangerter Highway-only crash rates are summarized in Table ES-2.

Table ES-2. Before-and-After (Two-Year) Crash Rates for Crashes Only Involving Vehicles Traveling On Bangerter Highway

		Crash Rate Per MEV	
		Before	**After**
Redwood Road	Rear-end	0.72	0.78
	Right-angle	0.00	0.08
	Other	0.27	0.08
	Total	0.99	0.95
2700 West	Rear-end	0.76	0.69
	Right-angle	0.00	0.11
	Other	0.11	0.00
	Total	0.87	0.79
13400 South	Rear-end	0.98	0.56
	Right-angle	0.07	0.19
	Other	0.20	0.25
	Total	1.24	1.00
12600 South (control site)	Rear-end	0.69	0.95
	Right-angle	0.00	0.15
	Other	0.21	0.05
	Total	0.90	1.15

Similar to the crash frequency analysis, the total Bangerter Highway-only crash rates for the control intersection increased, while the rates for all AWS-equipped intersections decreased. This suggests that the AWS systems had the effect of reducing total Bangerter Highway-only crash rates. This is slightly different than the crash frequency results where total number of crashes increased slightly at Redwood Road. By including the exposure of the intersection (i.e., average annual daily traffic) the rates decreased at all AWS-equipped intersections.

Because of the limited amount of data it was determined to be impractical to perform detailed statistical analysis and comparisons of the data results. It was concluded, however, that the AWS system did not cause an increase in crash rates and the system was shown to have played at least some part in a decrease in overall crash rates as well as a decrease in crash frequency.

Speed Results

The speed study focused on the change in speed distributions for vehicles approaching one of the AWS-equipped intersections. Speed data was collected for each vehicle as it crossed 7 vehicle detection zones located between the intersection and a point 300 feet away from the intersection. In addition to being categorized according to distance from the intersection, the speeds were also categorized by amount of time before the start of the red interval (seconds before red or SBR). The change in speed distribution for each category over time was then analyzed using box plots and cumulative speed distribution plots.

The cumulative speed distributions were plotted so that the differences in speed distributions between the SBR categories and between the data analysis periods could be visually analyzed. Cumulative speed distributions for northbound vehicles at the 100 ft detection zone during the AM peak for each of the SBR categories and data analysis periods are presented in this executive summary.

The cumulative speed distribution plots show the change in the speed distribution for the analysis period. Figure ES-1 shows the speed distribution before the AWS system was installed. Figure ES-2 and Figures ES-3 show the speed distribution immediately after and approximately eight months after the installation of the AWS system. Figure ES-4 shows the speed distributions immediately after the change in lead flash timing to 4 seconds. Figure ES-5 shows the speed distribution approximately two years after the installation of the AWS system.

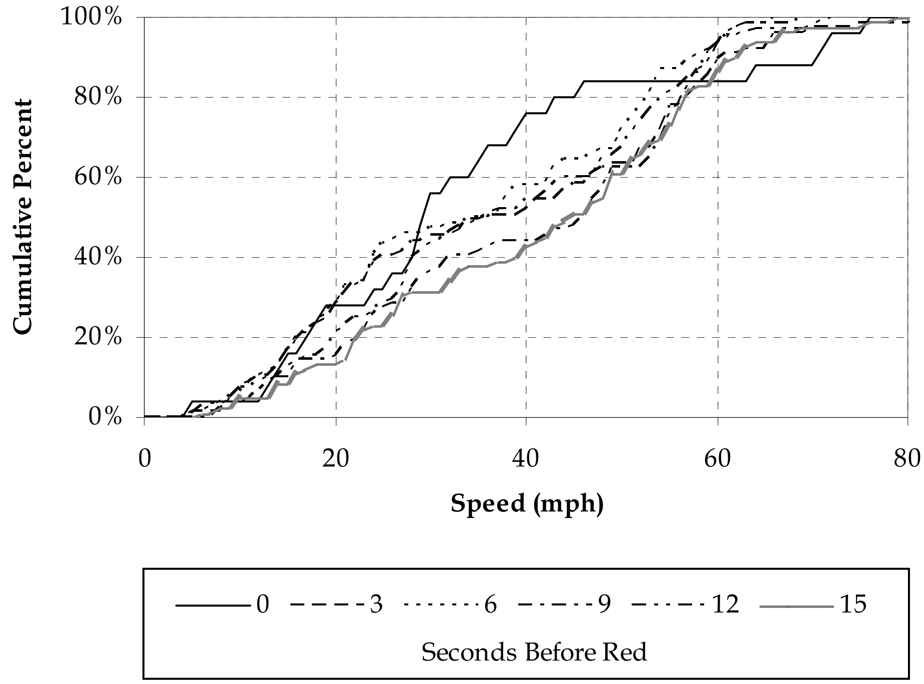

Figure ES-1. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone before the AWS system was installed.

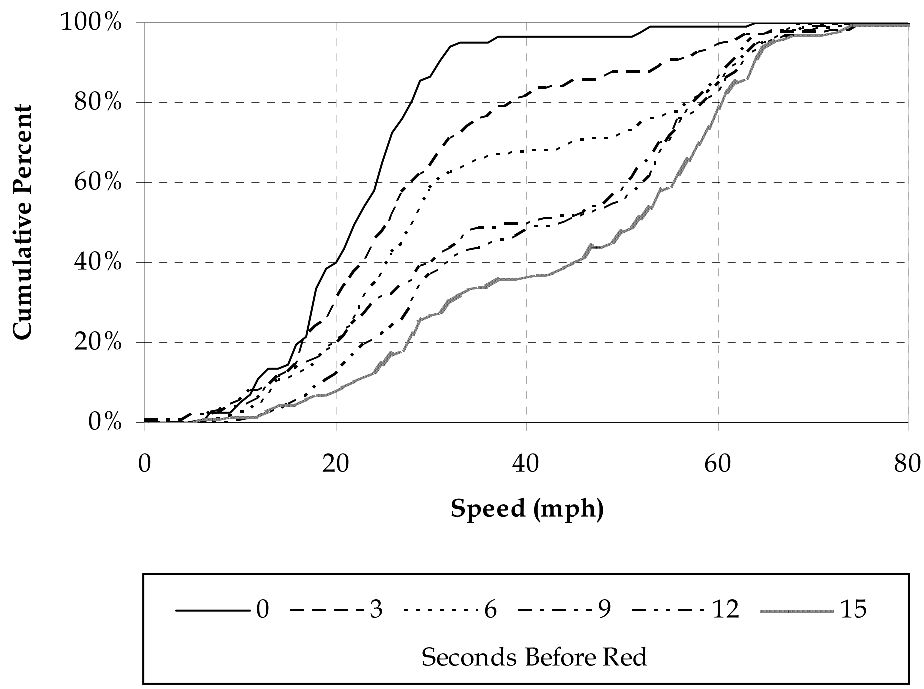

Figure ES-2. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone immediately after installation of the AWS system.

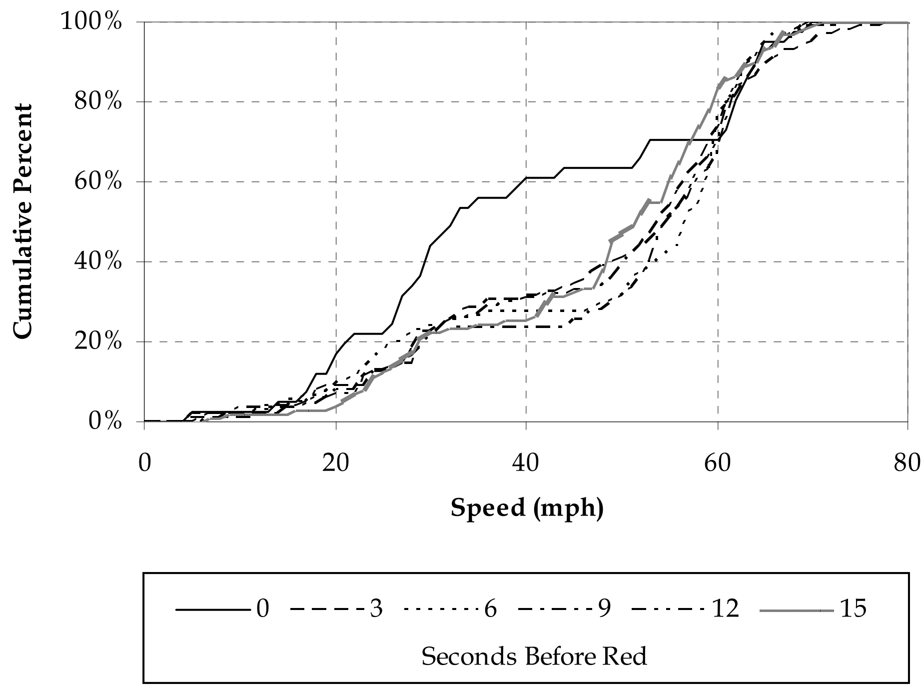

Figure ES-3. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone eight months after installation of the AWS system.

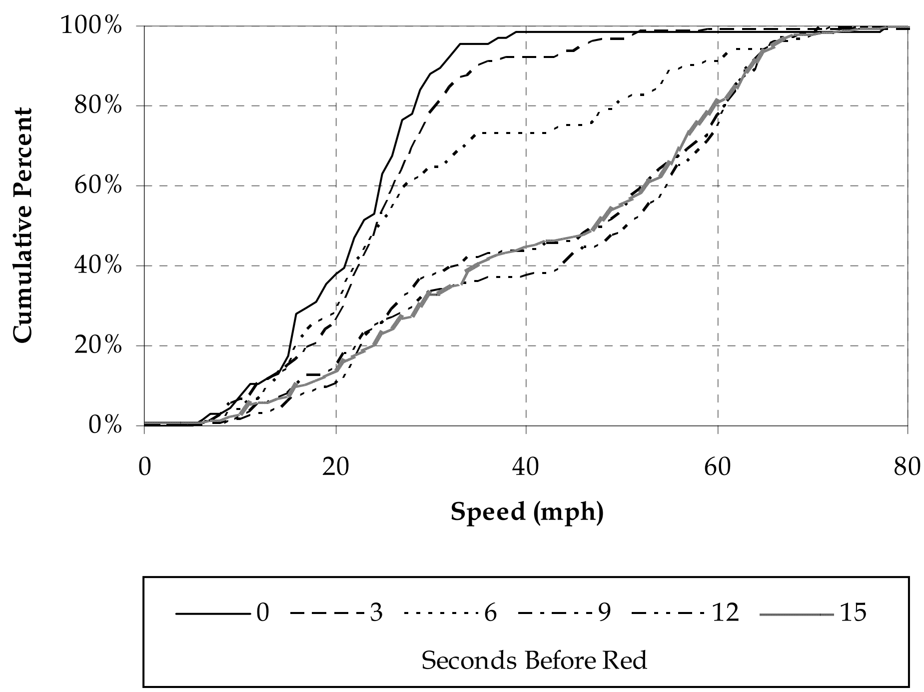

Figure ES-4. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone immediately after adjusting the lead flash to 4 seconds.

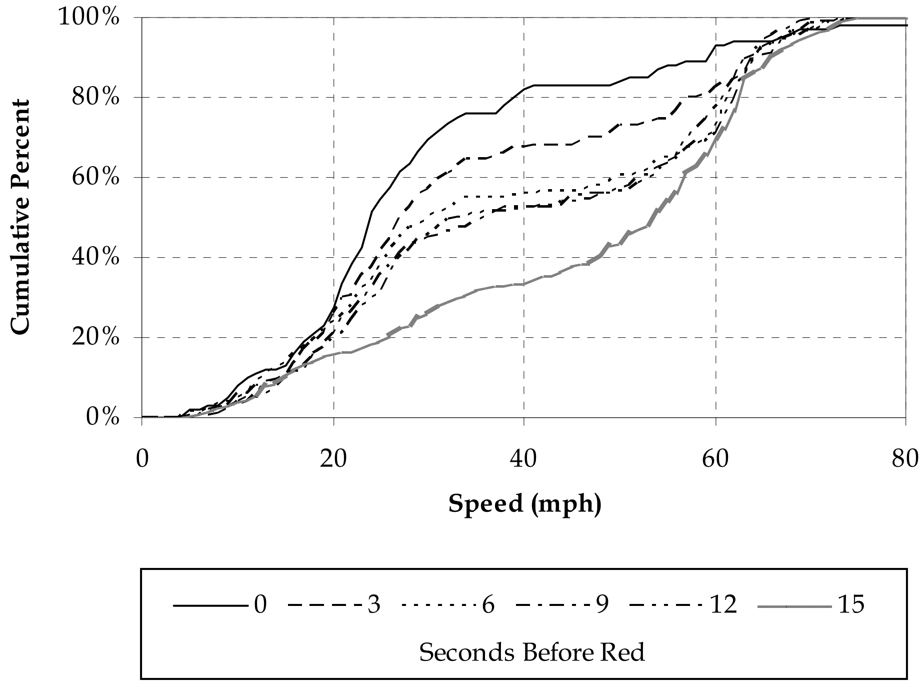

Figure ES-5. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone two years after installation of the AWS system.

It was found that the lowest 85th percentile speeds decreased from 62 mph to 31 mph immediately after the reduction in lead flash timing then increased to 52 mph two years later, which is 3 mph lower than the lowest 85th percentile speed before the installation of the AWS system. Although in general speeds decreased, they also became more variable, as illustrated by the fact that median speeds decreased more than did the 85th percentile speeds, which stayed about the same or, in some instances, increased. These trends suggest that the lead flash timing of 4 seconds resulted in lower speeds, which may lead to increased safety at the intersections, but that more variable speeds also resulted, which may have a negative impact on safety.

Red Light Running Results

RLR events were recorded at the study intersection with the resulting RLR rates calculated. Before the installation of the AWS system, the RLR rate for the northbound approach was approximately 7 events per thousand entering vehicles (PTEV).

Immediately after the installation of the AWS system and immediately after the changes in the lead flash timing, the RLR rate decreased to less than 2 events PTEV. However, the RLR rates for eight months and more than two years after the installation of the AWS system were 13.8 and 12.6 events PTEV, respectively. This may suggest that after drivers become accustomed to the AWS system, the AWS system may have encouraged more RLR. However, the increase in RLR could be a result of increased traffic volumes, construction, or changes in signal timing and coordination at the intersection. As recorded previously, however, an analysis of crash data did not show an increase in the overall number of RLR crashes at the intersection.

Conclusions

The conclusions that can be drawn from this research are that overall the AWS system has been effective as it has helped to improve operations at the intersection as operating speeds have been maintained throughout the corridor as evidenced by the speed distribution results. The additional information provided to the driver, however, has encouraged some drivers in the long-term to attempt to beat the light as evidenced by the increase in RLR, even with the "tightening" of the lead-flash time. The slight increase in RLR, however, has not led to a decrease in safety, as evidenced by the crash analysis results.

While this study has suggested both positive and negative results of the AWS system, it is difficult to make many strong conclusions on the effectiveness of the AWS system on safety because of the multitude of factors that changed at the intersections over the course of the study. Although it does appear as though the AWS system has been effective, to more conclusively determine the effect of the AWS system only, it would be necessary to collect data at more AWS-equipped and control intersections over a similar time period, but with less external changes to the system. Overall, however, the results are promising, particularly with respect to crash results and speed distributions. Although the RLR appears to have increased following long-term monitoring, this has not resulted in an increase in crash frequency or crash rate at the study intersection. The feedback on the installations has continued to be positive and the study successful.

1 Introduction

The purpose of this report is to present the long-term results of a study conducted to determine the effectiveness of a system that had not previously been used anywhere in the country, designed to increase the safety of a high-speed signalized intersection in Utah. This introduction includes a problem statement, background and overview of the study, previous results, the study objective and a report outline.

1.1 Problem Statement

A driver approaching a signalized intersection where the light has turned yellow must make a decision whether to stop or proceed. A signal that is properly designed will provide an opportunity for a safe and legal maneuver. However, as the approach speed increases, choosing the correct option becomes more difficult for the driver. The driver may decide to proceed when the correct option is to stop, and run the red light; or the driver may decide to stop when the correct option is to proceed, and could cause a rear-end crash. Because of this, many high-speed signalized intersections have high rates of red-light running (RLR), conflicts, and crashes (*1*, *2*).

One countermeasure that is used at such intersections is the installation of a dynamic advance warning signal (AWS) system (*3*). This system consists of a sign and warning lights that are placed upstream of the intersection. The purpose of an AWS system is to warn drivers of an approaching intersection or the impending signal change at an approaching intersection. The desired results include a reduction in RLR and a safer speed distribution, with the ultimate goal being improved safety at the intersection. There has been concern in the past that in the long-run, dynamic AWS systems may actually encourage higher speeds, which results in decreased safety. A possible reason for this concern is that after an extended period of time, drivers may learn to use the system to accelerate on the yellow and "beat the light" (*4*, *5*).

While many studies have addressed the question of the effectiveness of AWS systems, few have included data from more than six months after the installation of an AWS system. This results in a lack of information on the long-term effects of AWS systems. In addition, most studies addressing the effectiveness of AWS systems have focused on effects on RLR, speed distributions, and conflict rates. Few studies have focused on the effect of AWS systems on crash rates, which means that there is little information on the effect of AWS systems on this important safety metric (*6*). In order to evaluate the effectiveness of AWS systems, it was necessary to gather more information on the long-term effects of AWS systems, and on the effect of AWS systems on crash rates.

1.2 Background and Overview

The subject of this report is a study of the effects of an AWS system at an intersection of Bangerter Highway in Riverton, UT. This system was installed by the Utah Department of Transportation (UDOT) in response to concerns about safety and abrupt stops by trucks which were damaging the pavement. The system consists of a blank-out overhead dynamic advance warning signal (BODAWS), flashers mounted next to the sign, and advance video detection. The system was installed at three intersections on Bangerter Highway and at one intersection on S.R. 201 in Salt Lake County during June 2005. Data on speeds and RLR were collected at one of the intersections on Bangerter Highway (Bangerter Highway and 13400 South) before and after the installation using the SmartSensor Advance™ sensor with Digital Wave Radar™ technology. Crash data for the three intersections were collected from UDOT reports compiled from law-enforcement crash reporting forms. Crash data were also collected for a control intersection with the before and after data compiled and compared to determine the effects of the AWS.

1.3 Previous Research

The first phase of this research was the subject of a previous UDOT research report UT-06.11, entitled “Evaluation of Advance Warning Signal Installation: Phase I Final Report” (*7*). The Phase I Final Report analyzed the results of the AWS installation from a period just prior to the installation to a time period extending eight months after the activation of the new system. The results of the Phase I report were used to form the basis of a separate research project, UDOT report UT-07.06, “Evaluation and Installation Guidelines for Utah Advance Warning Signal Systems” (*8*). Report UT-07.06 developed guidelines for installation of AWS systems, while summarizing the design criteria for such systems. This Phase II report presents results of the AWS installation for a time period extending more than two years after the activation of the new system. This report is complete in the presentation of results and can be understood without reading the Phase I report or the Evaluation and Installation Guidelines report, however, the reader is advised to refer to the Phase I report and the Evaluation and Installation Guidelines report for a full review and analysis of the BODAWS system.

1.4 Study Objective

The objective of this study is to determine the long-term effects of the BODAWS system on safety by analyzing long-term speed, RLR, and crash data.

1.5 Report Outline

Following this introduction, this report will first review the results of previous studies on the effectiveness of AWS systems, and then give the background of this study. Next, a description of the implementation and results of speed, RLR, and the crash rates analysis will be given, followed by study conclusions. The report will conclude with references and appendices.

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2 Literature Review

Traffic at a high-speed signalized intersection (HSSI) can be dangerous because of erratic driving behavior when the yellow interval begins. Two countermeasures that have been used to improve safety at these intersections are advance detection (AD) and AWS systems. The effectiveness of these countermeasures has been evaluated in several studies. This chapter will summarize the safety problems of a HSSI and explain two possible countermeasures used to improve safety. This chapter will also summarize the results of studies of the overall effectiveness of AWS systems.

2.1 Safety Problems at High Speed Signalized Intersections

When the signal at an intersection turns from green to yellow, drivers must decide whether to stop or to proceed through the intersection. This decision is very easy for drivers who are either very close to the intersection, or very far from the intersection. Those that are very close the intersection will almost always decide to proceed, entering the intersection before the light turns red. Those that are very far from the intersection will almost always decide to stop before entering the intersection. However, the decision is more difficult for drivers between 2 and 5 seconds from the intersection when the light turns yellow. A signal that is improperly timed will create a dilemma zone (DMZ) for these drivers, where they do not have enough time to enter the intersection before the light turns red, and do not have enough distance to stop before entering the intersection. Even when the signal is properly timed, the decision to stop or proceed when in this zone is difficult to make. The zone to which this refers is called the decision zone (DCZ). The DCZ is usually defined to be the area on the approach from the point where drivers have a 90 percent probability of stopping upon the start of the yellow interval to the point where drivers have a 10 percent probability of stopping upon the start of the yellow interval (*7*). For drivers in the DCZ, it is not easy to tell whether there is enough time to enter the intersection before the light turns red, or whether there is enough distance to safely stop before entering the intersection. As a result, driver behavior in the DCZ is more erratic and unpredictable. For example, some drivers will decide to proceed through the intersection when in fact they do not have enough time to enter the intersection before the light turns red. Others will decide to stop, even though they don't have enough distance to do so safely. This erratic behavior leads can to RLR, rear-end crashes, and other safety concerns. The problem becomes even more severe when drivers approach the intersection at high speeds (*7*, *9*).

Two possible methods for mitigating the safety problem at HSSI are AD and AWS systems. These two methods are discussed in the next two sections.

2.1.1 Advance Detection

One method that is used to alleviate the problem of erratic driving at HSSIs is AD. The purpose of AD is to allow the signal to change from green to yellow only when there are no vehicles in the DCZ. This is accomplished through the use of a detector, such as a magnetic loop or video detection camera, placed some distance upstream of the DCZ. When a vehicle is detected, the green interval is extended for a preset period of time to allow the vehicle to exit the DCZ. The amount of time that the green is extended depends on the length of the decision zone, the distance of the detector from the DCZ, and the speed of the vehicle. If no additional vehicles are detected during this time interval, then there is a 'gap' in traffic, the DCZ is empty, and the signal can be changed from green to yellow. If approach volumes are high, there may not be a gap large enough to allow the light to turn yellow. In this case, a maximum green time is set after which the light will turn yellow regardless of whether there are vehicles in the DCZ. The benefits of AD are lost when the maximum green time is reached (*5*, *7*).

2.1.2 Advance Warning Signals

An AWS system is another alternative to improve safety at HSSIs. There are two general categories of AWS systems: static and dynamic. This paper will address mainly dynamic AWS systems, but static AWS systems will also briefly be described here for comparison.

2.1.2.1 Static Advance Warning Signal Systems

A static AWS system usually consists of a warning sign accompanied by continuously alternate flashing yellow lights (flashers), but can also consist of a warning sign only. Two types of warning signs commonly used for this purpose are the "Signal Ahead" sign, and the symbolic signal ahead sign. These signs serve to warn drivers of the approaching signalized intersection. A symbolic signal ahead sign without flashers is shown in Figure 2-1 (*10*).

Figure 2-1. Static AWS Sign without Flashers (*10*).

2.1.2.2 Dynamic Advance Warning Signal Systems

In a dynamic AWS system, the message that is communicated to drivers can be changed according to the status of the downstream signal. This is usually accomplished with warning signs bearing the message "Prepare To Stop When Flashing," accompanied by flashers. The flashers are usually off, with the exception that they begin flashing a predetermined time before the signal turns yellow to warn drivers of the impending signal change, and remain flashing throughout the red interval. A dynamic AWS sign of this type is show in Figure 2-2 (*7*).

Figure 2-2. Dynamic AWS sign (*7*).

Another type of dynamic AWS sign consists of an electronic display which is usually blank, but which displays the message “Prepare to Stop” starting a predetermined time before the light turns yellow, until the end of the red interval. This type of sign can also be accompanied by alternating flashers (*3*).

The dynamic AWS sign is placed at a distance from the intersection and timed such that those drivers who have passed the sign before the beacons start flashing will have time to enter the intersection before the light turns red. Drivers who have not passed the sign when the beacons start flashing are too far away to enter the intersection before the light turns red. These drivers see the flashing beacons and are warned to stop. The purpose of dynamic AWS systems is to reduce unpredictable driving by warning drivers that the signal is about to change from green to yellow and that they should stop. Dynamic AWS signs are usually used with AD to maximize safety and functionality (*3*, *7*).

The BODAWS system is one type of dynamic AWS system. The BODAWS sign consists of an electronic display accompanied by flashers. A predetermined time before the signal turns yellow, the electronic display shows the message “Prepare to Stop” and the flashers are activated (*7*). More details on the BODAWS system will be provided in Chapter 3.

2.2 Studies of the Effectiveness of AWS Systems

The results of studies evaluating the effectiveness of dynamic AWS systems are mixed. Many studies show increased safety after the installation of an AWS system at an intersection (*9, 11*), or greater safety at intersections with AWS systems as compared to intersections without AWS systems (*2, 12*). However, other studies show a reduction or no significant difference (*1, 5, 6*). Some studies conclude that AWS systems can increase safety, but may not necessarily increase safety at all intersections or under all conditions (*1, 12*).

One possible reason that AWS systems result in reduced safety is because the positive effects are often considered to be short-term results of novelty only (*5*). After drivers become accustomed to the AWS system, they may actually use the system to “beat” or “race” the signal (*4, 11*). When drivers see the AWS start to flash, rather than stopping, they accelerate to an unsafe speed so that they can enter the intersection before the light turns red. Many of these drivers will not make it and run the red light at a very high speed. In order to determine the effectiveness of AWS systems, it is necessary to evaluate their long-term effect on safety, after the effects of novelty have ended. However, there is a lack of literature on the long-term effects of AWS systems. Of the documents reviewed, only four reported data from more than six months after the installation of an AWS system (*1, 2, 6, 11*).

There are several measures that can be used to evaluate the effectiveness of AWS systems. These include:

- speed distribution as related to signal phasing and start of flashing;
- speed distribution as related to distance from the intersection;

- frequency of conflicts such as abrupt stops, accelerating on the yellow, and running the red light;
- percent of vehicles in dilemma zone;
- percent of max-out green intervals; and
- crash rates.

While all of these measures are valuable, crash rates are the ultimate measure of intersection safety. Because of this, an evaluation of the effect of an AWS system on safety should include its effects on crash rates. However, there are relatively few studies that use crash rates as a measure of effectiveness. Most studies focus on the non-crash rate measures (*6*). This literature review will summarize the results of studies that use non-crash rate measures, but will focus on studies that do use crash rates.

To accomplish this objective, this section of the literature review is divided into two sub-sections. The first sub-section describes short-term studies of AWS systems that do not include crash rates as a metric. The second sub-section describes studies that include long-term data, or include crash rates as a measure of effectiveness, or both.

2.2.1 Short-term Studies That Do Not Include Crash Rates as a Measure of Effectiveness

A study in Minnesota used a camera to record RLR events at an intersection for approximately 54 days before the AWS system was installed and for approximately 54 days immediately after the AWS system was installed. The study found a 29 percent overall reduction in RLR, a 63 percent reduction for trucks, and an 18.2 percent reduction for cars. The Minnesota study did not show a decrease in the speed of the vehicles that ran the red light, and the authors expressed a concern that the drivers were using the flashers to “over drive” the system. The study did, however, find a considerable decrease in the speed of trucks that ran the red light (*11*).

A before-and-after study was conducted at two intersections in Texas where a dynamic AWS system was installed. The before data included two weeks immediately before the installation, and the after data included up to four months after the installation. The study found an average reduction of 43 percent in RLR (*9*).

McCoy and Pesti compared an AWS system to a system which consisted of AD only. It was found that AWS system resulted in improved performance in terms of reduction in percent of vehicles in the DCZ and percent of max-out green intervals. The authors warned, however, that anecdotal evidence suggested that the positive effects may be a result of the system's novelty, and that the positive effects may be reduced over time. There was no significant difference in percent of vehicles running the red light, stopping abruptly, and accelerating on the yellow (*5*).

2.2.2 Long-term Studies and Studies That Include Crash Rates as a Measure of Effectiveness

Sayed et al. used volume, traffic and AWS system data from 106 signalized intersections and covering three years to develop accident prediction models to estimate the effects of AWS systems on accident frequency. Intersections with AWS systems were compared to intersections without AWS systems, and it was found that intersections with AWS systems have on average 10 percent fewer total crashes and 12 percent fewer severe crashes. Reduction in rear-end crashes was negligible. However, none of these changes was found to be significant at the 95 percent level. Before and after crash rates for intersections where AWS systems were installed were also compared. On average, the total, severe, and rear-end crash rates were all reduced after the AWS systems were installed. However, the change in crash rates varied considerably for each intersection, from a large decrease in crash rates to a large increase in crash rates, and the results were again not found to be significant at the 95 percent confidence level. AWS systems were found to have a greater effect in reducing crash frequency at locations that have a high minor street volume than at locations with a low minor street volume (*6*).

Gibby et al. used 10 years of crash data for 40 high-speed isolated signalized intersections to determine the effect of AWS systems on intersection crash rate. Gibby divided the type of advance warning into four categories: none; AWS only; advance flashers only; and both advance signs and advance flashers. It was found that intersections with AWS systems had significantly lower total, right-angle, left-turn, and rear-end crash rates than intersections without AWS systems (*2*).

Pant and Huang reported on the effectiveness of two types of static advanced warning signs: passive symbolic signal ahead (PSSA), and continuously flashing symbolic signal ahead sign (CFSSA); and two types of dynamic advance warning signs: prepare to stop when flashing (PTSWF), and flashing symbolic signal ahead (FSSA). "After" data was collected at least six months after the sign change at the intersections. Data collected to evaluate the effectiveness of the signs included speed data for various distances before the intersection and various states of the dynamic signs and signals. Conflicts such as RLR, abrupt stops and accelerating through yellow were also recorded. It was found that the PTSWF signs seemed to encourage higher speeds on a tangent approach than did the static signs when the flashers were off when vehicles arrived at the AWS sign and the light was green or yellow when the vehicles crossed the stop bar. For the curved approach with PTSWF signs, speeds increased when the flashers were inactive and the signal was yellow, but stayed the same when the flashers were inactive and the light was green. The tangent approach with PTSWF signs showed no significant change in conflict rates, as defined by the occurrence of RLR, accelerating on the yellow, and abrupt stops. The curved approach with PTSWF signs showed an increase in conflict rates. For an intersection with a tangent approach and a FSSA sign, speeds upstream of the FSSA sign increased when the flasher was active and the signal was red. Speeds at all locations were higher when the flashers were active and the signal was green. For a curved approach with FSSA signs, the mean speed near the intersection decreased when the signal was red. Conflict rates for the tangent approach remained the same, or did not decrease for both types of approaches. The authors concluded that the use of dynamic AWS systems should be discouraged, especially on tangent approaches, because they seemed to encourage higher speeds (*1*).

A similar study by Pant and Yuhong compared dynamic PTSWF and FSSA signs to static CFSSA signs. The study found that the dynamic signs generally encouraged higher speeds near the intersection for tangent approaches. It was also found that the PTSWF sign may help reduce speeds on curved approaches during the red interval. The authors concluded that static CFSSA signs should be considered for installation before dynamic signs, and that the use of PTSWF signs on tangent approaches should be discouraged (*4*).

A Minnesota study compared RLR rates and speed distributions for two AWS-equipped intersections to an intersection with no AWS system. The data was collected at least five years after the installation of the AWS system. It was found that the non-AWS intersection had higher RLR rates than the intersections with an AWS system. It was also found that speeds were the same for all intersections during the green and red intervals, but speeds were higher for the intersections with AWS during the yellow interval. The study also included a before-and-after evaluation of accident rates at 14 intersections equipped with AWS systems. The study included three years of before data and three years of after data. It was found that intersections with an AWS sign located 1000 feet from the intersection had a significant decrease in both total and right-angle and rear-end crashes. These intersections started with a crash rate significantly above average for all intersections in the region. Intersections with an AWS sign located 550 feet from the intersection had a slight increase in both categories. These intersections started with a crash rate close to the regional average. It was concluded by the authors that intersections that have a higher-than-average crash rate can benefit from an AWS system. Crash rates for all 14 intersections for the most recent six years were compared to crash rates for the three "after" years, and little change was found (*12*).

2.3 Chapter Summary

This chapter has explained the safety problems at HSSIs, and the countermeasures used to improve safety. Studies evaluating the effectiveness of AWS systems were reviewed. The results of these studies varied, with some studies showing desirable effects after the installation of an AWS system, some showing negative effects, and some showing both. The reader is encouraged to refer to the literature review in UDOT reports UT-06.11 (*7*) and UT-07.06 (*8*) for additional information on the available literature on AWS systems. The next chapter of this report will present the background of this study.

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3 Background

This report describes the results of a study conducted to determine the effectiveness of an AWS system installed at three intersections on SR-154 (Bangerter Highway) in Riverton, Utah and at one intersection on S.R. 201 in Salt Lake County, Utah, in June 2005. The configuration of this particular system had not been implemented elsewhere in the country and was of particular interest to the state. This chapter focuses on the Bangerter Highway installations by describing the area where the AWS systems were installed, the need for AWS systems on Bangerter Highway, and the components and operation of the AWS system.

3.1 Location and Site Description

The location of the AWS systems installed on Bangerter Highway in Riverton, Utah is shown in Figure 3-1. The AWS systems were installed at the intersections of Bangerter Highway with 13400 South, 2700 West, and Redwood Road. In addition to the AWS sites, data were also collected at the intersection of Bangerter Highway and 12600 South for use as a control site.

Bangerter Highway is a divided suburban and rural multilane facility, with a posted speed limit of 60 mph. At the start of the study period, it had two lanes in each direction, but by the end of the study period an additional lane was added in each direction through a re-striping project. Bangerter Highway has limited access, with intersections spaced about one mile apart in the study area. The land uses surrounding Bangerter Highway in the study area include suburban development and rural open areas, with commercial and residential developments concentrated around each intersection, as shown in Figure 3-2 (*7*).

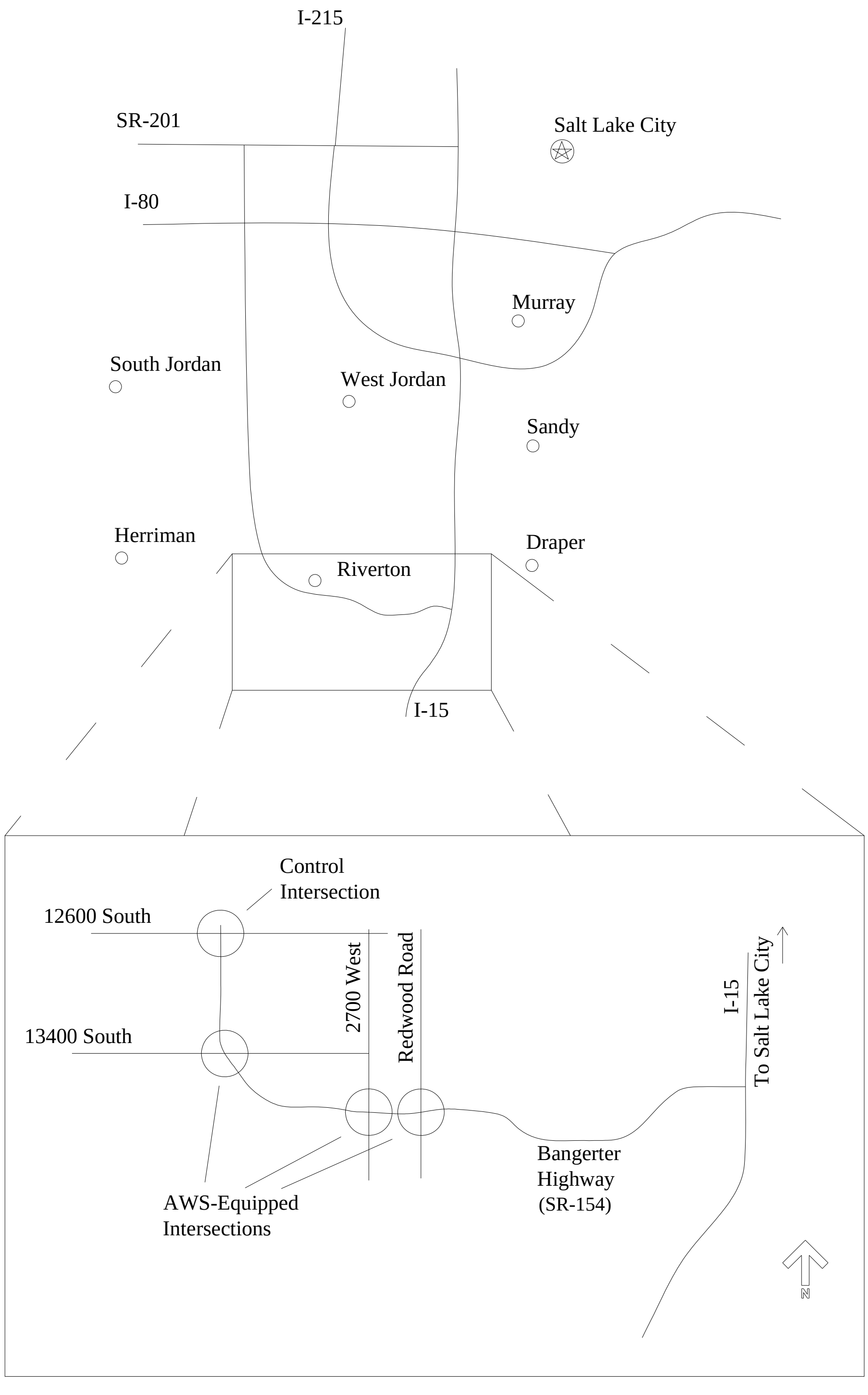

Figure 3-1. Study location (*7*).

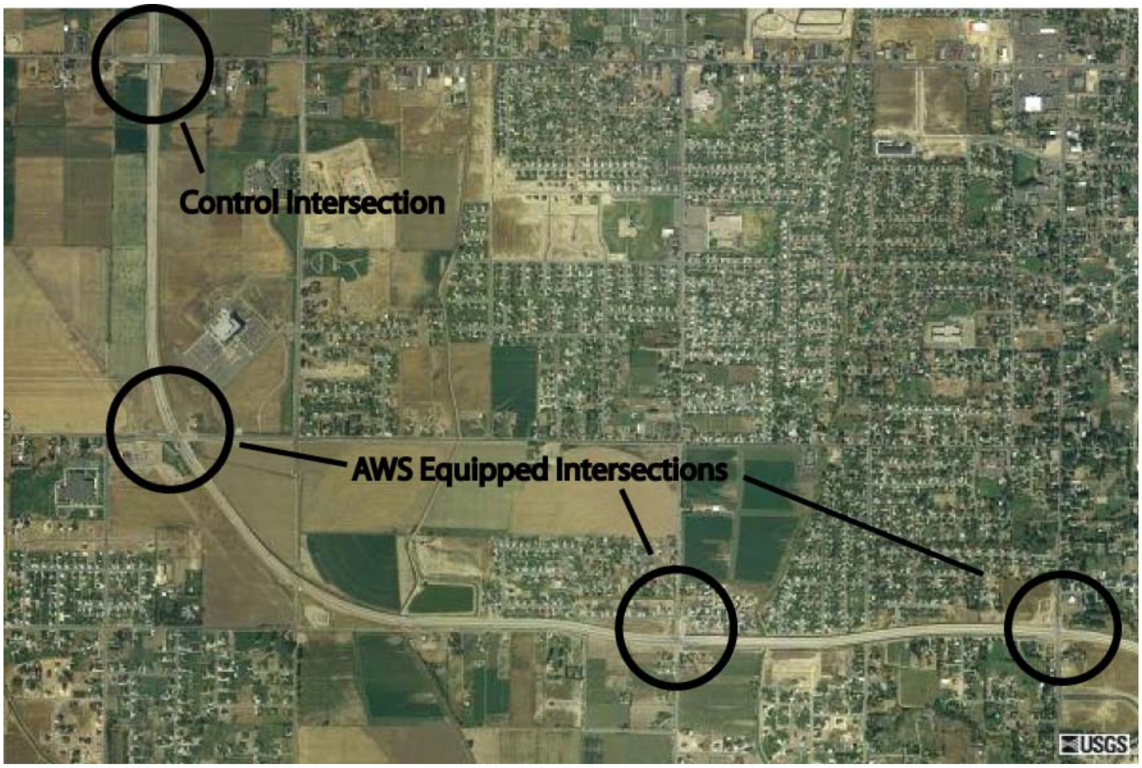

Figure 3-2. Study and Control Intersections Aerial Photograph (*13*).

3.2 AWS System Need

Before the AWS systems were installed, UDOT officials expressed concerns about the high frequency of skidding and load spills caused by abrupt stops by trucks at intersections along Bangerter Highway. UDOT officials also had concerns about possibility of crashes and RLR at these intersections. In response to these concerns, UDOT hired a consultant (Project Engineering Consultants) to design a system to mitigate the safety problems (*7*).

The consultant designed a system based on a study completed by McCoy and Pesti for the Nebraska Department of Roads (*14*). The consultant used the recommendations of the study to determine AWS location and timing, and to determine AD locations. The consultant and UDOT officials also proposed the use of a large electronic display located over the traffic lanes, instead of yellow warning signs located on the sides of the road. The components and operation of the AWS system are detailed in the next section.

3.3 Components and Operation of the AWS system

The AWS system consists of two major components: the AWS component, and the AD component. The AWS component includes an electronic LED display that, when activated, displays the message “PREPARE TO STOP.” When it is not activated, the display is blank. The sign is accompanied by two flashers, which flash alternately when the sign is activated, and are dark when the sign is inactive. Because of the “blank out” nature of the signs, they have been referred to in the Phase I research as “Blank-out overhead dynamic advance warning signal” (BODAWS) systems. The sign and flashers are mounted on a mast arm above the traffic lanes, as illustrated in Figure 3-3. The AWS sign was installed 445 feet from the stop bar, in accordance with McCoy and Pesti’s recommendations for a 55 mph design speed, and a 65 mph 85th percentile speed (*14*). This location is designed to allow only drivers who are at least one stopping distance away from the intersection to see the sign (*7*).

Figure 3-3. AWS sign (*7*).

The AD component consists of a video detection camera mounted on a light pole with one optical detection zone that covers all lanes of travel. The camera is located 705 feet from the intersection, with the optical detection zone at 755 feet from the intersection, again in accordance with guidelines from the McCoy and Pesti study (*14*). With these guidelines, the distance between the AWS sign and the advance detector is determined to be the distance traveled by a vehicle during the passage time (gap-out time), plus the minimum distance needed for a driver to perceive the AWS sign.

The operation of the AWS system involves the interaction of the AWS sign with the downstream signal. Specifically, the operation of the AWS system is defined by the amount of time before the start of the yellow interval that the AWS sign is activated. This amount of time is called the lead flash time. The lead flash time was initially set according to the McCoy and Pesti guidelines to be 6 seconds. This is defined as the time it takes a vehicle to travel from the last location where the AWS sign is legible to the stop bar. It is also equal to the time it takes a vehicle to travel the stopping distance.

Preliminary results of the study showed that a high number of vehicles were running the red light at very high speeds. It was theorized that the AWS system gave drivers enough time to accelerate through the intersection before or shortly after the light turned red. In an effort to mitigate this problem, the lead flash time was changed from 6 seconds to 5 seconds on April 21, 2006, then from 5 seconds to 4 seconds on May 23, 2006. The lead flash has remained constant at 4 seconds throughout the remainder of the study.

3.4 Data Collection

UDOT contracted with researchers at Brigham Young University (BYU) to evaluate the effectiveness of the AWS systems. A before-and-after crash rate study was conducted for the three AWS-equipped intersections and the control intersection. The ‘before’ period included in the study was June 8, 2003 to June 7, 2005. The ‘after’ period was June 8, 2005 to June 7, 2007. This was two years before and two years after the installation of the AWS system.

A before-and-after speed and RLR study was conducted for the intersection with 13400 South (one of the locations where the AWS system was installed). The 'before' period for this analysis included April 27, 2005 to June 7, 2005. The 'after' period included data collected from June 8, 2005 to October 20, 2007. This was about six weeks before the installation of the AWS system and about two years and four months after. The 'after' period was divided into five periods to facilitate speed and RLR data analysis. These periods will be explained in Chapter 4.

3.5 Chapter Summary

This chapter explained the background of the study. Because UDOT officials were concerned about possible RLR and crashes at intersections on Bangerter Highway, a consultant was retained to design a system that would improve safety. The consultant designed a system based on the work of McCoy and Pesti, and recommended the use of an electronic LED sign installed above the traffic lanes. Before installation of the AWS system, UDOT contracted with researchers at BYU to evaluate the effectiveness of the AWS system installation according to speed, RLR, and crash data measures of effectiveness. Initial results of the evaluation recommended a change in the lead flash time from the value recommend by McCoy and Pesti to reduce the possibility of "beating the system" to include the DCZ distance in the analysis. Details on the long-term analysis results for the crash rate, speed and RLR are provided in the chapters that follow.

4 Crash Rate Analysis

One of the measures of effectiveness that was used in the evaluation of the AWS systems was crash rates. Crash rates are one of the principal measures of intersection safety, therefore, a significant reduction in crash rates is oftentimes correlated to an improvement in safety. This study compares the change in crash rates for each of the study intersections after the installation of the AWS system to the change in crash rates for the control intersection for the same time period. This chapter will first describe the implementation of the crash rates study, then it will present the results and give a discussion of the results.

4.1 Implementation

The implementation of the crash rates study involved the collection of raw data and the processing of the data. The raw data were obtained from UDOT and police reports. Data were selected for inclusion in the study were categorized according to intersection, time period, type of crash, and route of travel of involved vehicles. The crash rates were then calculated using average daily traffic (ADT) numbers from UDOT ADT maps. Finally, the results were presented in tables for comparison purposes.

4.1.1 Raw Crash Data

Crash data was obtained for the four intersections (three study sites and one control site) on Bangerter Highway for the time period between June 8, 2003 and June 8, 2007. The numbers and types of crashes occurring through the end of 2006 were obtained from UDOT records. These records were provided in spreadsheet format, and included a summary of data obtained from reports produced by police officers at the scene of the crash. Numbers and types of crashes occurring during the first part of 2007 were obtained directly from police reports as they were not available in summary form at the time of the analysis. Both the UDOT records and the police reports included crashes that occurred between mile posts three and seven on Bangerter Highway. This mile post range covers the three AWS-equipped intersections as well as the control intersection at 12600 South. The center mile posts for the four intersections were also provided by UDOT.

4.1.2 Criteria for Inclusion in Study

To be included in the crash study, each crash must have had at least one vehicle traveling on Bangerter Highway and the crash must have been intersection-related. The crash records provided by UDOT and the police reports were used to determine if each crash met these criteria, as explained in the paragraphs that follow.

The UDOT crash records and the police reports include an entry for the direction of travel (north, south, east, or west) of each vehicle involved in each crash. The direction of travel of each vehicle was used to determine if each vehicle was traveling on Bangerter Highway. Bangerter Highway runs east-west where it intersects Redwood Road and 2700 West. Vehicles that were traveling east or west near the Redwood Road and 2700 West intersections were traveling on Bangerter Highway. Vehicles that were traveling north or south in the same area were traveling on a cross street. Just west of 2700 West, the alignment of Bangerter Highway shifts to the north. As a result, Bangerter Highway runs north-south where it intersects 13400 South and 12600 South. Vehicles that were traveling north or south near the 13400 South and 12600 South intersections were traveling on Bangerter Highway, while vehicles that were traveling east or west in the same area were traveling on a cross street.

The UDOT crash reports also include entries for manner of collision (collision type) for each crash, and entries for vehicle maneuver for each vehicle involved in a crash. These were the two entries used to determine if a crash occurred at an intersection (i.e., if it was intersection-related). In the range of mile posts for which crash data were provided the only cross streets were the four streets included in this study. Therefore, crashes which involved a vehicle executing a turning maneuver were determined to have occurred at one of the intersections. These included crashes with vehicles executing "Turning Left," "Turning Right," and "Making U-turn" maneuvers. Likewise, crashes which had a collision type that indicated an intersection-related incident were included in the study. These included collision types "Angle," "Front to Rear," "Head On," and "Sideswipe Opposite Direction." The last two collision types were included because Bangerter Highway is divided by a concrete barrier, so it is extremely unlikely that head on or sideswipe crashes in the opposite direction occurred at a location other than an intersection.

The crashes that were selected for inclusion were assigned to one of the four intersections based on which intersection was nearest. This was done by comparing the mile post for the crash, as given in the crash records, to the mile post for the center of each intersection. With this criterion, some of the crashes would have been linked to an intersection through which the involved vehicles had already passed. Also, it was difficult to determine which intersection to assign a crash to, when it occurred near the mid-point between two intersections. However, virtually all crashes of these types were eliminated from inclusion in the study because of their collision types or the maneuvers of the involved vehicles.

4.1.3 Crash Categories

The crashes were divided into three primary categories: rear-end, right-angle, and other. Rear-end crashes included crashes involving vehicles traveling on the same approach which were involved in a front-to-rear collision. Right-angle crashes included crashes which involved vehicles traveling on approaches which were at a right angle to each other, and crashes which involved at least one vehicle executing a turning movement. Other crashes included crashes which do not fit in rear-end or right-angle categories, including head-on and single vehicle crashes.

Crashes were further categorized by the route of travel of the involved vehicles. The first category was crashes that included at least one vehicle traveling on Bangerter Highway. The second category was a subset of the first, and included crashes where all involved vehicles were traveling on Bangerter Highway. Crashes that did not involve any vehicles traveling on Bangerter Highway were not included in the study.

4.1.4 *Time Intervals*

The crashes were also divided into four, one-year time intervals, with two years before the activation of the AWS system and two years after the activation. The date ranges for each of these one-year intervals are summarized in Table 4-1.

Table 4-1. Time Intervals for Crash Rates Study

	Starting Date	Ending Date
Before	June 8, 2003	June 7, 2004
	June 8, 2004	June 7, 2005
After	June 8, 2005	June 7, 2006
	June 8, 2006	June 7, 2007

4.1.5 *Crash Rates Calculations and Presentation of Data*

The ADT values for each calendar year were obtained for Bangerter Highway at each of the four intersections, and for each of the four cross streets, from UDOT records. ADT values were used to calculate the crash rate per million entering vehicles (MEV) for each crash group. For the "all vehicles on Bangerter" category, only the ADT values for Bangerter Highway were used, as shown in Equation 1. For the "at least one vehicle on Bangerter" category, the sum of the Bangerter Highway and cross street ADTs were used, as shown in Equation 2. Tables summarizing the ADT values for each year and each location are provided in Appendix A.

The crash frequencies for each time interval and crash type were tabulated, along with the corresponding crash rates, as calculated with Equations 1 and 2. Tables showing the crash frequencies for each of the four one-year time intervals are presented in Appendix B. Tables showing the crash rates for each of the one-year time intervals are presented in Appendix C. Before-and-after summary tables are presented in Section 4.2. The before-and-after summary tables combine the data into two, two-year intervals which correspond to the entire period of data collection before the activation of the AWS system, and the entire period of data collection after the activation of the AWS system.

$$B\_RMEV_{ij} = \frac{N_1 \times 1{,}000{,}000}{(207 \times ADT_1) + (158 \times ADT_2)} \quad (1)$$

where: B_RMEV_{ij} = crash rate per million entering vehicles, for Bangerter-only crashes, for time interval *i* and crash type *j*;

N_1 = number of crashes involving only vehicles traveling on Bangerter Highway for time interval *i* and crash type *j*;

i = index for time intervals;

j = index for crash types;

ADT_1 = average daily traffic on Bangerter Highway of the first calendar year overlapped by the time interval; and

ADT_2 = average daily traffic on Bangerter Highway of the second calendar year overlapped by the time interval.

$$All\_RMEV_{ij} = \frac{N_2 \times 1{,}000{,}000}{(207 \times \sum ADT_1) + (158 \times \sum ADT_2)} \quad (2)$$

where: All_RMEV_{ij} = crash rate per million entering vehicles for all-approaches crashes, for time interval *i* and crash type *j*;

N_2 = number of crashes involving at least one vehicle traveling on Bangerter Highway for time interval *i* and crash type *j*;

i = index for time intervals;

j = index for crash types;

$\sum ADT_1$ = sum of average daily traffic on all intersection approaches of the first calendar year overlapped by the time interval; and

$\sum ADT_2$ = sum of average daily traffic on all intersection approaches of the second calendar year overlapped by the time interval.

4.2 Crash Data Results

This section summarizes the results of the crash study including an analysis of both crash frequencies and crash rates. Both of these metrics will be used to evaluate the effect of the AWS system on crashes.

4.2.1 Crash Frequency Results

The before-and-after crash frequencies for crashes involving only vehicles traveling on Bangerter Highway are summarized in Table 4-2. As can be seen in this table, the total Bangerter Highway-only crash frequency for the control intersection increased from 17 crashes before the installation of the AWS system to 23 crashes after installation. The frequency at the intersection with Redwood Road also increased, but only slightly, from 22 crashes before to 23 crashes after. Bangerter Highway-only crash frequencies at the other AWS-equipped intersections decreased slightly. Because Bangerter Highway-only crash frequencies increased at Redwood Road and decreased at the other AWS-equipped intersections, and because of the relatively small magnitude of the changes, no strong conclusion can be made regarding the effect of the AWS system on total Bangerter Highway-only crashes. It does seem apparent, however, that the AWS systems did not cause a dramatic increase in total Bangerter Highway-only crash frequencies, as demonstrated by the fact that total Bangerter Highway-only crash frequency at the control intersection increased by 5 crashes, while the frequencies at the other intersections increased by 1 crash at the most, or decreased. Tables with the Bangerter Highway-only crash frequencies separated into four one-year time intervals can be found in Appendix B.

Total crash frequencies for crashes involving at least one vehicle traveling on Bangerter Highway (total all-approach crash frequencies) are summarized in Table 4-3. The results of this analysis exhibit similar general patterns as Bangerter Highway-only frequencies, with frequencies increasing at the control intersection and Redwood Road, and decreasing or staying the same at the other intersections. Again, because frequencies at AWS-equipped intersections both increased and decreased, and because of the small magnitude of the changes, no strong conclusion can be made. However, it can again be surmised that the AWS systems did not cause a large increase in crash frequencies and therefore did not have a negative impact on safety at the AWS-equipped intersections.

Table 4-2. Before-and-After (Two-Year) Crash Frequencies for Crashes Only Involving Vehicles Traveling On Bangerter Highway

		Number of Crashes	
		Before	**After**
Redwood Road	Rear-end	16	19
	Right-angle	0	2
	Other	6	2
	Total	22	23
2700 West	Rear-end	14	13
	Right-angle	0	2
	Other	2	0
	Total	16	15
13400 South	Rear-end	15	9
	Right-angle	1	3
	Other	3	4
	Total	19	16
12600 South (control site)	Rear-end	13	19
	Right-angle	0	3
	Other	4	1
	Total	17	23

When considering specific crash types, again no specific conclusion can be made from the crash frequencies for the rear-end, right-angle, and other categories for either the Bangerter Highway-only crashes or all-approaches crashes. These frequencies exhibit either similar trends between the control and AWS-equipped intersections, or mixed trends among the AWS-equipped intersections. It should be noted that the number of right-angle crashes appears to have increased in the after period, however, a more detailed analysis of these trends would indicate that this is consistent at nearly all intersections along the southern end of Bangerter Highway during this time period. Of these crashes, less than one crash per year at the AWS-equipped intersections are RLR related, consistent with trends throughout the corridor. The slightly upward trend in right-angle crashes may be caused by a number of factors not generally related to the installation of the AWS systems such as traffic, weather, land use changes, driver behavior, and so forth. As the number of crashes is relatively small, there is not enough data for any statistical comparisons between the before and after data.

Table 4-3. Before-and-After (Two-Year) Crash Frequencies for Crashes Involving at Least One Vehicle Traveling On Bangerter Highway

		Number of Crashes	
		Before	**After**
Redwood Road	Rear-end	16	19
	Right-angle	1	7
	Other	6	3
	Total	23	29
2700 West	Rear-end	14	13
	Right-angle	2	4
	Other	2	1
	Total	18	18
13400 South	Rear-end	15	9
	Right-angle	6	8
	Other	3	4
	Total	24	21
12600 South (control site)	Rear-end	13	19
	Right-angle	4	8
	Other	4	2
	Total	21	29

4.2.2 Crash Rate Results

The before-and-after Bangerter Highway-only crash rates are summarized in Table 4-4. Similar to the crash frequency analysis, the total Bangerter Highway-only crash rates for the control intersection increased, while the rates for all AWS-equipped intersections decreased. This suggests that the AWS systems had the effect of reducing total Bangerter Highway-only crash rates. This is slightly different than the crash frequency results where total number of crashes increased slightly at Redwood Road. By including the exposure of the intersection (i.e., ADT) the rates decreased at all AWS-equipped intersections.

Table 4-4. Before-and-After (Two-Year) Crash Rates for Crashes Only Involving Vehicles Traveling On Bangerter Highway

		Crash Rate Per MEV	
		Before	**After**
Redwood Road	Rear-end	0.72	0.78
	Right-angle	0.00	0.08
	Other	0.27	0.08
	Total	0.99	0.95
2700 West	Rear-end	0.76	0.69
	Right-angle	0.00	0.11
	Other	0.11	0.00
	Total	0.87	0.79
13400 South	Rear-end	0.98	0.56
	Right-angle	0.07	0.19
	Other	0.20	0.25
	Total	1.24	1.00
12600 South (control site)	Rear-end	0.69	0.95
	Right-angle	0.00	0.15
	Other	0.21	0.05
	Total	0.90	1.15

Crash rates for crashes involving at least one vehicle traveling on Bangerter Highway (all-approaches crashes) are summarized in Table 4-5. As can be seen, the total crash rates for the control intersection and Redwood Road increased, while the total crash rates for the other AWS-equipped intersections decreased, which is similar to the results of the crash frequency analysis. When each crash type is analyzed separately, only the rear-end crash type shows a meaningful pattern, with the rear-end type all-approaches crash rate increasing for the control intersection and decreasing for the all of the AWS-equipped intersections, suggesting that the AWS systems may have had an effect of reducing rear-end crashes. The data also show a slight increase in right-angle crash rates, consistent with the crash frequency analysis. This trend appears consistent along the southern end of Bangerter Highway and does not exceed typical rates along the corridor.

Table 4-5. Before-and-After (Two-Year) Crash Rates for Crashes Involving at Least One Vehicle Traveling On Bangerter Highway

		Crash Rate Per MEV	
		Before	**After**
Redwood Road	Rear-end	0.56	0.54
	Right-angle	0.03	0.20
	Other	0.21	0.08
	Total	0.80	0.82
2700 West	Rear	0.67	0.59
	Right	0.10	0.18
	Other	0.10	0.05
	Total	0.86	0.81
13400 South	Rear	0.57	0.29
	Right	0.23	0.25
	Other	0.11	0.13
	Total	0.92	0.67
12600 South (control site)	Rear	0.42	0.61
	Right	0.13	0.26
	Other	0.13	0.06
	Total	0.68	0.93

4.3 Chapter Summary

This chapter described the implementation and results of a study performed to determine the effect of an AWS system on crash frequencies and rates. Crash data were collected for four intersections. Three of the intersections were equipped with the AWS system and one intersection was used as a control site. The crash data were processed to obtain crashes that were related to one of the four intersections, and to separate them into categories by crash type. It was found that total crash rates for crashes only involving vehicles traveling on Bangerter Highway increased for the control intersection, while they decreased for the intersections with the AWS system. It was also found that rear-end crash rates for crashes involving at least one vehicle traveling on Bangerter Highway increased for the control intersection and decreased for the AWS-equipped intersection. These patterns may suggest that the AWS systems reduced the Bangerter Highway-only total crash rate and the rear-end all-approaches crash rate. However, the changes in crash frequency were small, and other crash categories showed no pattern. Therefore, the only conclusion that can be made with confidence is that the AWS systems did not significantly increase crash rates during the first two years following installation.

It is important to state here that in the words of Hauer, “the noted change in safety reflects not only the effect of [the AWS system] but also the effect of factors such as traffic, weather, vehicle fleet, driver behavior, cost of car repairs, inclinations to report accidents and so on. It is not known what part of the change can be attributed to [the AWS system] and what part is due to the various other influences” (*15*). Hauer further states that “the noted change in safety may be in part due to spontaneous regression-to-mean and not due to [the AWS system]” (*15*).

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5 Speed and Red-Light-Running Data Analysis

The purpose of this chapter is to describe the implementation of the speed and RLR study, and to present the results of this study. The first section details the implementation of the speed and RLR study, including explanations on the technologies used to collect the data and how the data were reduced and processed. The next section presents and discusses the results of the study, including a discussion on the possible impact of the AWS systems on intersection safety, as measured by changes in RLR rates and speed distributions. The final section summarizes the main points of the chapter.

5.1 Implementation

This section describes the implementation of the RLR and speed study. The first sub-section includes the configuration and operation of data-collection devices at the study intersections. The second sub-section describes the methods used to process the data and present the results.

5.1.1 Data Collection

Speed and RLR data were collected on Bangerter at its intersection with 13400 South (one of the locations where AWS was installed). Data were collected using the SmartSensor Advance™ sensor with Digital Wave Radar™ technology developed by Wavetronix, LLC of Lindon, Utah. The sensor was mounted on the back of each AWS sign, facing the intersection, as shown in Figure 5-1. The sensor detected vehicle passage and vehicle speed for seven sensor zones. The leading zone was located 300 feet from the intersection stop bar, and each succeeding zone was placed at 50 foot intervals, with the last zone being at the intersection stop bar. The layouts of the sensor zones, as well as the locations of the sensor, AD video detection camera and AD optical detection zone, are illustrated in Figure 5-2. As each vehicle passed through each sensor zone, the speed of the vehicle was measured by the radar sensor. The speed for each vehicle was then recorded and stored on a connected laptop computer, along with a timestamp and the location of the vehicle. RLR events were detected using a data logger in conjunction with the radar sensor. The data logger monitored both the status of the signal and the radar sensor detections of vehicles leaving the stop bar zone. If a vehicle left the stop bar zone while the signal was red, a RLR event was recorded with a time stamp (*7*).

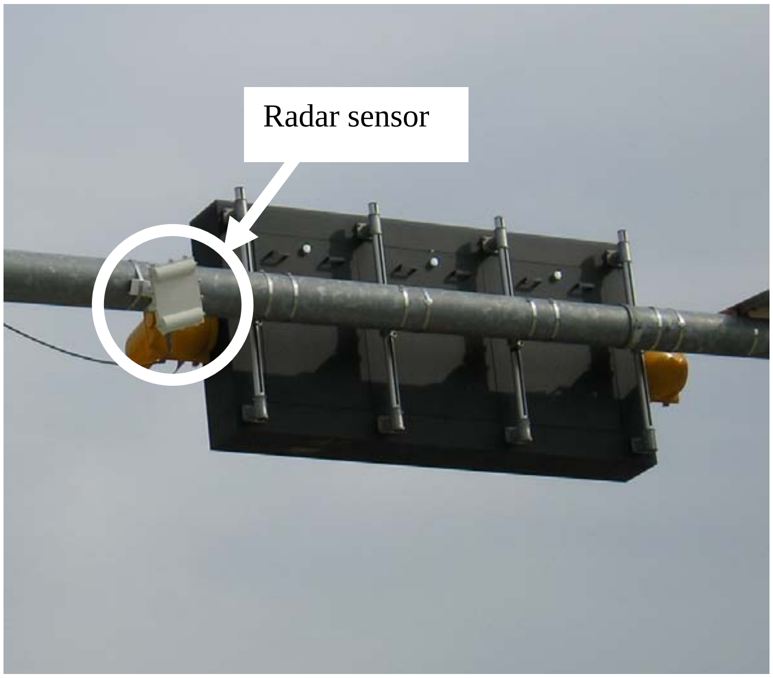

Figure 5-1. SmartSensor Advance ™ Digital Wave Radar™ sensor (*7*).

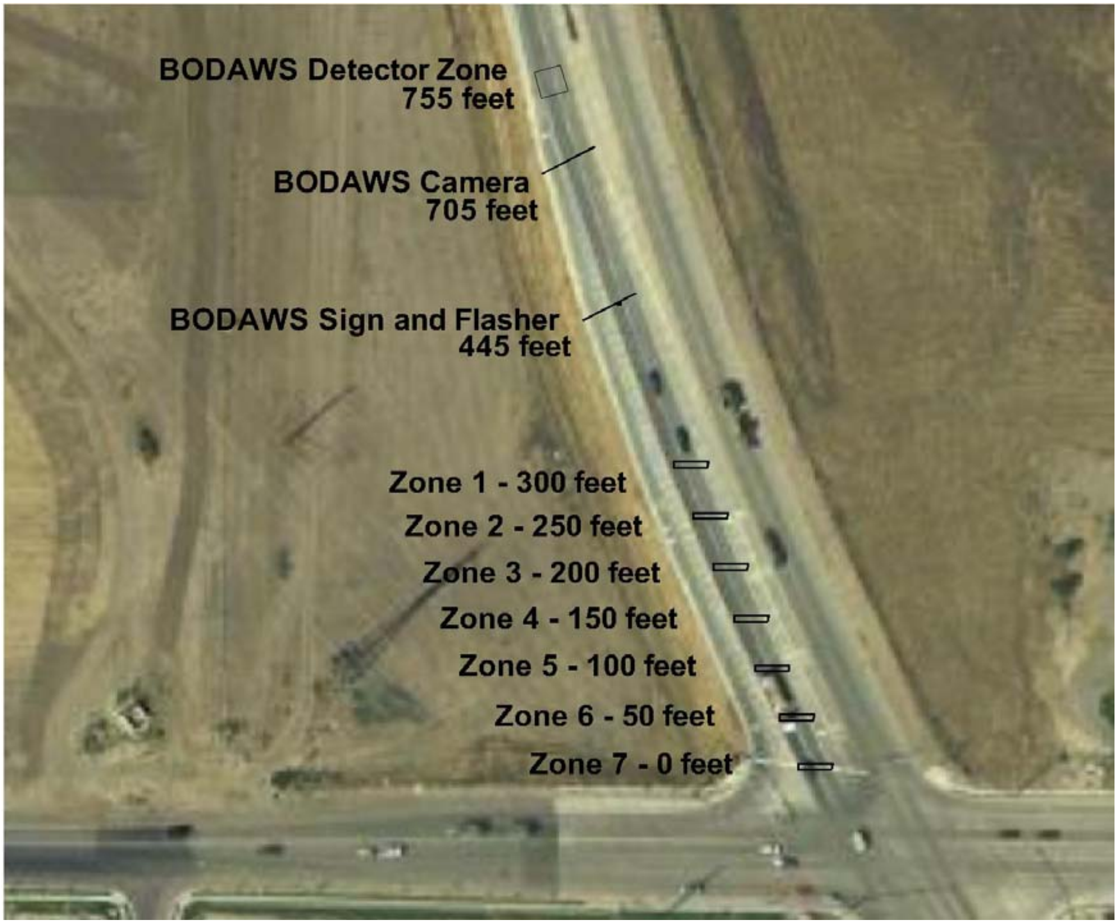

Figure 5-2. Sensor zones and detection equipment layout (*7*).

Speed and RLR data were collected for six weeks before the installation of the AWS system and for two years and four months after the installation of the AWS system. To facilitate analysis, data was selected to form six different time periods. These time periods were organized and labeled Period 1 (P1) through Period 6 (P6). P1 represents data collected before the installation of the AWS system. P2 includes data immediately after the installation. P3 includes data several months after the installation, while the lead flash time was set to 6 seconds. The data for the transition between the 6 second lead flash and 4 second lead flash, as indicated previously, are included in P4 and P5. P6 includes data more than two years after the installation of the AWS system and was used to determine long-term effectiveness. The name, dates, and description of each period are summarized in Table 5-1.

Table 5-1. Dates and Descriptions for Data Analysis Periods

Period Name	Date Range	Description
P1	Apr. 27 – Jun. 7, 2005	Before installation of the AWS system
P2	Jun. 8 – Jul. 22, 2005	Immediately after installation of the AWS system
P3	Feb. and Mar. 2006	Eight months after installation of the AWS system
P4	May 1-23, 2006	Immediately after the change in lead flash from 6 seconds to 5 seconds
P5	May 23 – Jun. 22, 2006	Immediately after the change in lead flash from 5 seconds to 4 seconds
P6	Sept. and Oct., 2007	28 months after the installation of the AWS system

5.1.2 Data Processing

The speed data were processed with custom Visual Basic and Visual Basic for Applications (VBA) programs. The first program, called Data Sorting, processed the raw data generated by the Digital Wave Radar™ and the data logger to produce files appropriate for further data reduction. For the speed data, the Data Sorting program produced a .log file which had a record for each vehicle speed detected by the radar sensor. Each record had entries for the date, time, distance from the intersection, speed, time before the start of the red interval, direction of travel, and time period. The program was developed to produce a separate .log file for the RLR data. Each RLR event had a separate record, and each record included entries for the date, time, speed, time after the start of the red interval, direction of travel, time period, and total volume at the stop bar.

A second program, called Speed Data Plotting, used the speed data file to divide the speed into categories using five criteria: 1) direction of travel, 2) the distance of the vehicle from the intersection, 3) the time of day, 4) the number of seconds before the start of the red interval, and 5) the data collection period. The direction of travel was either northbound or southbound. The distance of the vehicle from the intersection was 50, 100, 150, 200, 250, or 300 feet. There were three possibilities for time of day: AM peak (7:00 am – 9:00 am), noon peak (11:00 am – 1:00 pm), and PM peak (4:00 pm – 6:00 pm). Speeds recorded outside these intervals and on weekends were not used in the analysis. The number of seconds before the start of the red interval was recorded as an integer value for each vehicle speed recorded. Only speeds with an associated time-before-red of

0, 3, 6, 9, 12, or 15 seconds were summarized in the analysis although all data were collected. The data collection periods were P1 through P6, as previously defined.

After the speed data was processed, the Speed Data Plotting program produced cumulative distribution plots so that the speed distributions could be visually analyzed. The distributions were plotted with speed in miles per hour on the abscissa and cumulative percent on the ordinate. The distributions were grouped by direction of travel and distance from the intersection of the vehicles, and by data analysis period and time of day, with each group having one line for each second before red (SBR) category. Grouping the plots in this way facilitated an evaluation of the change in speed distributions between each SBR category.

The Speed Data Plotting program also produced box plots for the speed data. The box plots graphically represent the distribution of the speed data, and consist of three parts. The first part is the box itself, which represents the middle 50 percent of the data. The second part is a line which divides the box and represents the median or middle of the data. The third part is the whiskers, which extend above and below the box and represent the highest and lowest 25 percent of the data. To mitigate the effect of outliers, the length of each whisker is limited to 1.5 times the height of the box. The speeds represented by the lower edge of the box and upper edge of the box are called the first quartile and the third quartile respectively. The ends of the whiskers represent the minimum and maximum speeds. The line through the box represents the second quartile or median speeds. The box plots are plotted vertically, with speed in miles per hour on the ordinate. The box plots are grouped together by direction of travel and distance from the intersection of the vehicles and by time of day and time before red, with each group consisting of one box plot for each data analysis period. Grouping the plots in this way facilitates visual analysis of the change in speed distributions between data analysis periods.

The Speed Data Plotting program used the RLR file to determine the RLR rates for each direction for each of the six periods. All RLR events that occurred more than four seconds after the start of the red interval or at speeds of less than 20 mph were not included in the study. The RLR events were used to calculate the RLR rate per 1000 entering vehicles for each direction and period. The total number of entering vehicles used to calculate the RLR rates was obtained from the Digital Wave Radar™ log, and is not the same as would be calculated using ADT values. For this reason, only relative changes in RLR rates were considered in the evaluation. The RLR rates were tabulated and are given in Section 5.2. The RLR data was also used to plot a cumulative distribution of the RLR speed for each period and direction. This plot is also given in the results section.

5.2 Speed and Red-Light-Running Data Results

This section presents and discusses the results of the speed and RLR study. Because of the large number of combinations evaluated, only six cumulative speed distribution plots and three box plots for northbound vehicle speeds during the AM peak at 100 feet from the intersection are presented in this chapter. These plots and their discussion are representative of the trends of all the plots. All of the cumulative distribution plots for speeds of northbound vehicles for P4 through P6 are included in Appendix D. Cumulative distribution plots for P1 through P3 can be found in the Phase I report (*7*). All of the box plots for the speeds of AM peak northbound vehicles are included in Appendix E. The cumulative distributions and box plots are given first, followed by tables of RLR rates and a plot of RLR speeds. For each of these, key trends are discussed, along with possible implications for intersection safety.

5.2.1 Cumulative Speed Distribution Plots

The cumulative speed distributions were plotted so that the differences in speed distributions between the SBR categories and between the data analysis periods could be visually analyzed. Cumulative speed distributions for northbound vehicles at the 100 ft detection zone during the AM peak for each of the SBR categories and data analysis periods are presented in this section. Cumulative speed distributions for northbound vehicles for data analysis periods P4 through P6 and for all of the detection zones are presented in Appendix D.

The cumulative speed distribution plots show the change in the speed distribution for each analysis period. Figure 5-3 shows the speed distribution before the AWS system was installed (P1). Figure 5-4 and Figure 5-5 show the speed distribution immediately after and approximately eight months after the installation of the AWS system (P2 and P3). Figure 5-6 and Figure 5-7 show the speed distributions immediately after the change in lead flash timing to 5 seconds and 4 seconds (P4 and P5), respectively. Figure 5-8 shows the speed distribution approximately two years after the installation of the AWS system (P6). The lowest and highest 85th percentile speeds for the plots are summarized in Table 5-2.

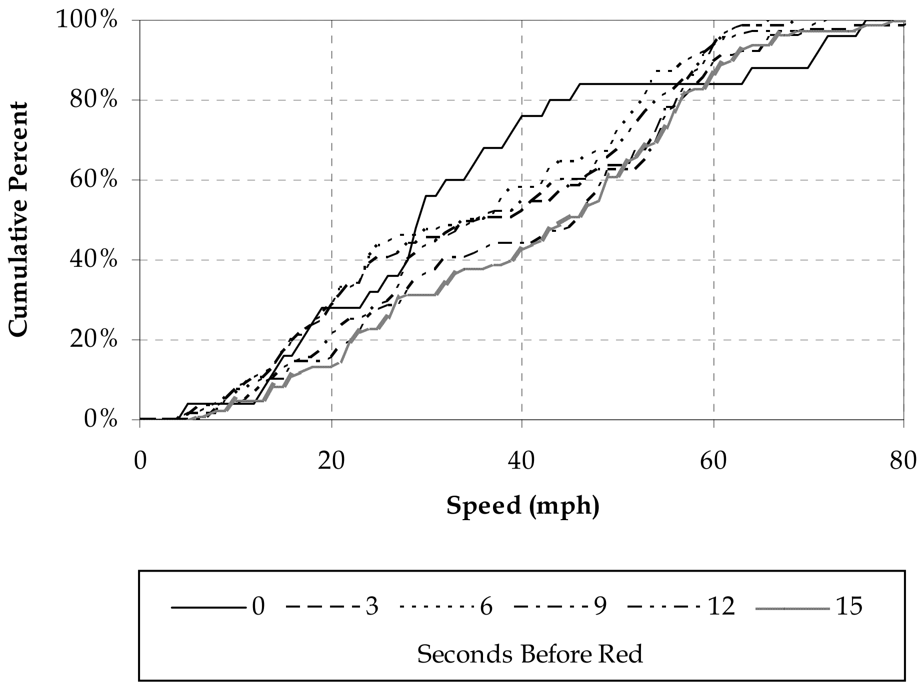

Figure 5-3. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone for P1.

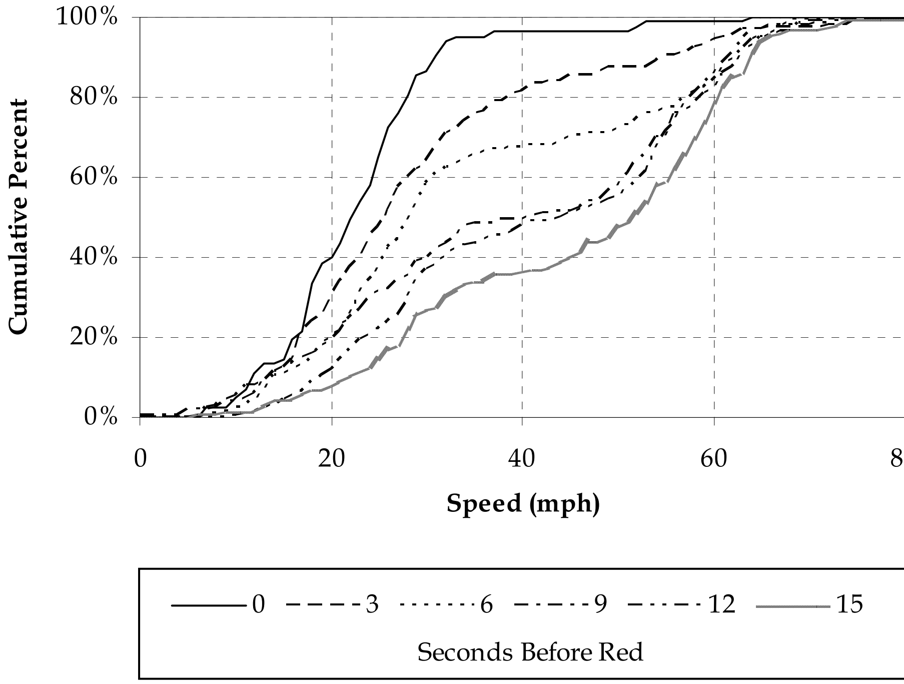

Figure 5-4. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone for P2.

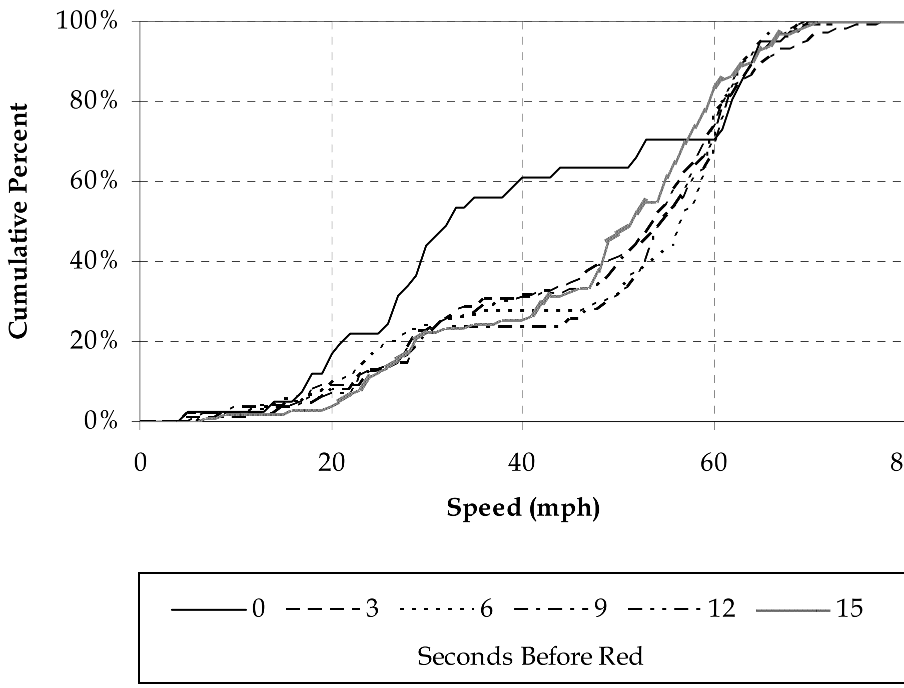

Figure 5-5. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone for P3.

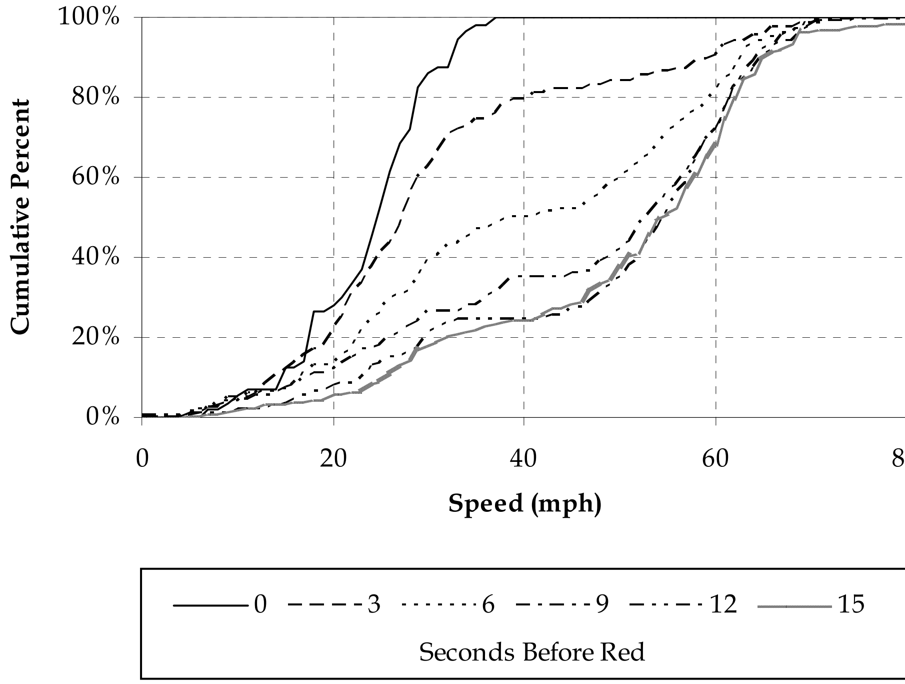

Figure 5-6. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone for P4.

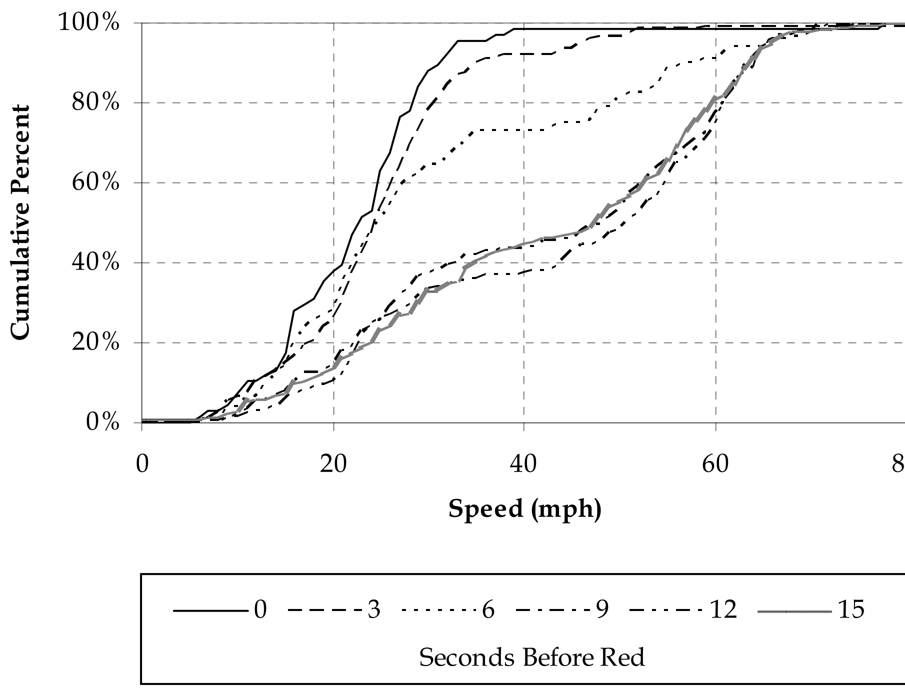

Figure 5-7. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone for P5.

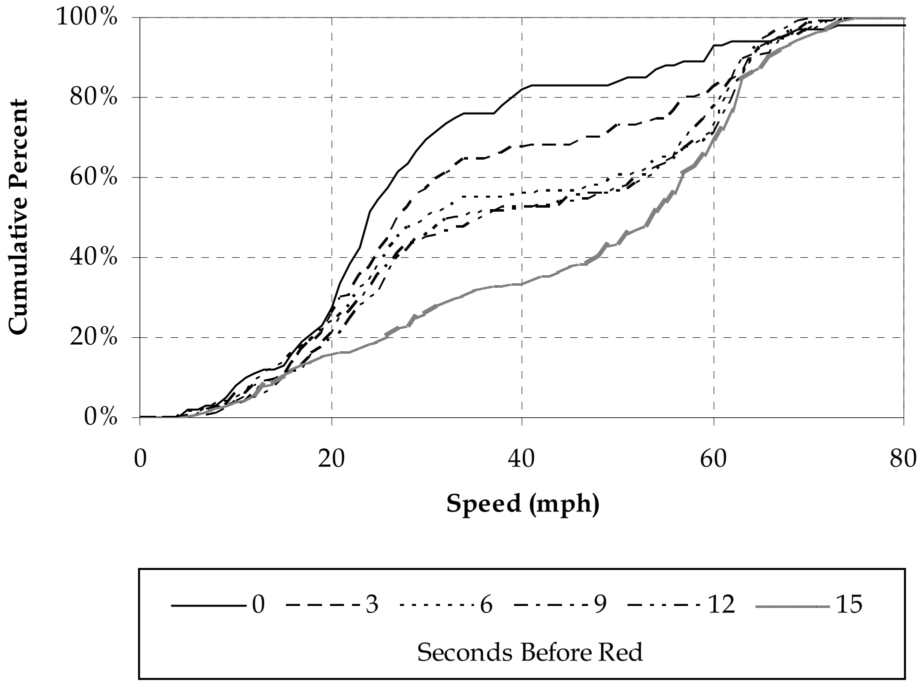

Figure 5-8. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone for P6.

Table 5-2. Lowest and Highest 85th Percentile Speeds

Period[1]	Lowest 85th Percentile Speed (mph)	Highest 85th Percentile Speed (mph)
P1	55	65
P2	30	64
P3	62	64
P4	31	65
P5	31	64
P6	52	65

[1] Refer to Table 5-1 for details and descriptions of the time periods

The next two sections describe the speed trends illustrated in the cumulative speed distribution plots. The analysis is divided into two parts: 0, 3, and 6 SBR; and 9, 12, and 15 SBR. The analysis focuses on P1, P3, and P6, since these periods represent results that have not been affected by the effects of novelty.

5.2.1.1 Speed Trends for 0, 3, and 6 Seconds Before Red

The 85th percentile speeds for vehicles 100 feet from the intersection 0, 3 and 6 SBR increased from P1 to P3, then the 3 and 6 SBR speeds remained the same while the 0 SBR speeds decreased from P3 to P6. The P6 85th percentile speeds for 3 and 6 SBR were higher than the P1 speeds, while the 85th percentile speeds for 0 SBR for P6 were lower than those of P1. The median speeds for 3 and 6 SBR increased significantly from P1 to P3 while the median speed for 0 SBR remained the same. Median speeds decreased from P3 to P6 to levels lower than the median speeds of P1.

During P3, most of the 0, 3 and 6 SBR drivers would have seen the activated AWS sign. However, many drivers did not respond by slowing down, but rather drove faster, as illustrated by the increase in median and 85th percentile speeds from P1 to P3. As drivers became familiar with the AWS system, they may have used the information it provided to determine when they would have enough time to pass through the intersection. While the increase may not necessarily be negative for the 3 and 6 SBR drivers, who had enough time to pass through the intersection, it may be of concern for the 0 SBR drivers, who would likely run the red light.

The significant reductions in median speeds from P3 to P6 were theorized to have been a result of the change in lead flash timing from 6 seconds to 4 seconds. If all P3 drivers who saw the activated AWS sign stopped, no vehicle would enter the intersection during the yellow interval, so the yellow interval became unused time. As drivers realized that they could use the yellow interval to enter the intersection before the start of the red interval, they began to lose respect for the AWS system. When the lead flash timing was reduced by 2 seconds, the unused yellow time was reduced, such that respect for the AWS sign was regained to some extent. However, some drivers continued to disregard the AWS sign, as is illustrated by the slightly higher 85th percentile speeds during P6, particularly during the 0 and 3 SBR periods.

The overall effect of the AWS system from P1 to P6 for 0, 3 and 6 SBR speeds seems to be a reduction in speeds for the majority of vehicles. This reduction in speeds is considered to be a positive safety impact of the AWS system.

5.2.1.2 Speed Trends for 9, 12, and 15 Seconds Before Red

Both the 85th percentile speeds and the median speeds for 9, 12, and 15 SBR increased from P1 to P3. From P3 to P6, 85th percentile speeds increased, while the median speeds went down, with the exception of the 15 SBR median speeds, which stayed about the same. Although the P3 median speeds decreased from P3 to P6, P6 median speeds were still greater than P1 median speeds. P6 85th percentile speeds were also greater than P1 85th percentile speeds.

The higher speeds during P3 and P6 may be attributed to drivers learning to take advantage of the information provided by the AWS sign. These speeds are for vehicles that were 100 feet from the intersection 9, 12, and 15 seconds before the start of the red interval, where they had more than enough time to enter the intersection before the start of both the yellow and red intervals. Most P3 and P6 drivers would have seen a blank AWS sign, which may have served to inform the drivers that they had enough time to enter the intersection before the start of the yellow interval. As a consequence they maintained a higher speed. P1 drivers, on the other hand, were provided with no information about the start of the yellow interval, which may have caused them to drive more cautiously in anticipation of a possible signal change.

The increase in speeds for vehicles 100 feet from the intersection 9, 12, and 15 SBR may be a desirable trend, since it would improve the capacity of the intersection at a time when vehicles shouldn't be slowing to stop. On the other hand, increased speeds may lead to decreased safety at the intersection.

5.2.2 Speed Box Plots

Box plots have also been generated to help represent the distribution of the speed data. By comparing the median speed represented by successive box plots the general change in speeds (i.e., increase or decrease) can be determined. The change in range or variability of speeds can also be determined by comparing the minimum, maximum, first quartile and third quartile speeds.

Box plots for northbound vehicles at the 100 ft detection zone during the AM peak for the 0, 3, and 6 SBR categories are included in this section. Box plots for northbound vehicles the 100 ft detection zone during the AM peak for the 9, 12, and 15

SBR categories are included in Appendix E. These plots are not presented here because they exhibit similar trends to those of the 6 SBR plot. Appendix E also includes box plots for northbound vehicles during the AM peak for all other SBR categories and detection zones.

Figure 5-9, Figure 5-10, and Figure 5-11 show the speed distributions for northbound vehicles during the AM peak as they crossed the 100 ft detection zone.

Figure 5-9 shows the speed distribution for northbound vehicles at the 100 ft detection zone just as the light turned red (0 SBR). It can be seen that in general the speeds during P6 were less than the speeds during P1. The maximum, third quartile, and median speeds decreased, while the first quartile speed increased slightly and the minimum speed remained the same. This is a desirable trend, both because lower speeds would tend to increase safety at the intersection and because these vehicles should be slowing down to stop for the red light. There is also less variability in the speeds for P6 than for P1, as illustrated by the decrease in the difference between the minimum and maximum speeds, which would also tend to increase safety at the intersection.

The speeds during P2, P4, and P5 were lower than the speeds during the other periods. Each of these periods was associated with the time immediately after a change in the operation of the AWS system. P2 was immediately after the activation of the AWS system, and P4 and P5 were immediately after changes in the lead flash timing. These significantly lower speeds may be attributed to the effects of novelty. It was theorized that drivers drove more cautiously when interacting with an unfamiliar system.

The speeds during P3 were significantly higher than the speeds during the other periods. During this period the lead flash time was 6 seconds. Again, it was theorized that the amount of time gave drivers too much warning. As they became familiar with the AWS system, drivers had learned to accelerate when they saw the activated AWS sign, to “beat the light” and avoid being delayed at the intersection. In contrast to speeds during P3, speeds during P6 remained low, despite the fact that drivers had had enough time to become familiar with the new lead flash timing. This shows that the 4 second lead flash was effective at reducing speeds for vehicles at the 100 foot detection zone as the light was turning red.

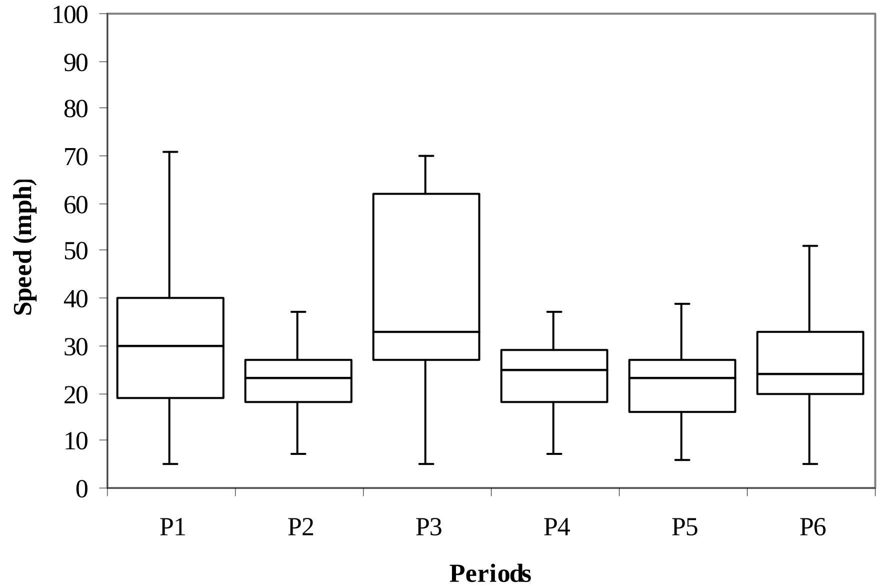

Figure 5-9. Box plots of speed data for the northbound 100 foot detection zone during the AM peak for 0 seconds before red.

Figure 5-10 shows the speed distribution for vehicles at the 100 foot detection zone 3 seconds before the light turned red. This plot shows the same general trends as the 0 SBR plot, except that there was not a similar decrease in the variability of speeds from P1 to P6. The range of speeds did not change considerably, with the minimum, maximum, first quartile, and third quartile speeds remaining relatively constant. The median speed did change, however, somewhat significantly. This change in median speed tends to illustrate that, while many drivers drove slower in response to the new AWS timing, a significant portion of drivers drove just as fast as they did before the installation of the AWS system. As a result, the variability of speeds increased, which may lead to decreased safety at the intersection.

The fact that many drivers drove just as fast after the introduction of the new lead flash timings as they did before the installation of the AWS system may be explained in part by an analysis of the operation of the AWS system. Most of the P6 drivers would have seen the activated AWS sign, but as the data indicate, some did not respond by slowing down. Drivers that are 100 feet away from the intersection 3 seconds before the light turns red still have enough time to enter the intersection. It is likely that drivers became aware of this fact as they became familiar with the new lead flash timing. As a result, they would disregard the AWS sign when they felt they could still make it through the intersection. This is in contrast to another portion of the drivers who, it appears, respected the AWS system warning and responded by slowing down.

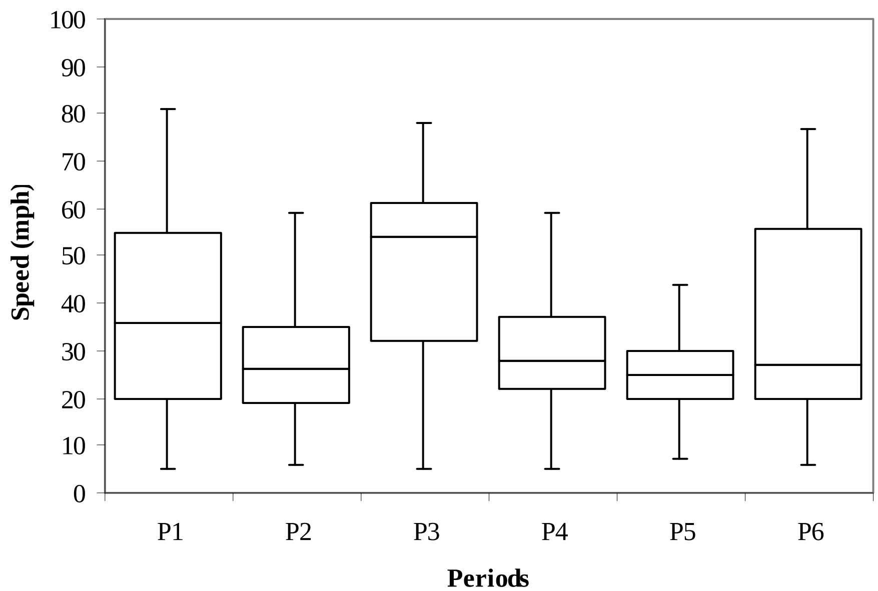

Figure 5-10. Box plots of speed data for the northbound 100 foot detection zone during the AM peak for 3 seconds before red.

Figure 5-11 shows the speed distributions for vehicles at the 100 foot detection zone 6 seconds before the light turned red. As illustrated in Figure 5-11, the median speed decreased significantly from P1 to P6. However, the third quartile and maximum speeds increased. This increase, combined with the decrease in the median speed lead to an increased range or variability from P1 to P6. Like the P6 drivers for the 3 SBR plot, these P6 drivers had enough time to enter the intersection before the light turned red. However, these P6 drivers would not have seen the activated AWS sign. Despite this difference, the P6 speeds for 6 SBR are comparable to the P6 speeds for 3 SBR.

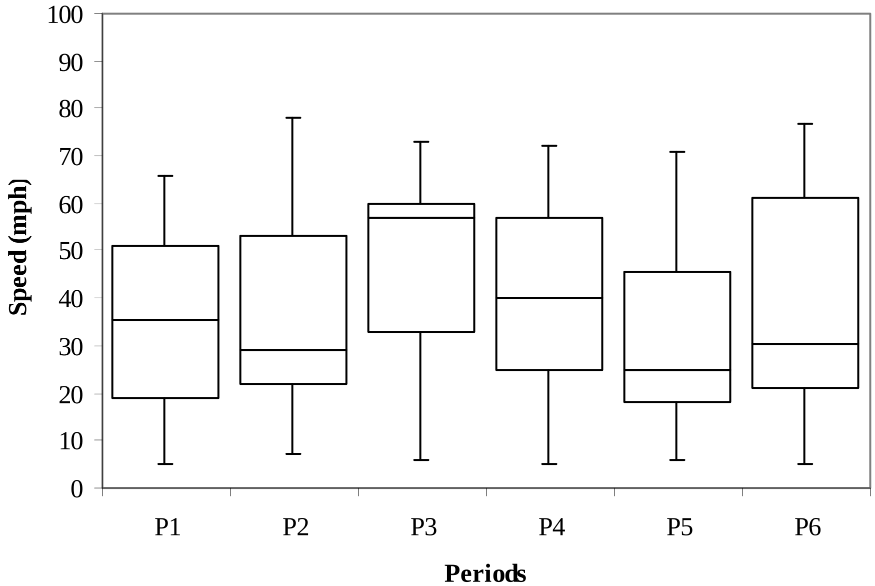

Figure 5-11. Box plots of speed data for the northbound 100 foot detection zone during the AM peak for 6 seconds before red.

5.2.3 Red Light Running Analysis

As shown in Table 5-3, the northbound RLR rates for P2, P4, and P5 were much lower than the P1 rates, while the rates for P3 and P6 were higher than the P1 rates. P2, P4, and P5 corresponded to periods immediately after a change in the operation of the AWS system. RLR rates could have been lower during these periods because drivers drove more cautiously when they were not familiar with the operation of the AWS system. P3 and P6, on the other hand, corresponded to periods when the operation of the AWS system had not changed for a period of several months. RLR rates could have been higher during P3 and P6 because drivers were more familiar with the AWS system and abused the system by accelerating when they saw the activated AWS sign. It is important to note as well that there were a number of other changes in the vicinity of the intersection that may have influenced the overall RLR at the intersection. These changes included lane additions, lane reconfiguration on the cross street (13400 South), signal timing changes, adjacent land use changed, and overall area wide growth.

Table 5-3. Northbound Red Light Running Rates

Period[1]	RLR rate (per 1000 entering vehicles)
P1	7.01
P2	1.01
P3	13.8
P4	0.930
P5	1.74
P6	12.6

[1] Refer to Table 5-1 for details and descriptions of the time periods

Figure 5-12 shows the speed distribution for vehicles that ran the red light at speeds greater than 20 mph at less than 4 seconds into the red interval. The RLR speeds for P2 and P6 are less then the RLR speeds for P1, and those for P3, P4 and P5 are greater than those of P1. The highest speeds were recorded during P3, which, like the RLR rates for P3, suggests that the lead flash during P3 may have been too long. Drivers may have felt that they had enough time to accelerate through the intersection when they saw the activated AWS sign. The lowest RLR speeds were recorded during P6, which may suggest that the 4 second lead flash was effective at encouraging lower speeds.

As indicated, the RLR rates and speeds may have also been affected by a number of other factors at the intersection. For example, over the course of the study, significant changes in land used were made around the intersection, including an empty field being developed into a Home Depot. The developments around the intersection likely increased the number of right-turning northbound bound vehicles, which may have been traveling greater than 20 mph as they made the right turn. The configuration of the Digital Wave Radar™ sensor may have also contributed to recording right-turn movements as RLR. Because the northbound approach to the intersection was curved, and because the radar waves emanated from sensor in a spherical pattern, the stop bar detection zone may have been in front of the actual stop bar, as illustrated in Figure 5-13 (*7*). As a result, right turning vehicles may have been recorded as running the red light when in fact they were turning after stopping at the stop bar.

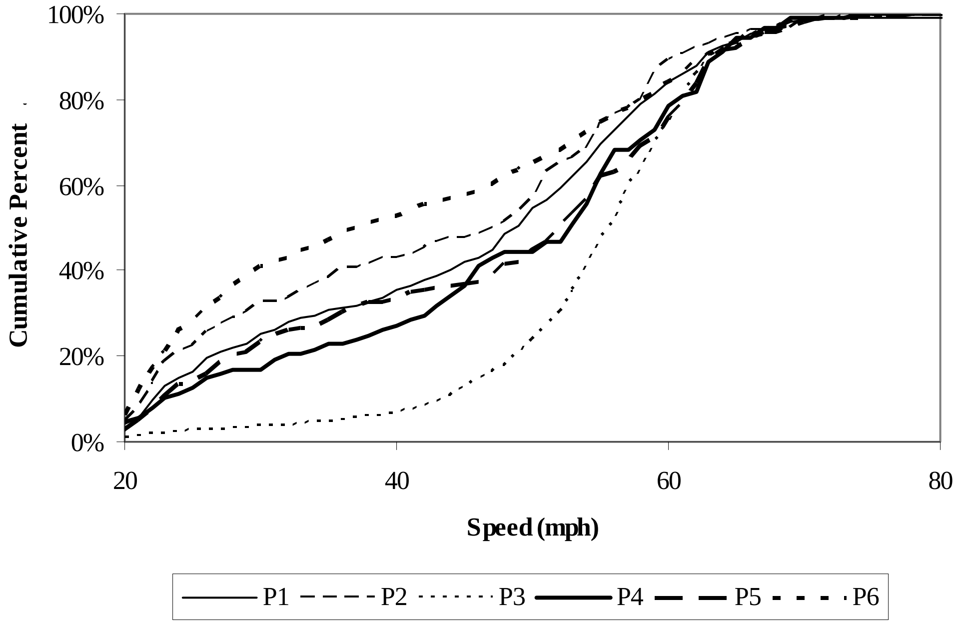

Figure 5-12. Northbound red light running speed distribution

Figure 5-13. Spherical path of radar waves and skewed intersection geometry (*7*).

Another factor that could have changed the RLR rates and speeds is changes in the signal timing plan. During the study, the signals were changed from non-coordinated to coordinated, which could have increased the portion of vehicles that arrived at the intersection close to the start of the red interval. Also during the study, 13400 South was widened, and a variable-control lane was added to the eastbound approach. The construction along with increased volumes may have increased congestion at the intersection, which would have affected RLR rates and speeds.

The increase in RLR rates may suggest that the AWS signs encouraged RLR. However, given that there were so many significant changes at the intersection during the course of the study, it becomes very difficult to determine the effect of the AWS system on RLR rates. The changes in the RLR could have been affected by one or more factors other than the AWS system, and there is no way to tell what combination of factors influenced the outcome. It is also possible that the sensitivity of the data collection equipment may have changed slightly over time. Consequently, no conclusion can be made with confidence.

5.3 Chapter Summary

This chapter has summarized the implementation and results of the speed and RLR studies. Speed and RLR data were collected using the SmartSensor Advance™ sensor with Digital Wave Radar™ technology located on the northbound and southbound approaches of the intersection of Bangerter Highway and 13400 South. Speeds of vehicles were recorded for seven detection zones placed at 50-foot intervals from the stop bar to 300 feet from the intersection. The speeds were correlated with the time before red. RLR data were also collected with the Digital Wave Radar™ sensor technology, in conjunction with a data logger which recorded the status of the signal. The number and speed of vehicles that crossed the stop bar at more than 20 mph and less than 4 seconds into the red interval were recorded.

Using the collected data, speed cumulative and box plots were created and visually analyzed to determine the effect of the AWS system on speed distributions. It was found that the lowest 85th percentile speeds decreased from 62 mph to 31 mph immediately after the reduction in lead flash timing, then increased, to 52 mph two years later, which is 3 mph lower than the lowest 85th percentile speed before the installation of the AWS system. Although in general speeds decreased, they also became more variable, as illustrated by the fact that median speeds decreased more than did the 85th percentile speeds, which stayed about the same or, in some instances, increased. These trends suggest that the lead flash timing of 4 seconds resulted in lower speeds, which may lead to increased safety at the intersections, but that more variable speeds also resulted, which may have a negative impact on safety, however, this impact was not observed during the study period..

Like the speeds, the RLR rates decreased immediately after the installation of the AWS system and the changes in the lead flash timing. However, after a period of time with no change to the AWS system, the RLR rates increased to levels above those measured before the installation of the AWS system. RLR speeds were highest after the 6-second lead flash timing had been in place for several months, and lowest when the 4-second lead flash timing had been in place for more than one year. This suggests, like overall speed distributions, that the 4-second lead flash was more effective at reducing speeds than the 6-second lead flash.

Although general trends in the speed and RLR data have been noted, it is difficult to determine the overall effect of the AWS system. As this study took place over a period of several years in a high growth area, a number of other changes were made at the intersection which could have affected the speed distributions and RLR rates.

6 Conclusions

This report has described research conducted to determine the effectiveness of an advance warning signal (AWS) system installed on Bangerter Highway in Riverton Utah. The background of the research will be given here, followed by a summary of important results and recommendations.

6.1 Background

An AWS system was installed at three high-speed signalized intersections (HSSIs) where Utah Department of Transportation (UDOT) officials had concerns about pavement damage caused by abrupt stops by trucks, and about the possibility of red-light running (RLR) and crashes caused by erratic driver behavior at the time of a signal change. A consultant hired by UDOT designed a system with operation and configuration based on the work of McCoy and Pesti (*14*). The design of the AWS sign was new, consisting of a blank-out overhead dynamic advance warning signal (BODAWS) (*7*).

Researchers at Brigham Young University (BYU) conducted research to determine the effectiveness of the AWS system. The research included collecting speed and RLR data at one of the intersections with the AWS system, and collecting crash data at all three of the AWS-equipped intersections and a control intersection. The data was used to conduct a before-and-after analysis to determine possible effects of the AWS system on crash rates, RLR and speed distributions. Initial results of this analysis were described in a Phase I report (*7*). The Phase I report was the basis for an evaluation and installation guidelines report (*8*). This Phase II report continues the same study with an emphasis on long-term results and the effect of the AWS system on crashes.

6.2 Study Results

Study results are provided for crash, speed, and RLR at the intersection. Overall, the AWS system has had a positive impact on the community, with positive results noted in all areas of analysis. Given the nature of the study, however, it is difficult to quantify the extent of the impact as it relates to the AWS system. Although the overall results are positive in most aspects, to use the words of Hauer "the noted change in safety reflects not only the effect of the AWS system but also the effect of factors such as traffic, weather, vehicle fleet, driver behavior, cost of car repairs, inclinations to report accidents and so on. It is not known what part of the change can be attributed to the AWS system and what part is due to the various other influences" (*15*). The changes may also be due to spontaneous regression-to-mean and not due to the AWS system, hence the conclusions provided.

The following sections provide a more detailed summary of the results in each of the three areas analyzed. Again, please note that although positive and negative impacts are reported, the overall portion of the impact as a function of the AWS system is difficult to quantify.

6.2.1 Crash Results

The crash study focused on the frequency and rate of crashes related to the study intersections. Two years of 'before' data was compared to two years of 'after' data. The analysis showed that crash rates for total Bangerter-only crashes and rear-end all-approaches crashes increased for the control intersection while they decreased or stayed the same for the other intersections. The other crash categories showed no pattern, with no significant increase or decrease in crash rates. Because of the limited amount of data it was determined to be impractical to perform statistical analysis of the data results. It was concluded, however, that the AWS system did not cause an increase in crash rates, and the system was shown to have played at least some part in a decrease in overall crash rates as well as a decrease in some crash types (e.g., rear-end crashes).

6.2.2 Speed Results

The speed study focused on the change in speed distributions for vehicles approaching one of the AWS-equipped intersections. Speed data was collected for each vehicle as it crossed seven vehicle detection zones located between the intersection and a point 300 feet away from the intersection. In addition to being categorized according to distance from the intersection, the speeds were also categorized by amount of time before the start of the red interval. The change in speed distribution for each category over time was then analyzed using box plots and cumulative distribution plots.

The speed results analysis started with the Phase I report, which included data from before the installation of the AWS system, immediately after the installation, and 8 months after the installation. The results of the Phase I analysis showed that speeds initially decreased after the installation of the AWS system, with the lowest 85^{th} percentile speed going from 55 mph to 30 mph. However, eight months after the installation, the speeds had increased to levels higher than those before the installation, with the lowest 85^{th} percentile speed increasing to 62 mph. The Phase I report recommended that the lead flash timing be reduced from 6 seconds to 4 seconds in an effort to decrease speeds.

This phase II report includes results of an analysis for immediately after the lead flash timing change, and for two years after the lead flash timing change. It was found that the lowest 85^{th} percentile speeds decreased from 62 mph to 31 mph immediately after the reduction in lead flash timing, then increased, to 52 mph two years later, which is 3 mph lower than the lowest 85^{th} percentile speed before the installation of the AWS system. Although in general speeds decreased, they also became more variable, as illustrated by the fact that median speeds decreased more than did the 85^{th} percentile speeds, which stayed about the same or, in some instances, increased. These trends suggest that the lead flash timing of 4 seconds resulted in lower speeds, which may lead to increased safety at the intersections, but that more variable speeds also resulted, which may have a negative impact on safety. A negative impact, however, was not observed during the study period.

6.2.3 Red Light Running Results

RLR events were recorded at the study intersection with the resulting RLR rates calculated. Before the installation of the AWS system, the RLR rate for the northbound approach was approximately 7 events per thousand entering vehicles (PTEV). Immediately after the installation of the AWS system and immediately after the changes in the lead flash timing, the RLR rate decreased to less than 2 events PTEV. However, the RLR rates for eight months and more than two years after the installation of the AWS system were 13.8 and 12.6 events PTEV, respectively. This may suggest that after drivers become accustomed to the AWS system, the AWS system may have encouraged more RLR. However, the increase in RLR could be a result of increased traffic volumes, construction, or changes in signal timing and coordination at the intersection; all of which are events that occurred at the intersection during the analysis period. The overall effect of the AWS system on RLR is difficult to determine.

6.3 Conclusions and Future Research

The overall conclusions that can be drawn from this research would indicate that overall the AWS system has been effective as it has helped to improve operations at the intersection as operating speeds have been maintained throughout the corridor as evidenced by the speed distribution results. The additional information provided to the driver, however, has encouraged some drivers in the long-term to attempt to beat the light as evidenced by the increase in RLR, even with the “tightening” or reduction of the lead-flash time. The slight increase in RLR, however, has not led to a decrease in safety, as evidenced by the crash analysis results.

While this study has suggested both positive and negative results of the AWS system, it is difficult to make many strong conclusions on the effectiveness of the AWS system on safety because of the multitude of factors that changed at the intersections over the course of the study. Although it does appear as though the AWS system has been effective, to more conclusively determine the effect of the AWS system only, it would be necessary collect data at more AWS-equipped and control intersections over a similar time period, but with less external changes to the system. With more data and a more controlled environment, the effect of the AWS system on safety could be more easily determined. This type of an experiment, however, would be difficult to perform in the field and would likely require a more controlled laboratory environment to undertake.

Overall, however, the results are promising, particularly with respect to crash results and speed distributions. Although the RLR appears to have increased following long-term monitoring, this has not resulted in an increase in crash frequency or crash rate at the study intersection. The feedback on the installations has continued to be positive and the study has been a success.

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Appendix A. ADT Values

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Table A-1. Bangerter Highway ADT at Study Intersections

	2003	2004	2005	2006	2007
Redwood Road	28504	30551	32295	33715	33715
2700 West	24011	26410	23795	26675	26675
13400 South	19120	21800	21770	22095	22095
12600 South	22990	27110	27030	27435	27435

Table A-2. Minor Road ADT at Study Intersections

	2003	2004	2005	2006	2007
Redwood Road	9815	8875	8865	17655	17655
2700 West	3265	3285	4285	4475	4475
13400 South	12950	12950	12950	12950	12950
12600 South	16587	16757	14927	15390	15390

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Appendix B. Crash Frequencies

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Table B-1. Crash Frequencies for Crashes Only Involving Vehicles Traveling On Bangerter Highway

		Number of Crashes			
		Before		After	
	Year starting June 8 of:	2003	2004	2005	2006
Redwood Road	Rear-end	4	12	9	10
	Right-angle	0	0	0	2
	Other	4	2	2	0
	Total	8	14	11	12
2700 West	Rear-end	7	7	6	7
	Right-angle	0	0	1	1
	Other	2	0	0	0
	Total	9	7	7	8
13400 South	Rear-end	7	8	5	4
	Right-angle	1	0	0	3
	Other	1	2	1	3
	Total	9	10	6	10
12600 South (control site)	Rear-end	9	4	11	8
	Right-angle	0	0	2	1
	Other	2	2	0	1
	Total	11	6	13	10

Table B-2 Crash Frequencies for Crashes Involving at Least One Vehicle Traveling On Bangerter Highway

		Number of Crashes			
		Before		After	
	Year starting June 8 of:	**2003**	**2004**	**2005**	**2006**
Redwood Road	Rear-end	4	12	9	10
	Right-angle	0	1	4	3
	Other	4	2	3	0
	Total	8	15	16	13
2700 West	Rear-end	7	7	6	7
	Right-angle	2	0	1	3
	Other	2	0	0	1
	Total	11	7	7	11
13400 South	Rear-end	7	8	5	4
	Right-angle	3	3	3	5
	Other	1	2	1	3
	Total	11	13	9	12
12600 South (control site)	Rear-end	9	4	11	8
	Right-angle	1	3	5	3
	Other	2	2	0	2
	Total	12	9	16	13

Table B-3. Before-and-After (Two-Year) Crash Frequencies for Crashes Only Involving Vehicles Traveling On Bangerter Highway

		Number of Crashes	
		Before	**After**
Redwood Road	Rear-end	16	19
	Right-angle	0	2
	Other	6	2
	Total	22	23
2700 West	Rear-end	14	13
	Right-angle	0	2
	Other	2	0
	Total	16	15
13400 South	Rear-end	15	9
	Right-angle	1	3
	Other	3	4
	Total	19	16
12600 South (control site)	Rear-end	13	19
	Right-angle	0	3
	Other	4	1
	Total	17	23

Table B-4. Before-and-After (Two-Year) Crash Frequencies for Crashes Involving at Least One Vehicle Traveling On Bangerter Highway

		Number of Crashes	
		Before	**After**
Redwood Road	Rear-end	16	19
	Right-angle	1	7
	Other	6	3
	Total	23	29
2700 West	Rear-end	14	13
	Right-angle	2	4
	Other	2	1
	Total	18	18
13400 South	Rear-end	15	9
	Right-angle	6	8
	Other	3	4
	Total	24	21
12600 South (control site)	Rear-end	13	19
	Right-angle	4	8
	Other	4	2
	Total	21	29

Appendix C. Crash Rates

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Table C-1. Crash Rates for Crashes Involving Only Vehicles Traveling On Bangerter Highway

		Crash Rate per MEV			
		Before		After	
	Year starting June 8 of:	2003	2004	2005	2006
Redwood Road	Rear-end	0.37	1.05	0.75	0.81
	Right-angle	0.00	0.00	0.00	0.16
	Other	0.37	0.18	0.17	0.00
	Total	0.75	1.23	0.92	0.98
2700 West	Rear-end	0.77	0.76	0.66	0.72
	Right-angle	0.00	0.00	0.11	0.10
	Other	0.22	0.00	0.00	0.00
	Total	0.98	0.76	0.77	0.82
13400 South	Rear-end	0.95	1.01	0.63	0.50
	Right-angle	0.14	0.00	0.00	0.37
	Other	0.14	0.25	0.13	0.37
	Total	1.22	1.26	0.75	1.24
12600 South (control site)	Rear-end	1.00	0.40	1.11	0.80
	Right-angle	0.00	0.00	0.20	0.10
	Other	0.22	0.20	0.00	0.10
	Total	1.22	0.61	1.31	1.00

Table C-2. Crash Rates for Crashes Involving at Least One Vehicle Traveling On Bangerter Highway

		Crash Rate per MEV			
		Before		After	
	Year starting June 8 of:	2003	2004	2005	2006
Redwood Road	Rear-end	0.28	0.82	0.54	0.53
	Right-angle	0.00	0.07	0.24	0.16
	Other	0.28	0.14	0.18	0.00
	Total	0.56	1.02	0.96	0.69
2700 West	Rear-end	0.68	0.66	0.56	0.62
	Right-angle	0.19	0.00	0.09	0.26
	Other	0.19	0.00	0.00	0.09
	Total	1.06	0.66	0.65	0.97
13400 South	Rear-end	0.58	0.57	0.32	0.25
	Right-angle	0.25	0.21	0.19	0.32
	Other	0.08	0.14	0.06	0.19
	Total	0.91	0.93	0.57	0.76
12600 South (control site)	Rear-end	0.60	0.25	0.71	0.51
	Right-angle	0.07	0.19	0.32	0.19
	Other	0.13	0.13	0.00	0.13
	Total	0.79	0.57	1.04	0.83

Table C-3. Before-and-After (Two-Year) Crash Rates for Crashes Only Involving Vehicles Traveling On Bangerter Highway

		Crash Rate per MEV	
		Before	**After**
Redwood Road	Rear-end	0.72	0.78
	Right-angle	0.00	0.08
	Other	0.27	0.08
	Total	0.99	0.95
2700 West	Rear-end	0.76	0.69
	Right-angle	0.00	0.11
	Other	0.11	0.00
	Total	0.87	0.79
13400 South	Rear-end	0.98	0.56
	Right-angle	0.07	0.19
	Other	0.20	0.25
	Total	1.24	1.00
12600 South (control site)	Rear-end	0.69	0.95
	Right-angle	0.00	0.15
	Other	0.21	0.05
	Total	0.90	1.15

Table C-4. Before-and-After (Two-Year) Crash Rates for Crashes Involving at Least One Vehicle Traveling On Bangerter Highway

		Crash Rate per MEV	
		Before	**After**
Redwood Road	Rear-end	0.56	0.54
	Right-angle	0.03	0.20
	Other	0.21	0.08
	Total	0.80	0.82
2700 West	Rear-end	0.67	0.59
	Right-angle	0.10	0.18
	Other	0.10	0.05
	Total	0.86	0.81
13400 South	Rear-end	0.57	0.29
	Right-angle	0.23	0.25
	Other	0.11	0.13
	Total	0.92	0.67
12600 South (control site)	Rear-end	0.42	0.61
	Right-angle	0.13	0.26
	Other	0.13	0.06
	Total	0.68	0.93

Appendix D. Cumulative Speed Distribution Plots

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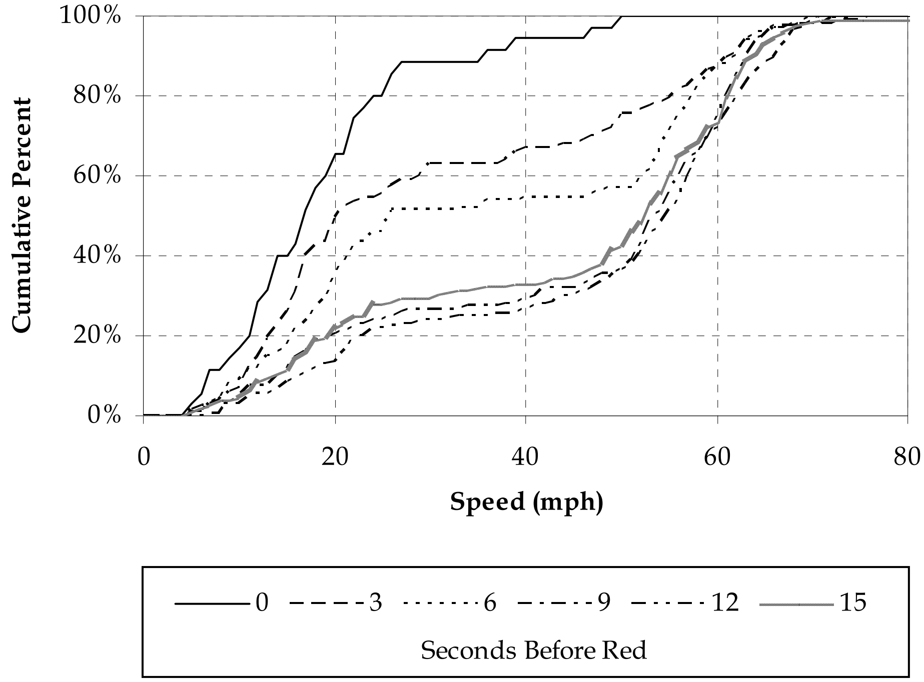

Figure D-1. Cumulative distribution plot for northbound AM peak speeds at the 50 foot detection zone for P4.

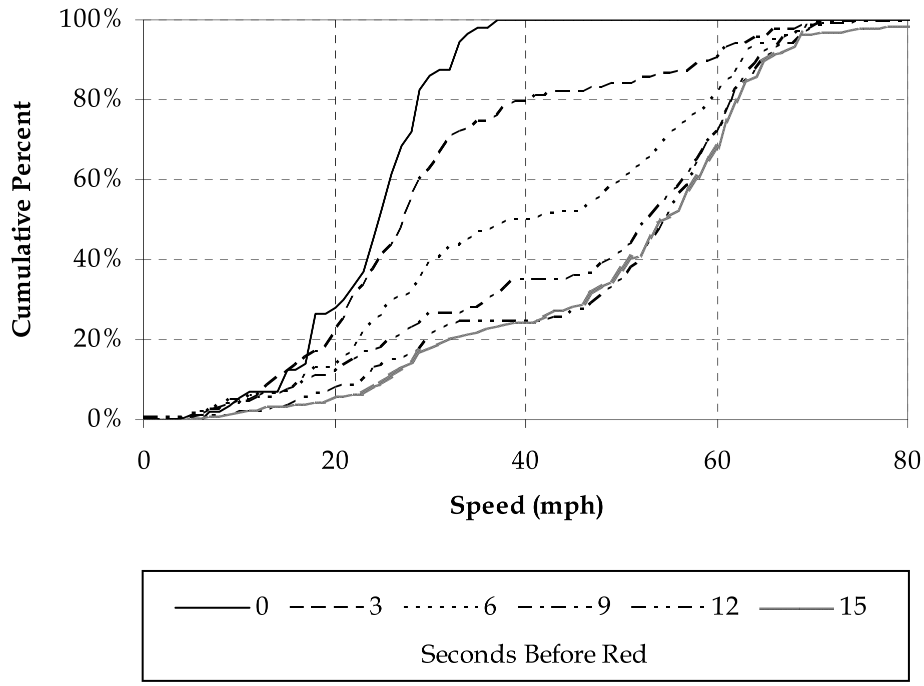

Figure D-2. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone for P4.

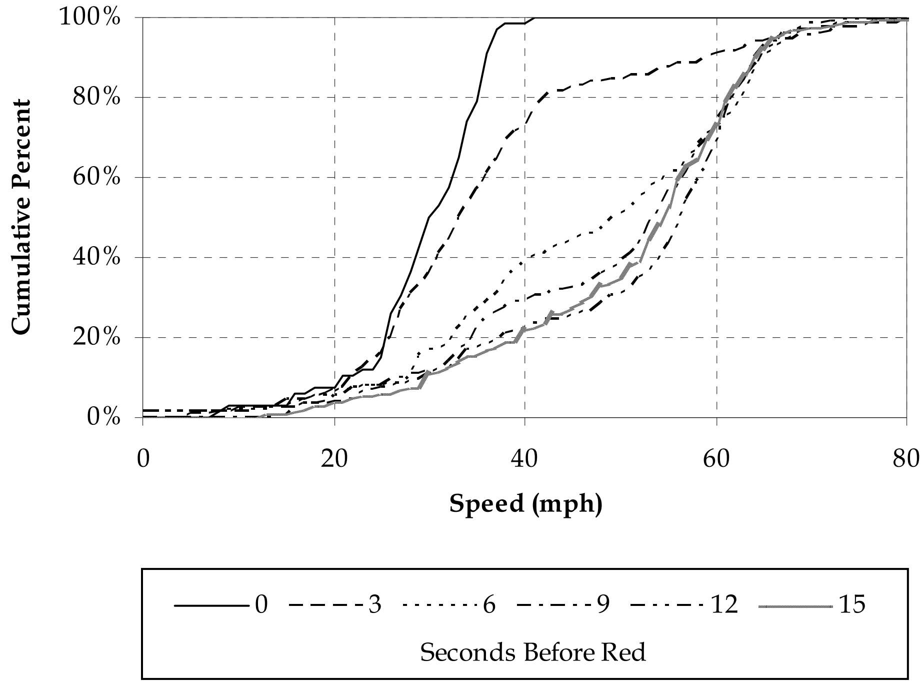

Figure D-3. Cumulative distribution plot for northbound AM peak speeds at the 150 foot detection zone for P4.

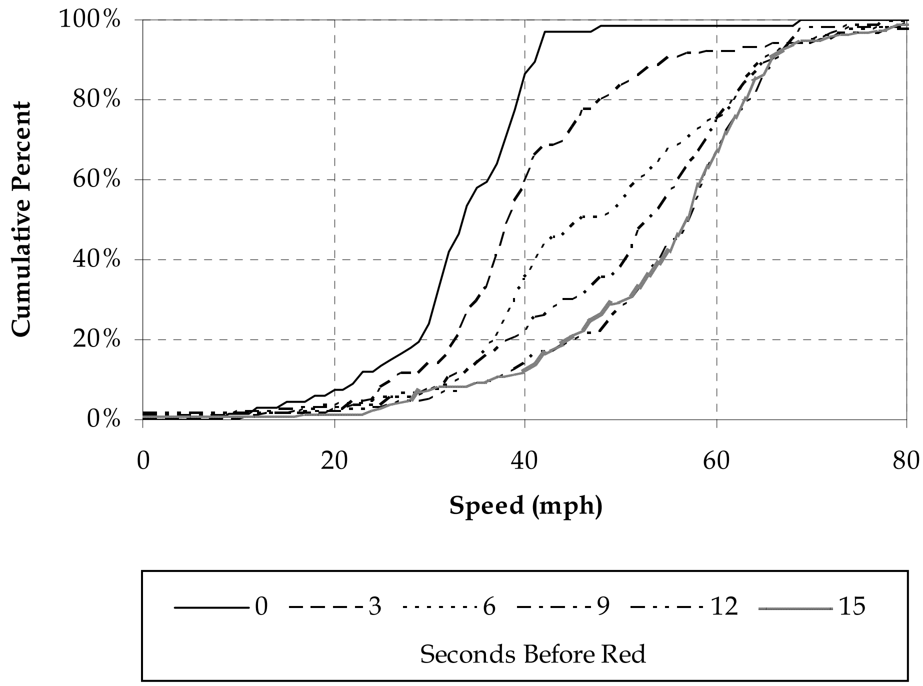

Figure D-4. Cumulative distribution plot for northbound AM peak speeds at the 200 foot detection zone for P4.

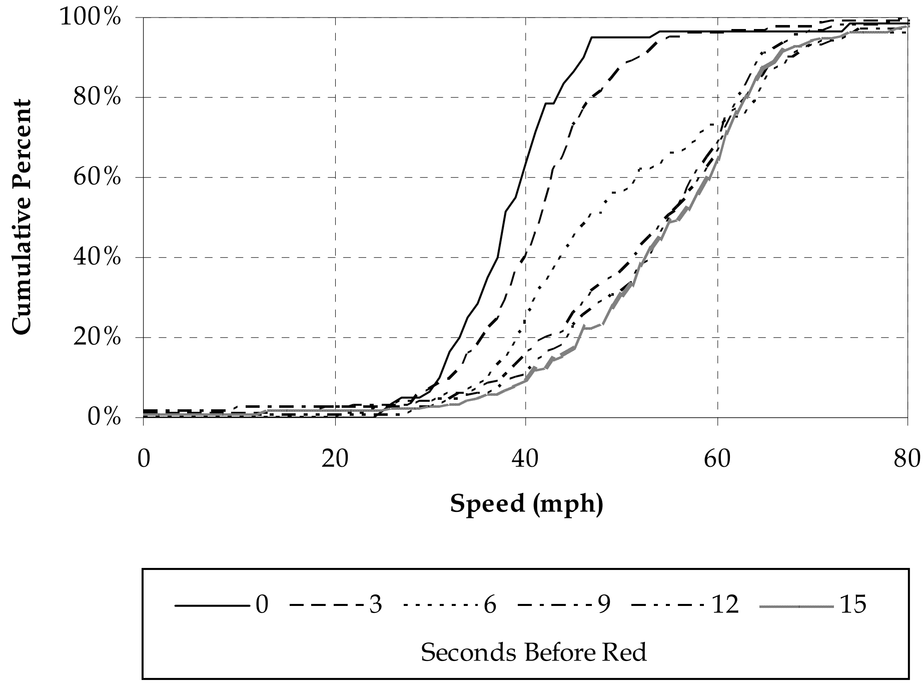

Figure D-5. Cumulative distribution plot for northbound AM peak speeds at the 250 foot detection zone for P4.

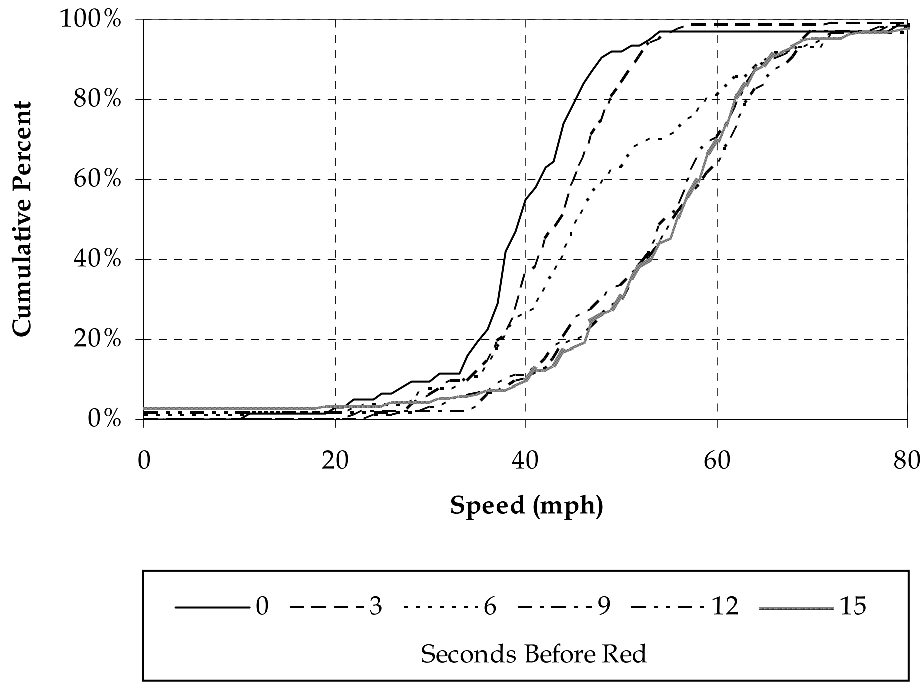

Figure D-6. Cumulative distribution plot for northbound AM peak speeds at the 300 foot detection zone for P4.

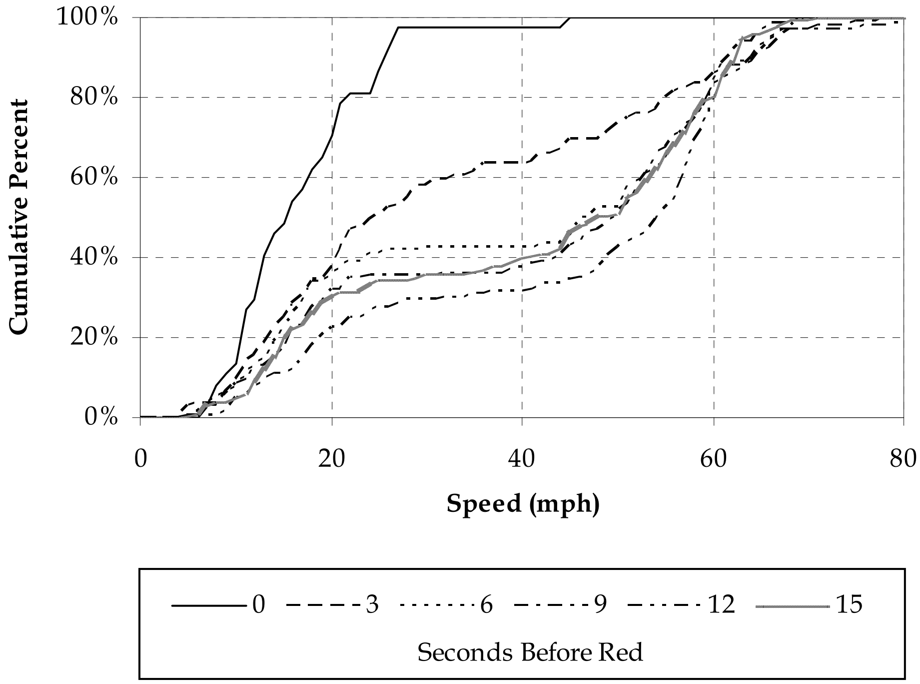

Figure D-7. Cumulative distribution plot for northbound noon peak speeds at the 50 foot detection zone for P4.

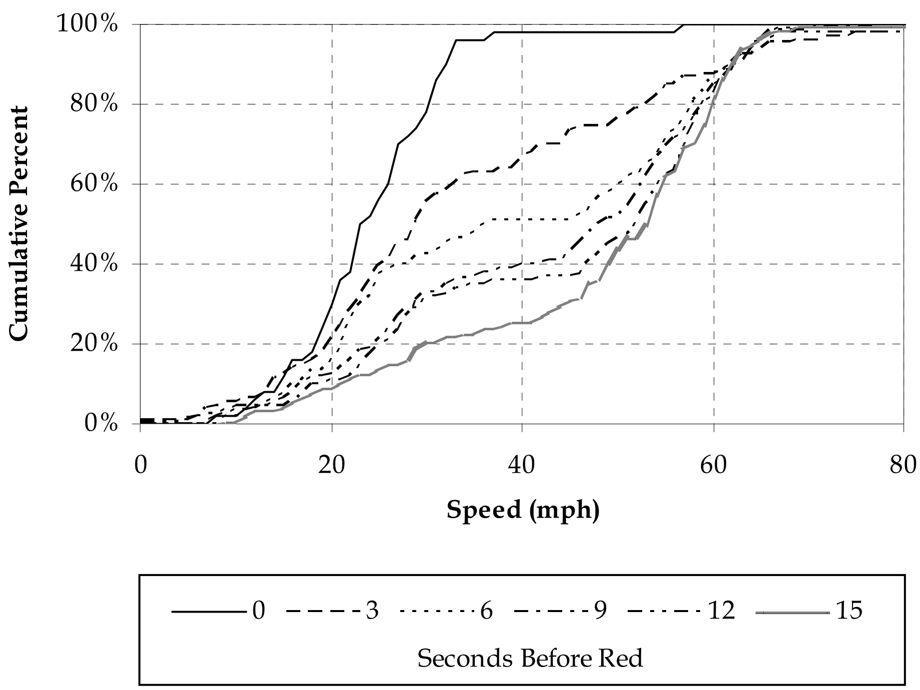

Figure D-8. Cumulative distribution plot for northbound noon peak speeds at the 100 foot detection zone for P4.

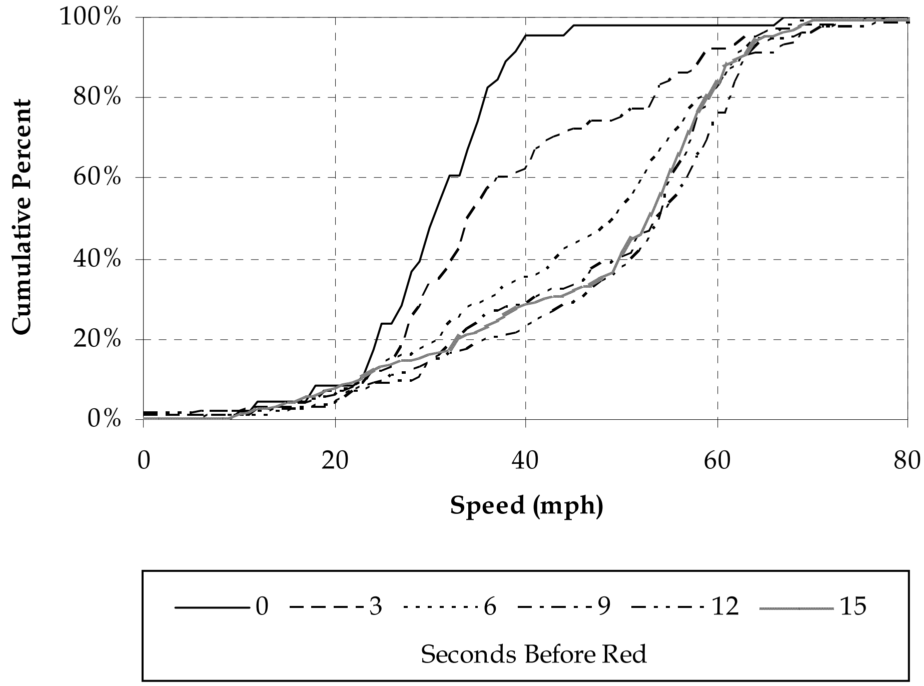

Figure D-9. Cumulative distribution plot for northbound noon peak speeds at the 150 foot detection zone for P4.

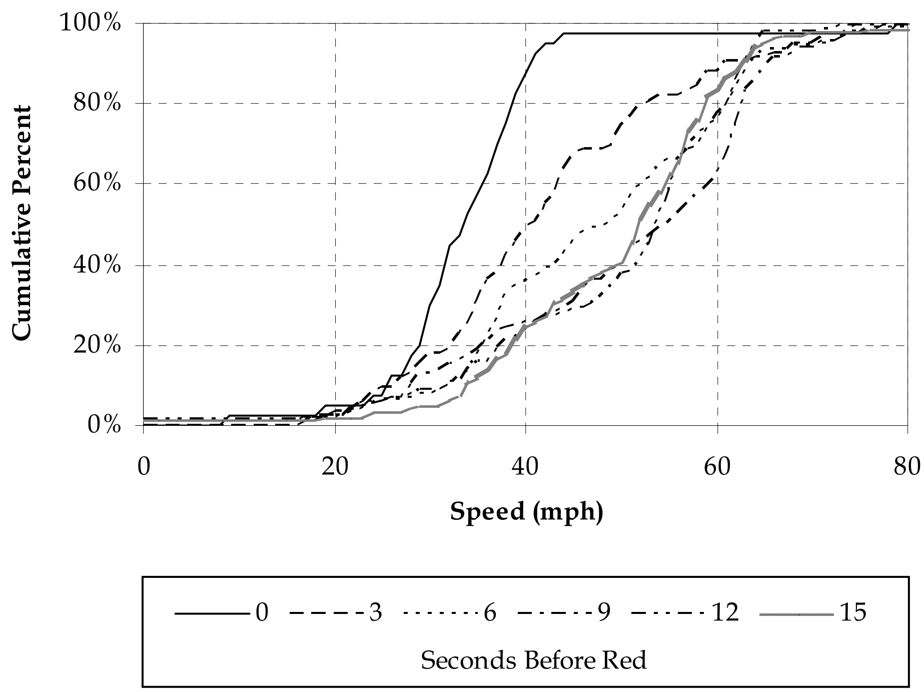

Figure D-10. Cumulative distribution plot for northbound noon peak speeds at the 200 foot detection zone for P4.

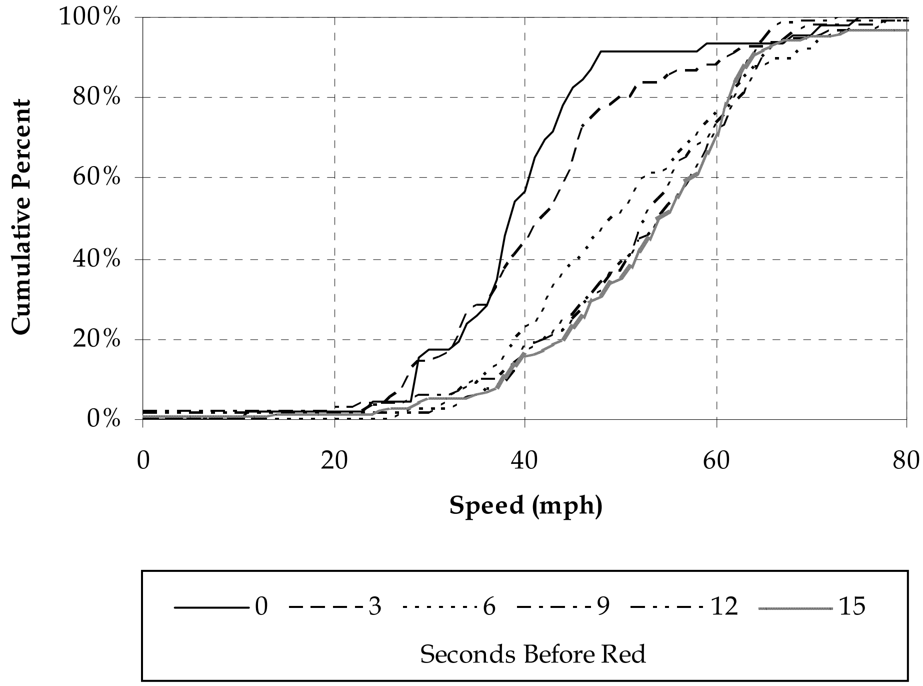

Figure D-11. Cumulative distribution plot for northbound noon peak speeds at the 250 foot detection zone for P4.

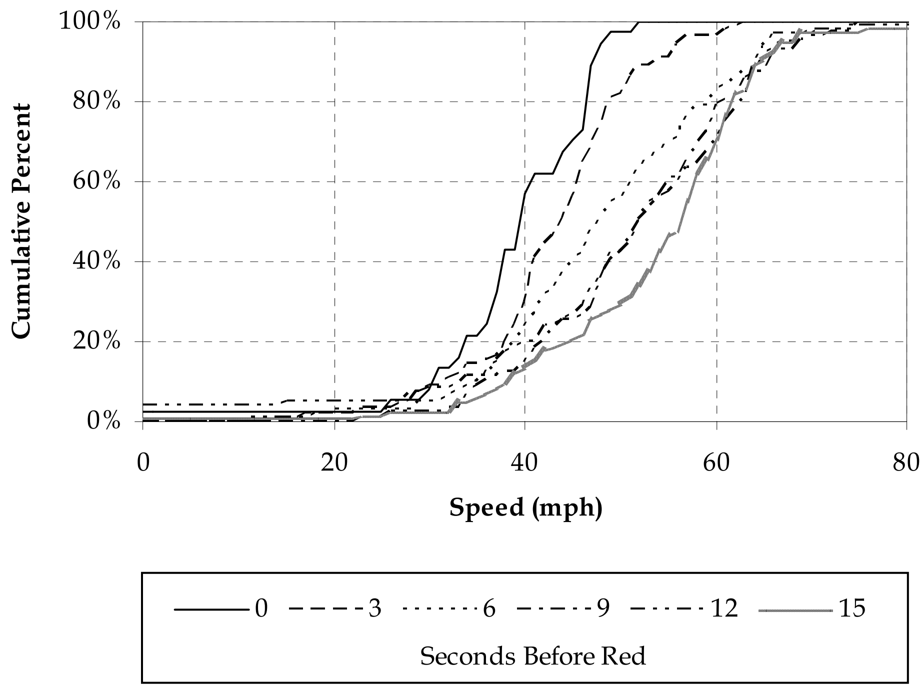

Figure D-12. Cumulative distribution plot for northbound noon peak speeds at the 300 foot detection zone for P4.

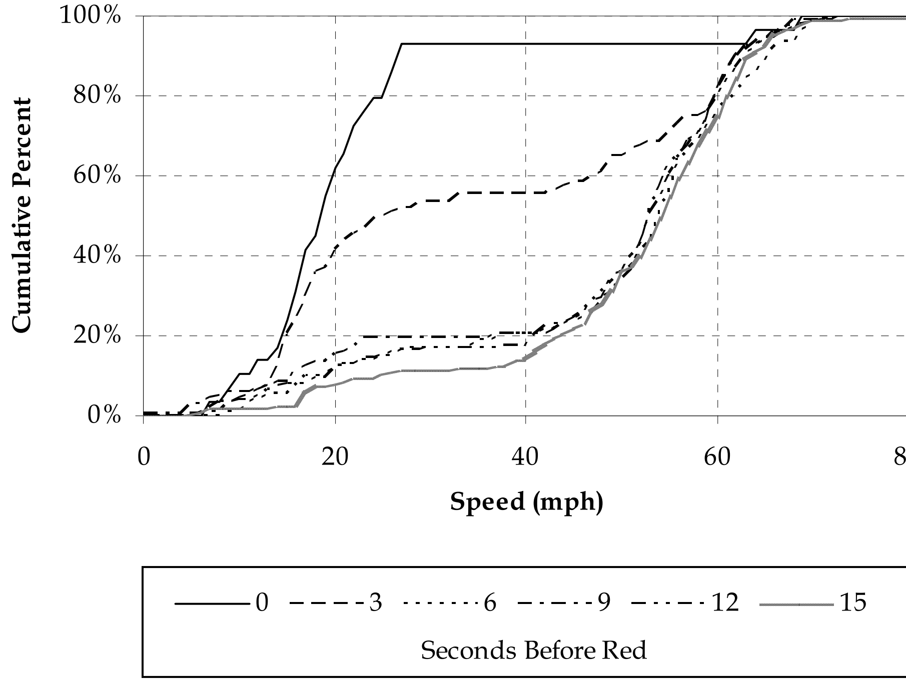

Figure D-13. Cumulative distribution plot for northbound PM peak speeds at the 50 foot detection zone for P4.

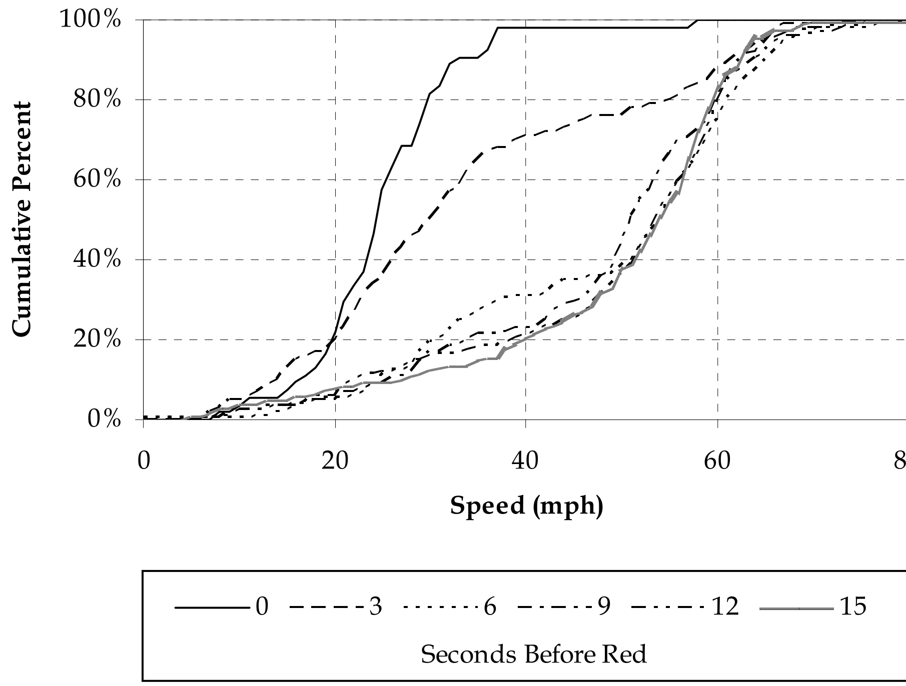

Figure D-14. Cumulative distribution plot for northbound PM peak speeds at the 100 foot detection zone for P4.

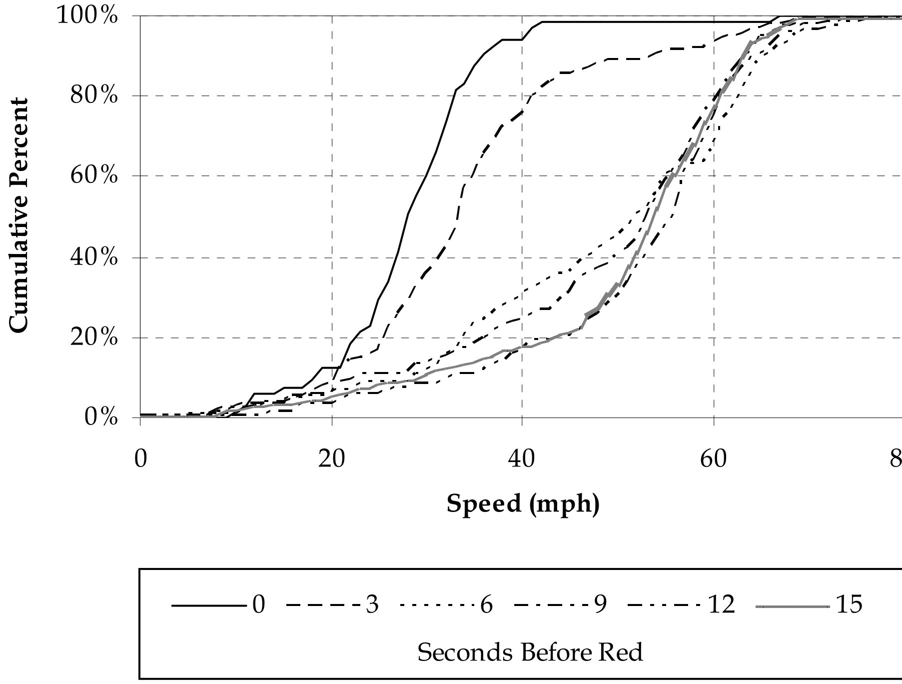

Figure D-15. Cumulative distribution plot for northbound PM peak speeds at the 150 foot detection zone for P4.

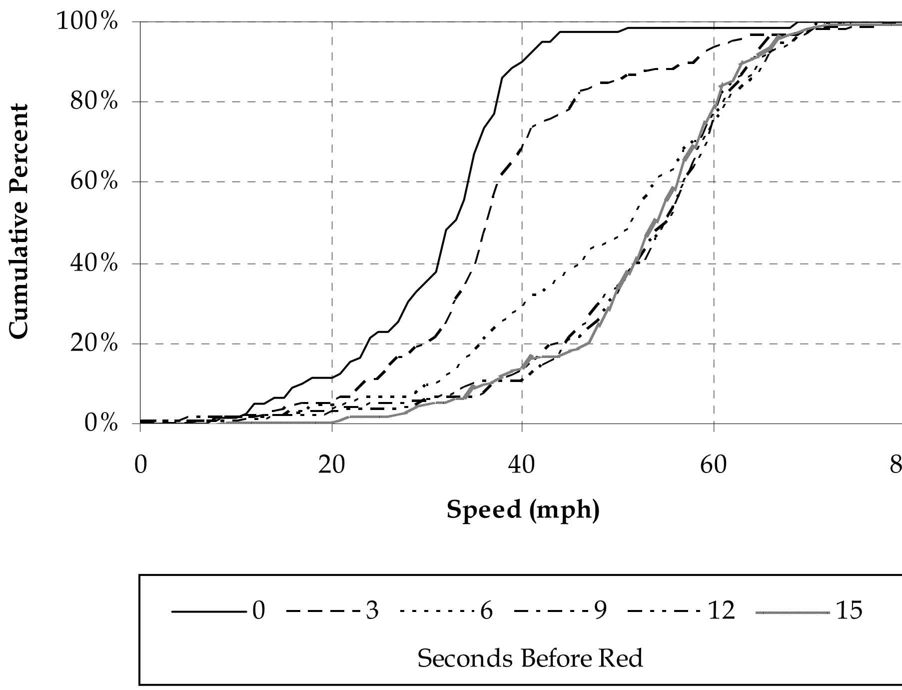

Figure D-16. Cumulative distribution plot for northbound PM peak speeds at the 200 foot detection zone for P4.

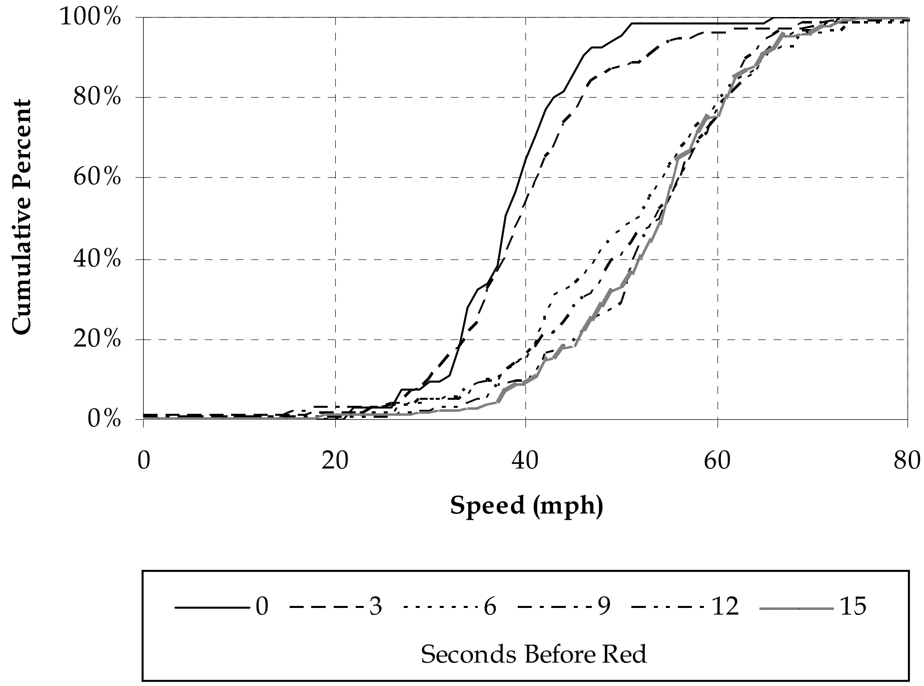

Figure D-17. Cumulative distribution plot for northbound PM peak speeds at the 250 foot detection zone for P4.

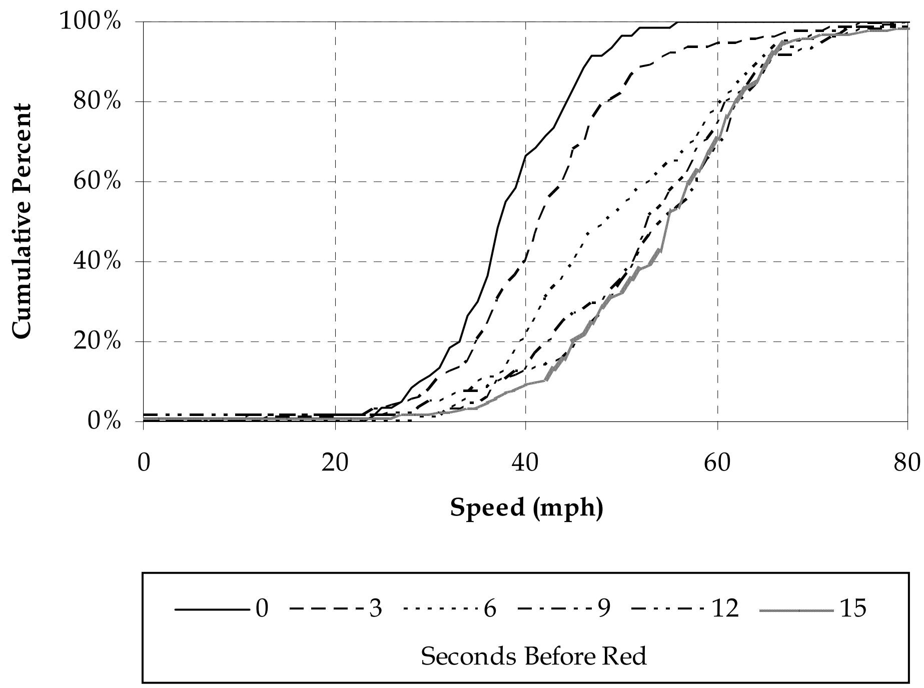

Figure D-18. Cumulative distribution plot for northbound PM peak speeds at the 300 foot detection zone for P4.

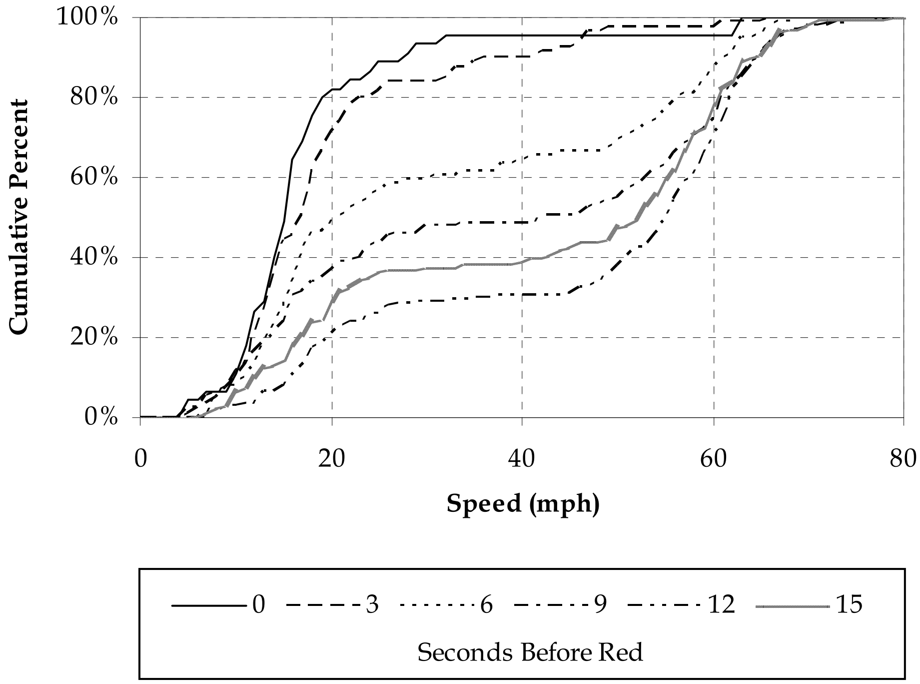

Figure D-19. Cumulative distribution plot for northbound AM peak speeds at the 50 foot detection zone for P5.

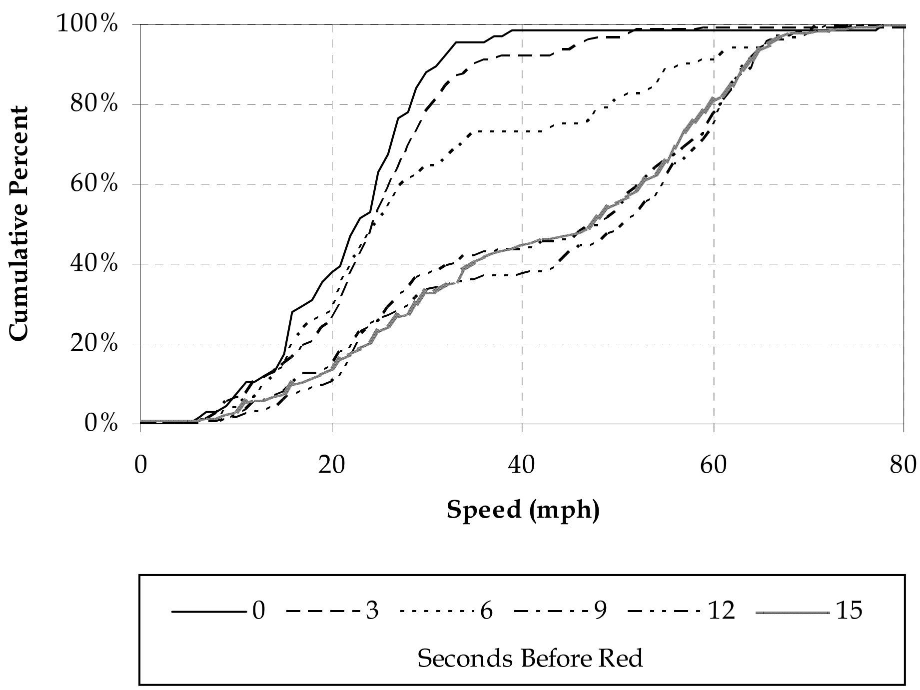

Figure D-20. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone for P5.

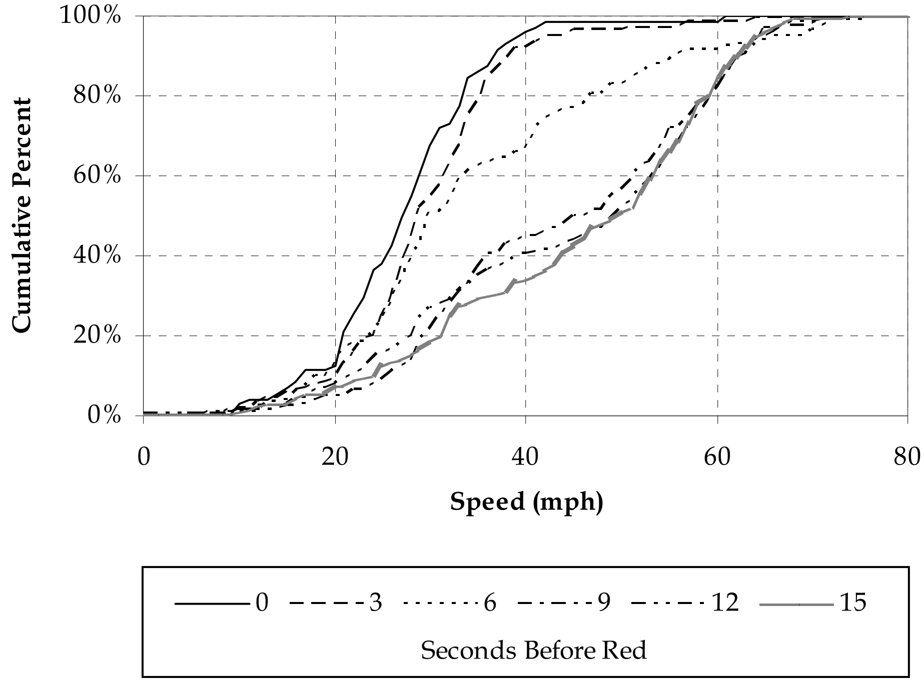

Figure D-21. Cumulative distribution plot for northbound AM peak speeds at the 150 foot detection zone for P5.

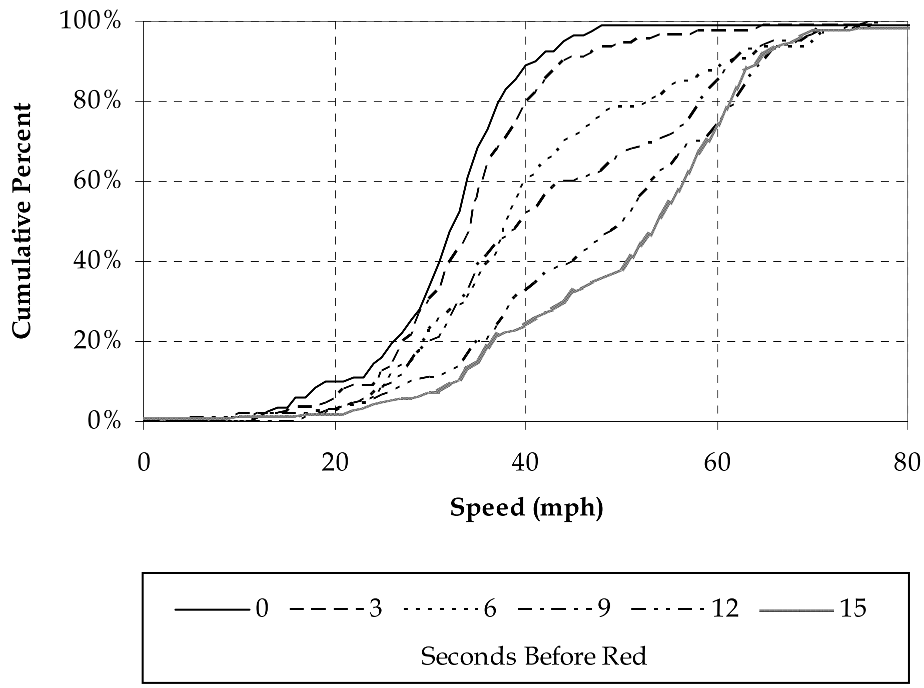

Figure D-22. Cumulative distribution plot for northbound AM peak speeds at the 200 foot detection zone for P5.

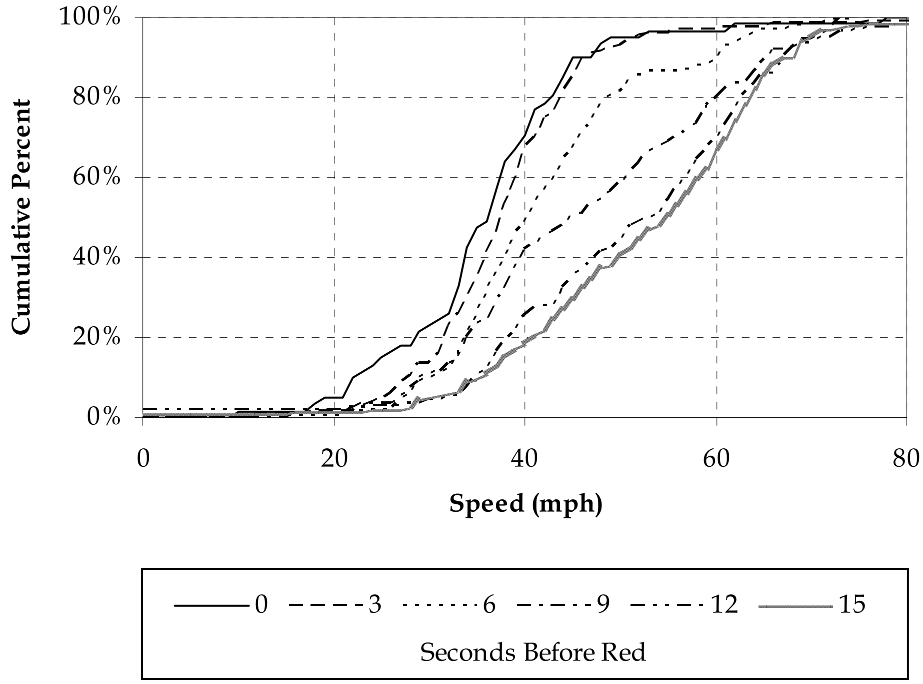

Figure D-23. Cumulative distribution plot for northbound AM peak speeds at the 250 foot detection zone for P5.

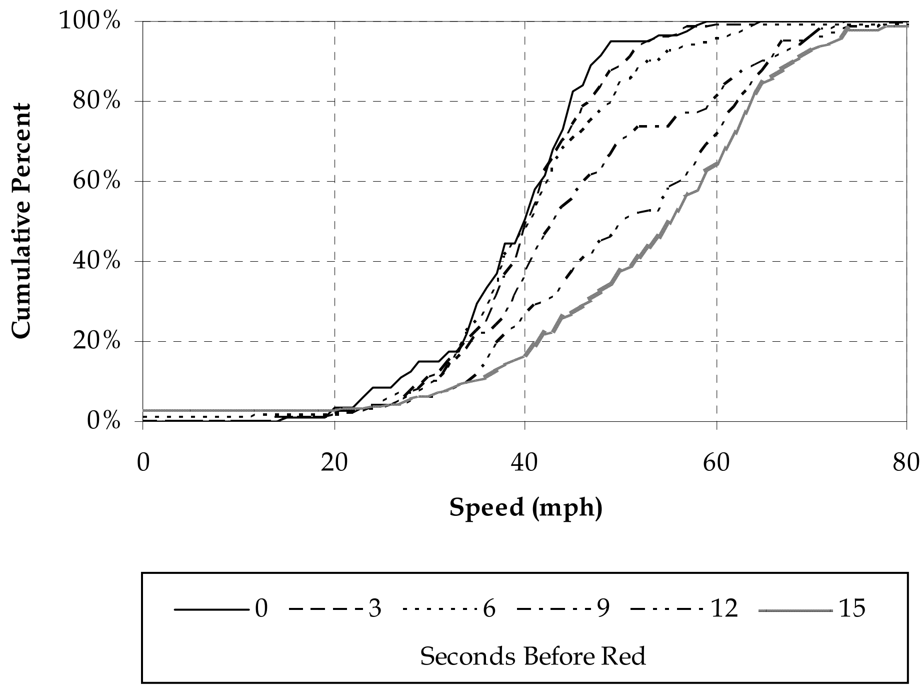

Figure D-24. Cumulative distribution plot for northbound AM peak speeds at the 300 foot detection zone for P5.

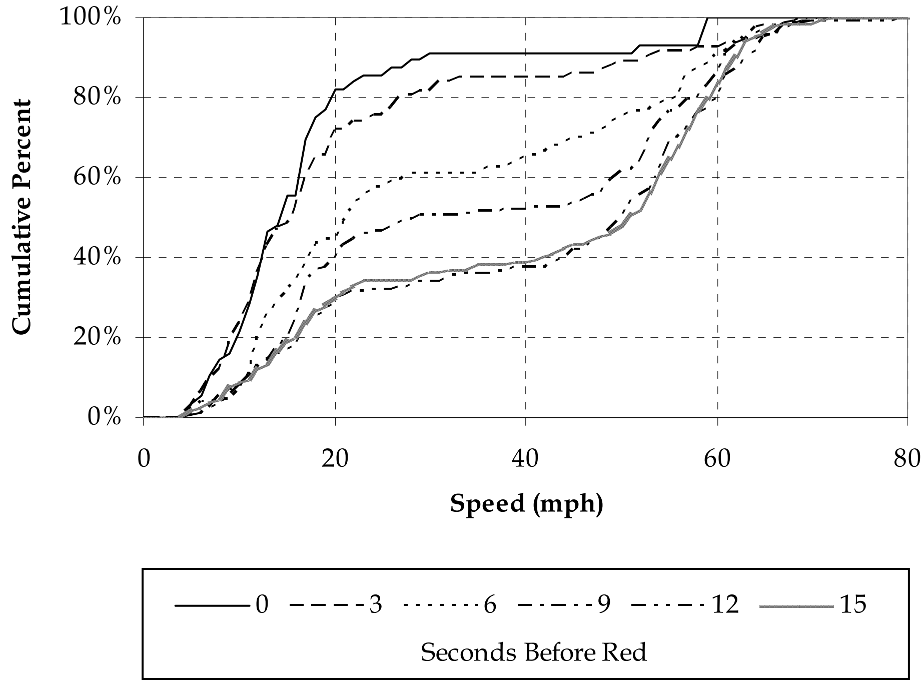

Figure D-25. Cumulative distribution plot for northbound noon peak speeds at the 50 foot detection zone for P5.

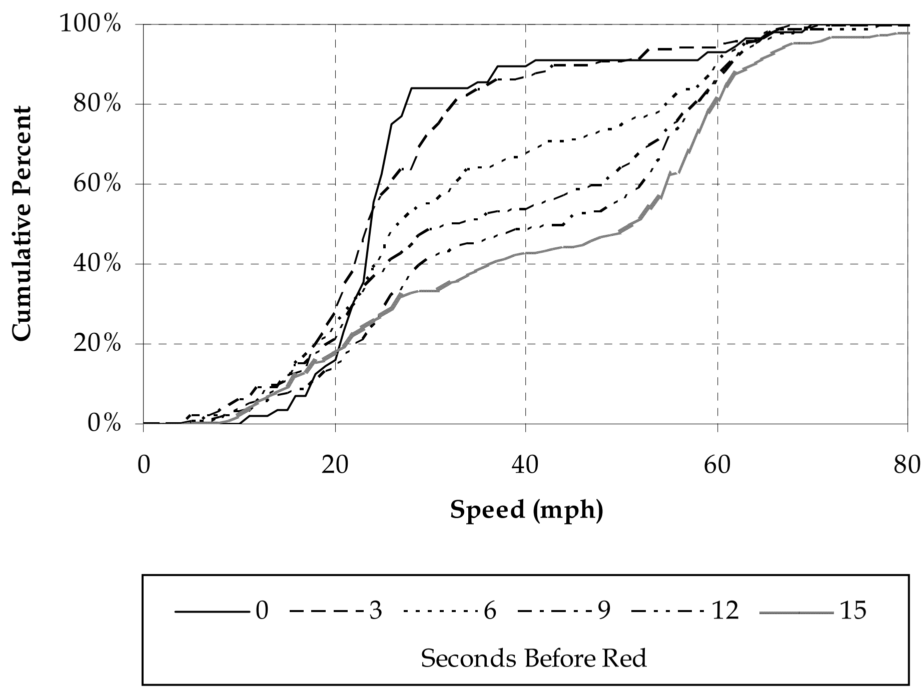

Figure D-26. Cumulative distribution plot for northbound noon peak speeds at the 100 foot detection zone for P5.

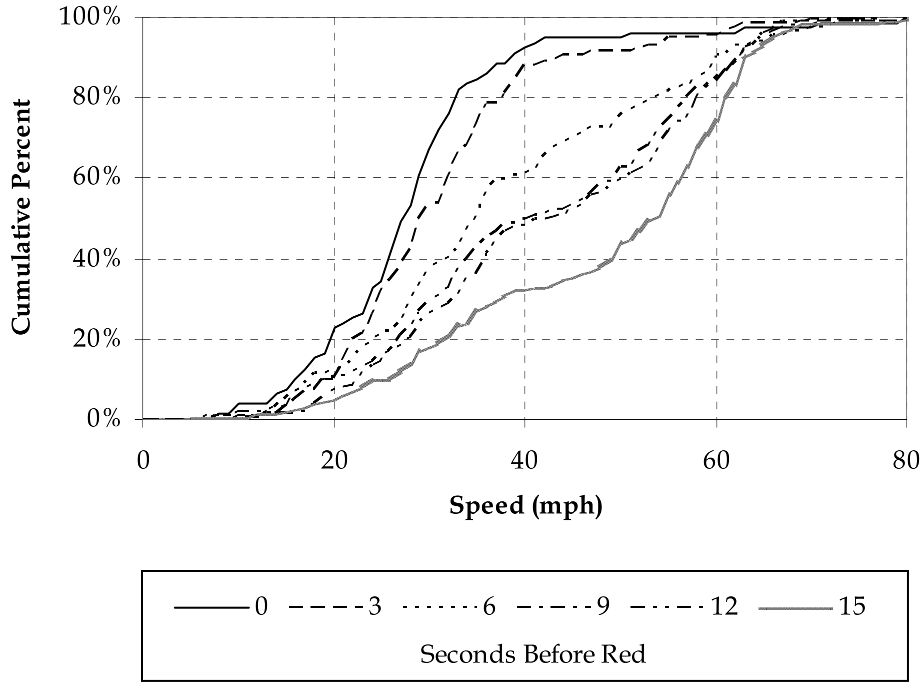

Figure D-27. Cumulative distribution plot for northbound noon peak speeds at the 150 foot detection zone for P5.

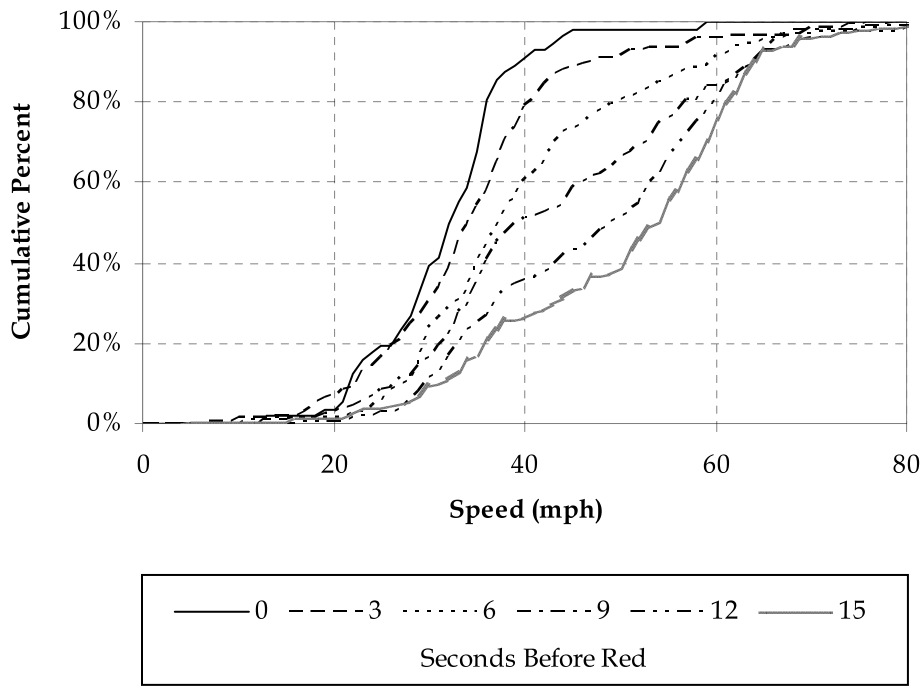

Figure D-28. Cumulative distribution plot for northbound noon peak speeds at the 200 foot detection zone for P5.

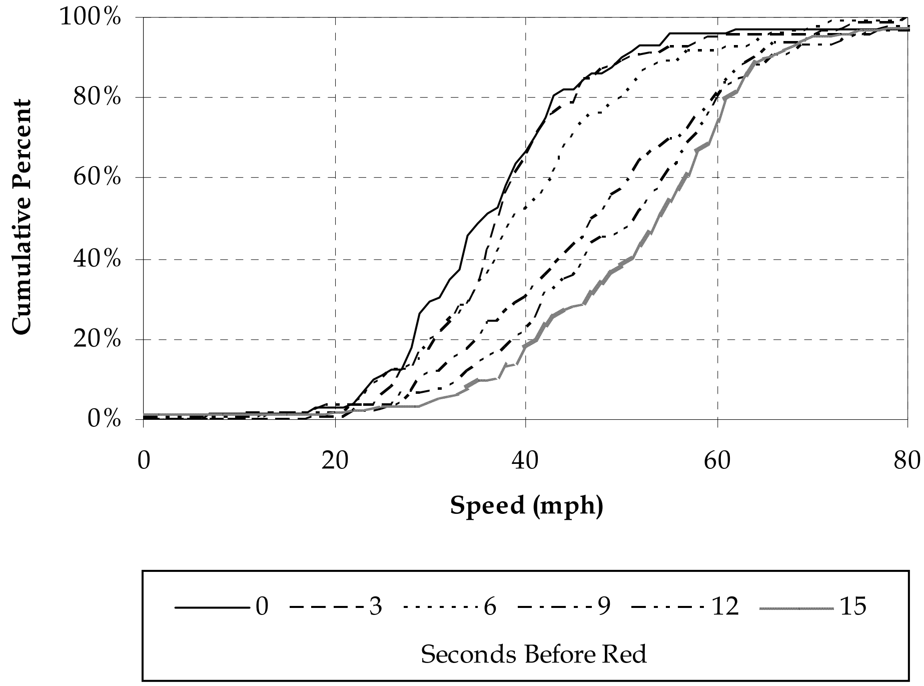

Figure D-29. Cumulative distribution plot for northbound noon peak speeds at the 250 foot detection zone for P5.

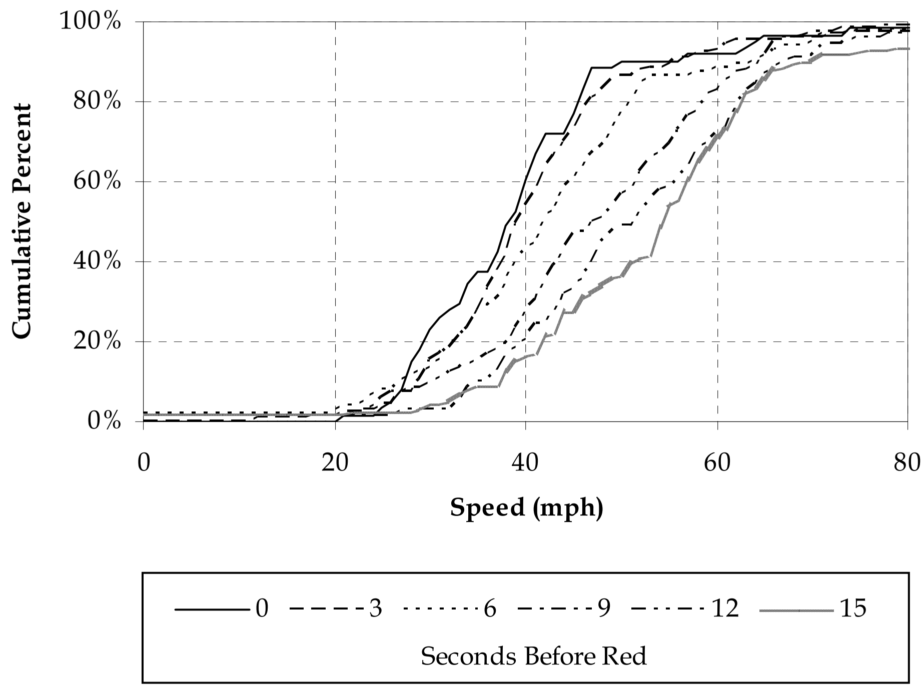

Figure D-30. Cumulative distribution plot for northbound noon peak speeds at the 300 foot detection zone for P5.

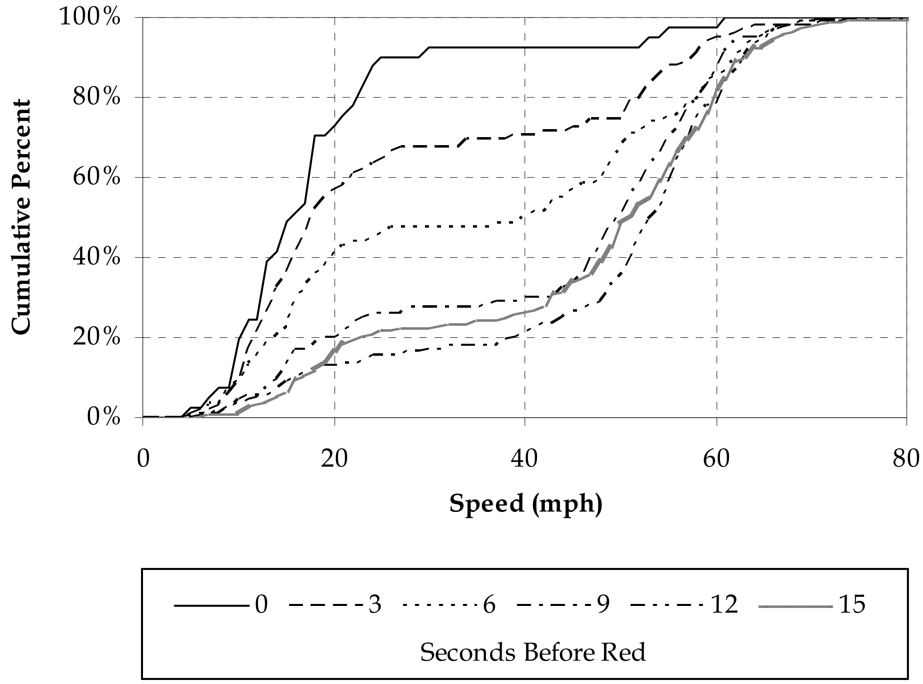

Figure D-31. Cumulative distribution plot for northbound PM peak speeds at the 50 foot detection zone for P5.

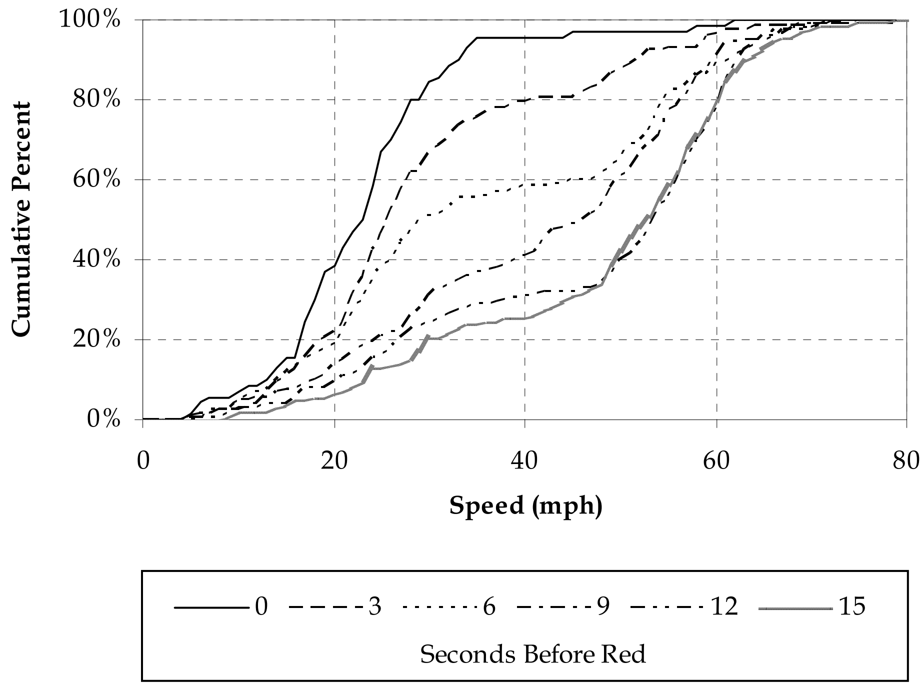

Figure D-32. Cumulative distribution plot for northbound PM peak speeds at the 100 foot detection zone for P5.

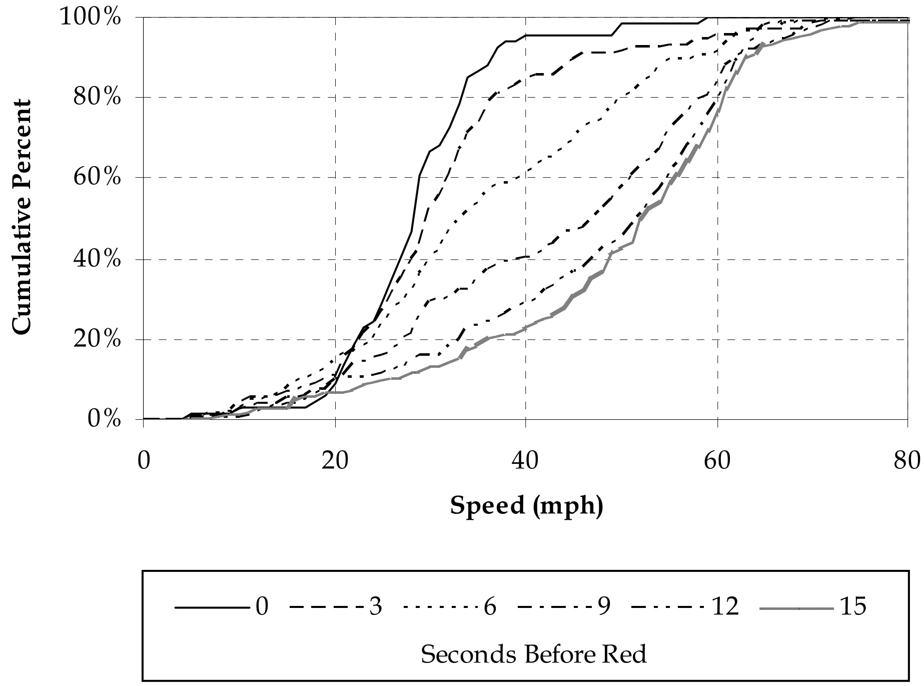

Figure D-33. Cumulative distribution plot for northbound PM peak speeds at the 150 foot detection zone for P5.

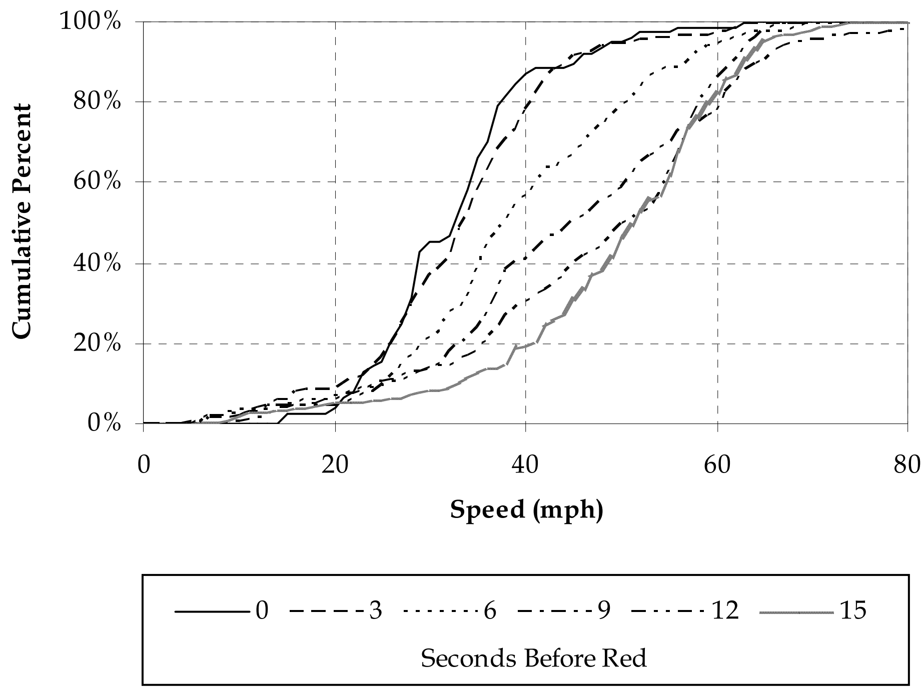

Figure D-34. Cumulative distribution plot for northbound PM peak speeds at the 200 foot detection zone for P5.

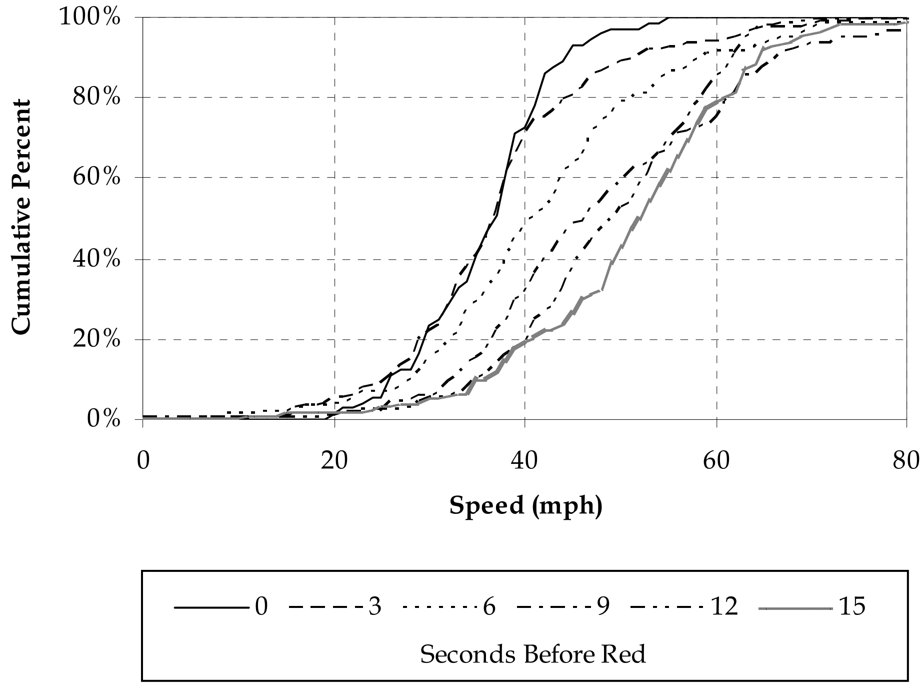

Figure D-35. Cumulative distribution plot for northbound PM peak speeds at the 250 foot detection zone for P5.

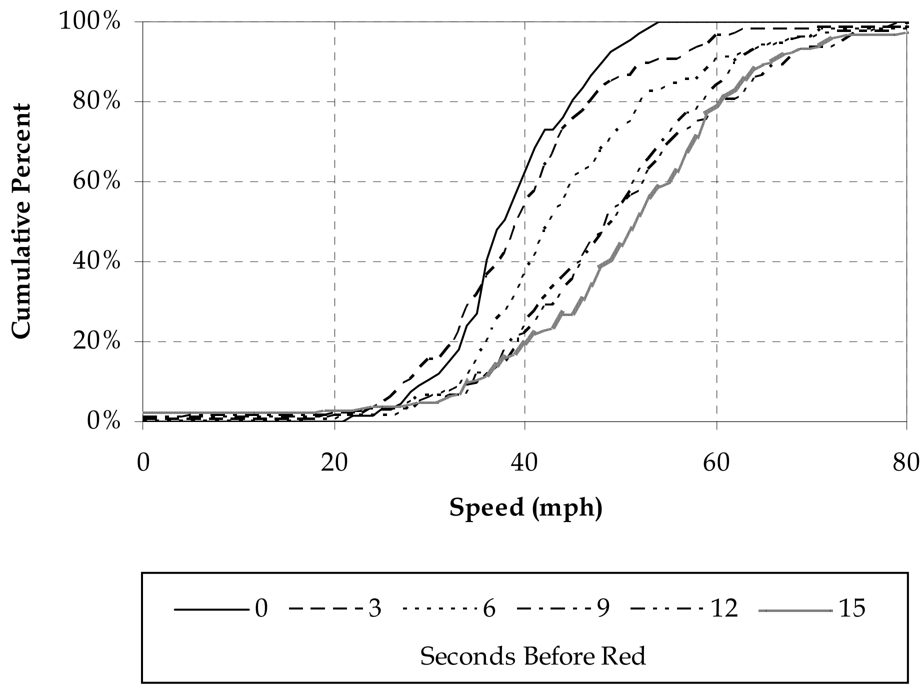

Figure D-36. Cumulative distribution plot for northbound PM peak speeds at the 300 foot detection zone for P5.

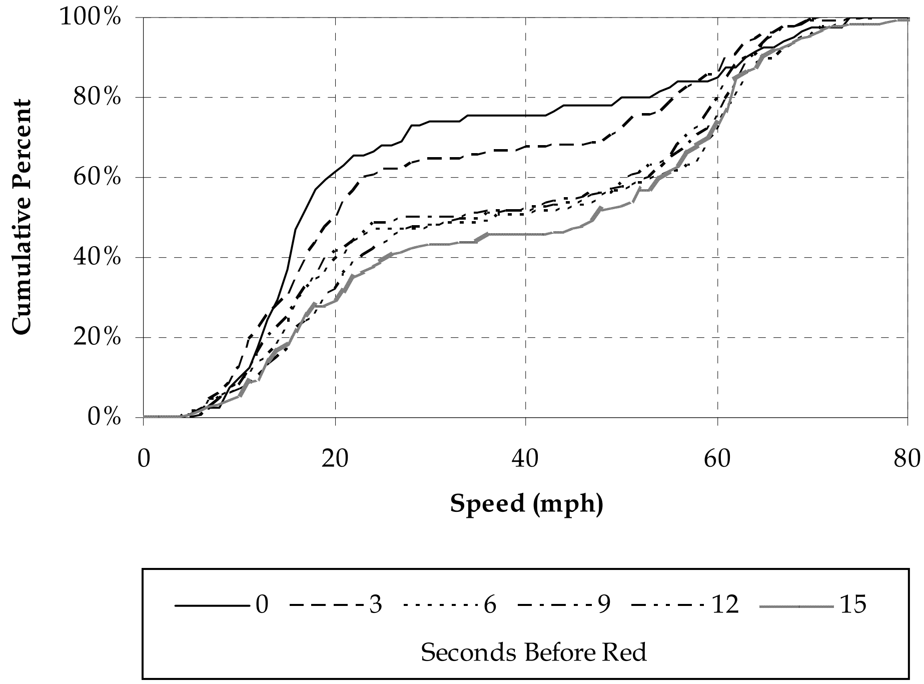

Figure D-37. Cumulative distribution plot for northbound AM peak speeds at the 50 foot detection zone for P6.

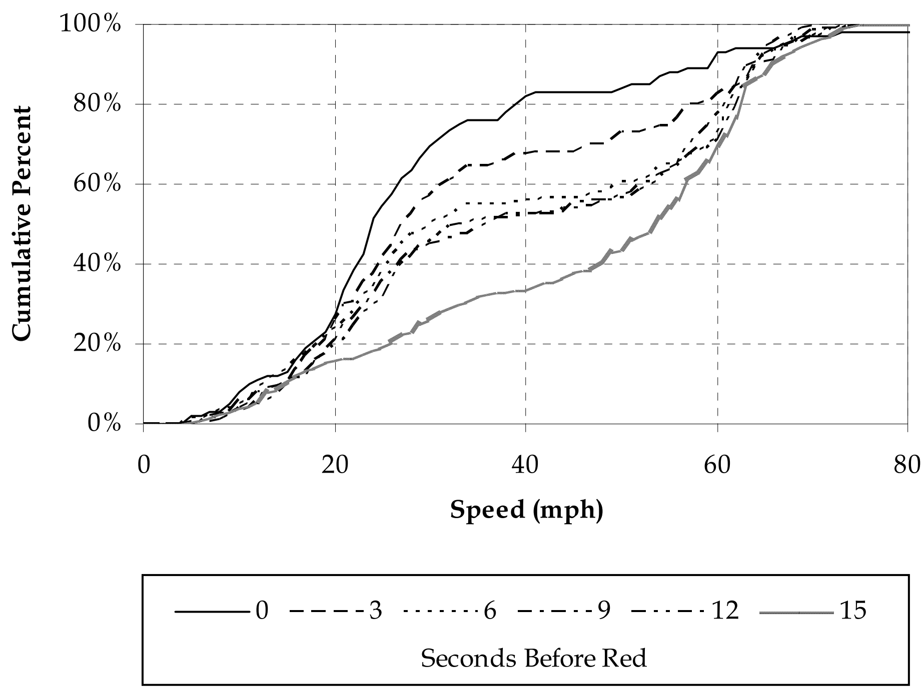

Figure D-38. Cumulative distribution plot for northbound AM peak speeds at the 100 foot detection zone for P6.

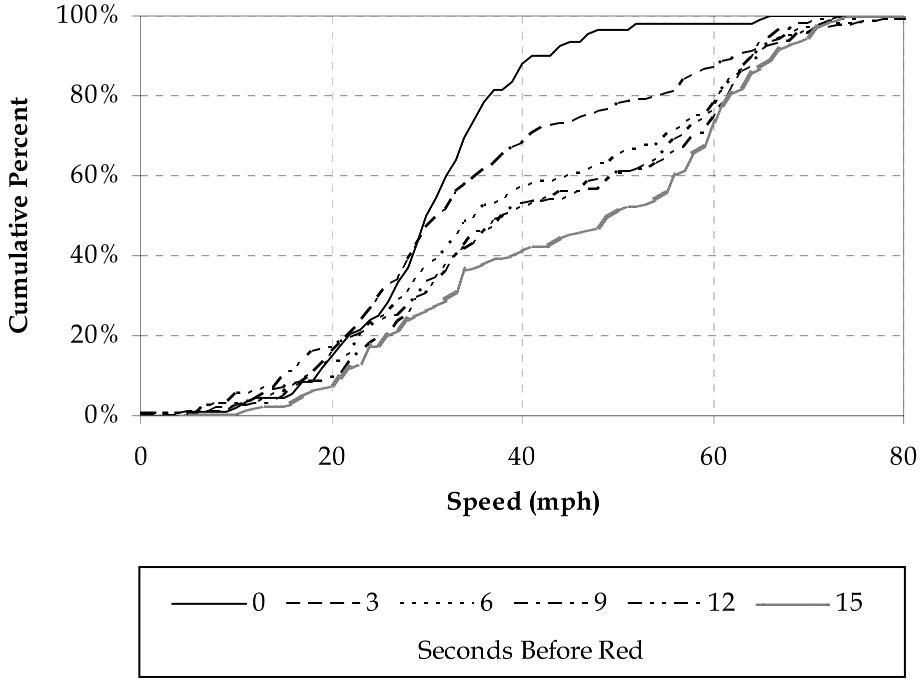

Figure D-39. Cumulative distribution plot for northbound AM peak speeds at the 150 foot detection zone for P6.

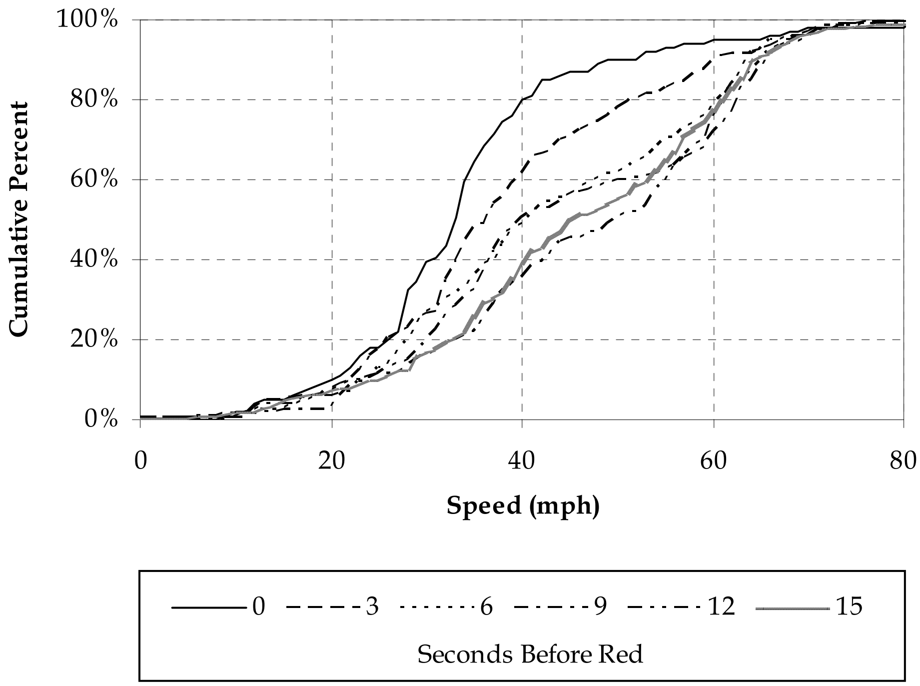

Figure D-40. Cumulative distribution plot for northbound AM peak speeds at the 200 foot detection zone for P6.

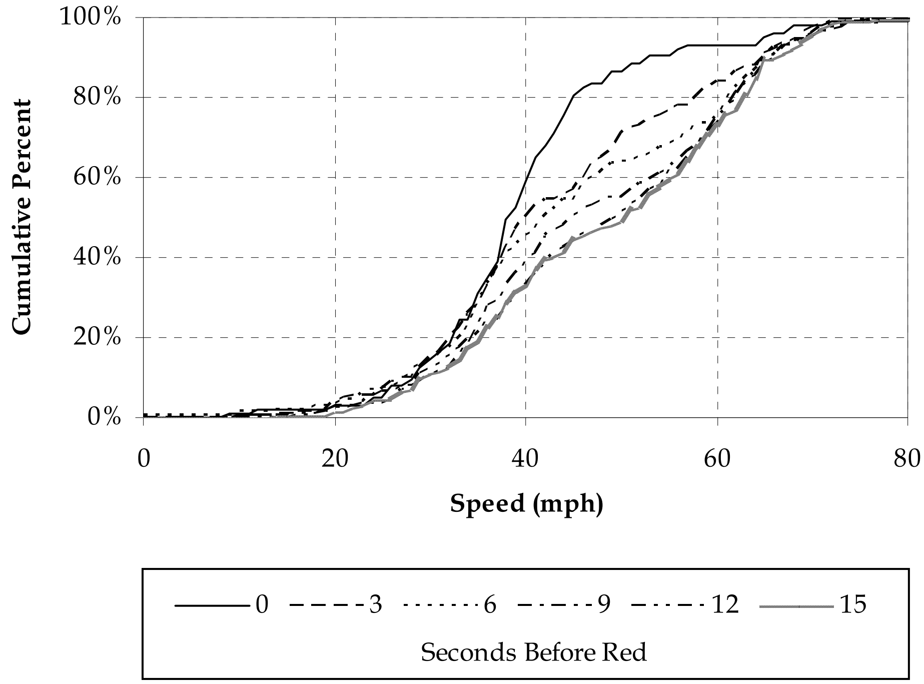

Figure D-41. Cumulative distribution plot for northbound AM peak speeds at the 250 foot detection zone for P6.

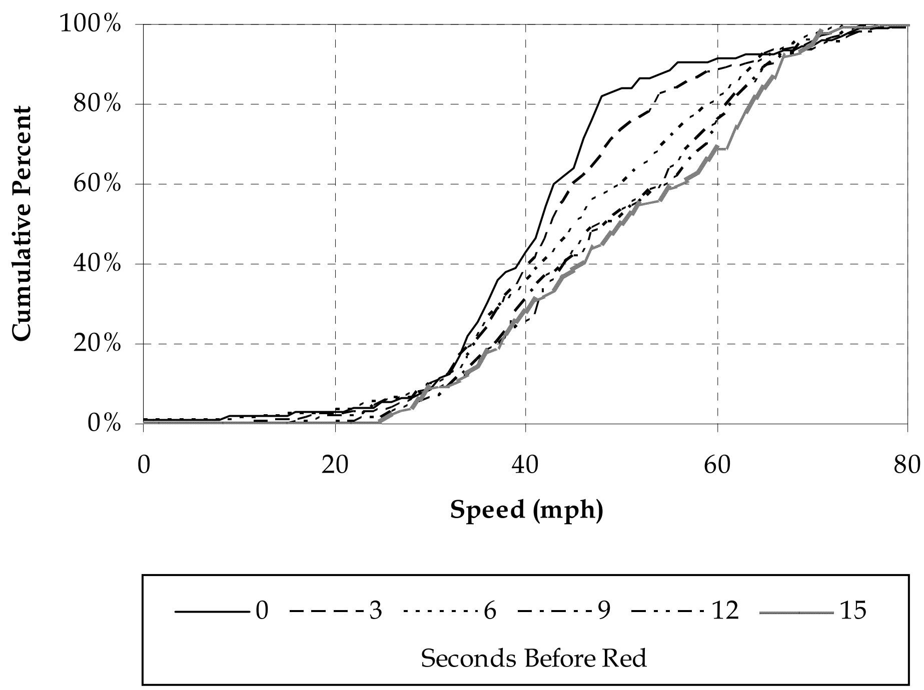

Figure D-42. Cumulative distribution plot for northbound AM peak speeds at the 300 foot detection zone for P6.

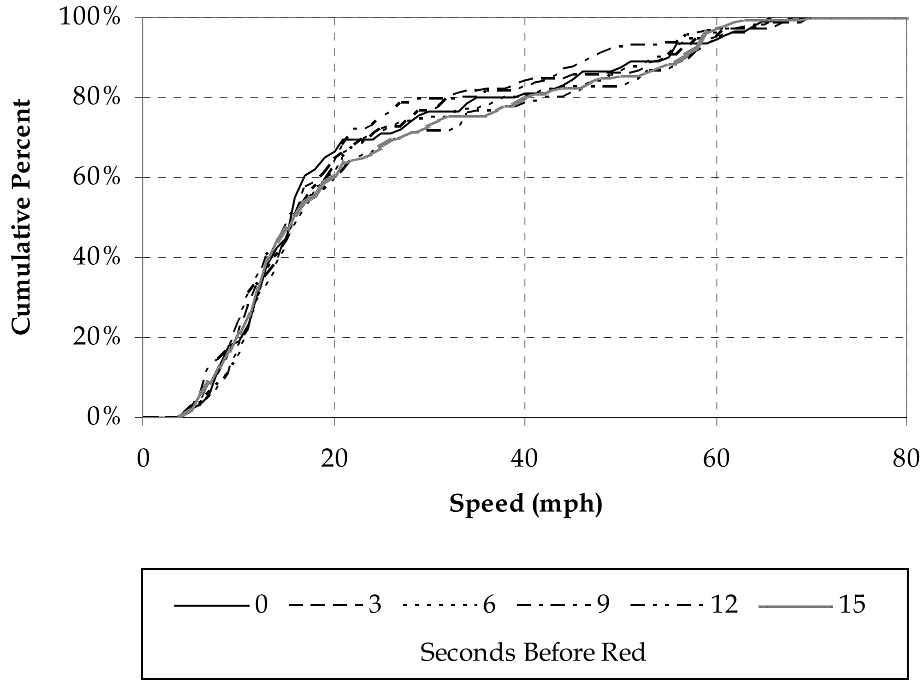

Figure D-43. Cumulative distribution plot for northbound noon peak speeds at the 50 foot detection zone for P6.

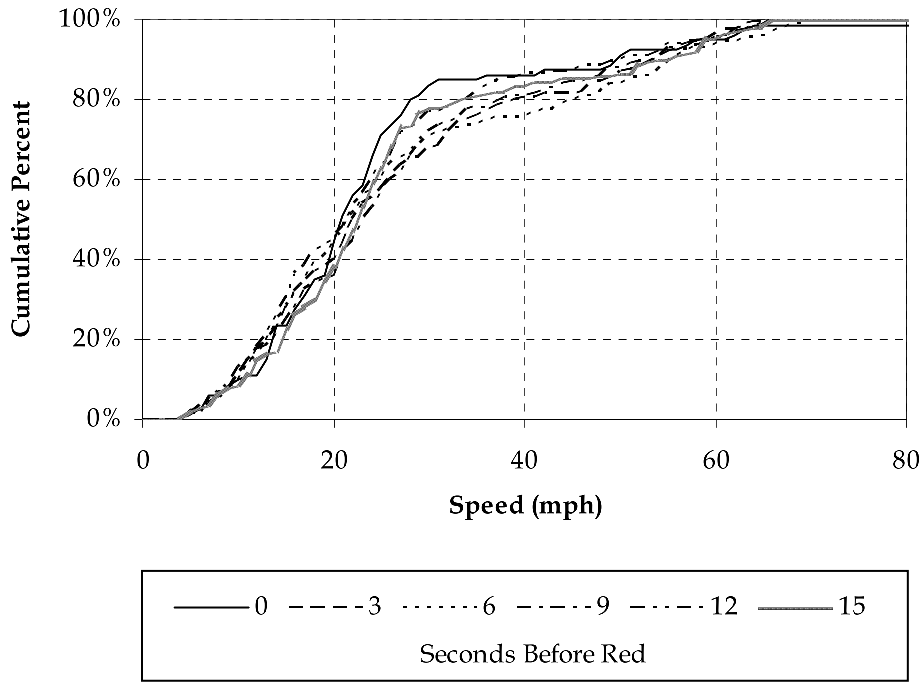

Figure D-44. Cumulative distribution plot for northbound noon peak speeds at the 100 foot detection zone for P6.

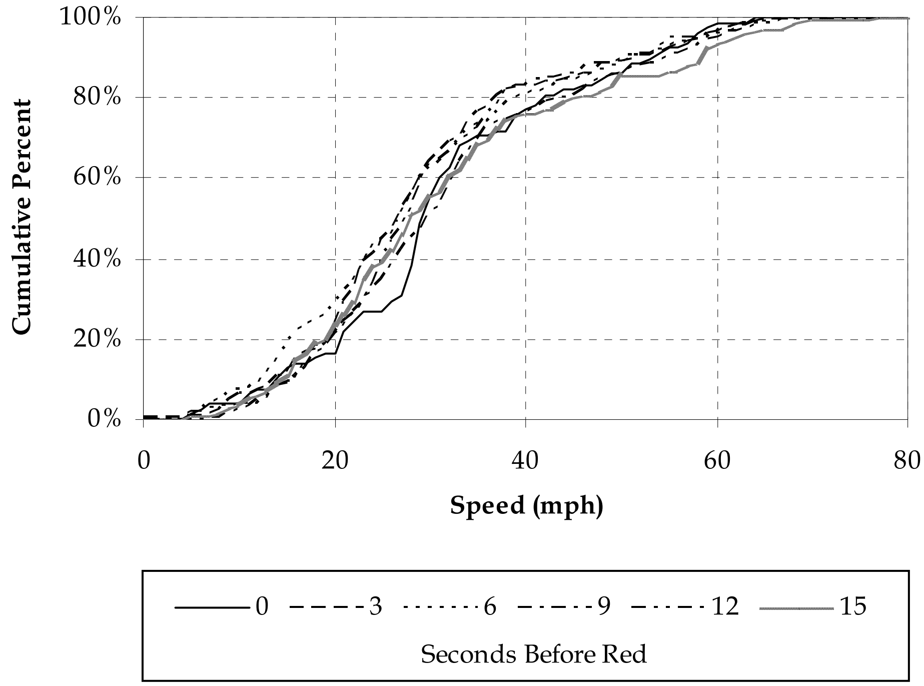

Figure D-45. Cumulative distribution plot for northbound noon peak speeds at the 150 foot detection zone for P6.

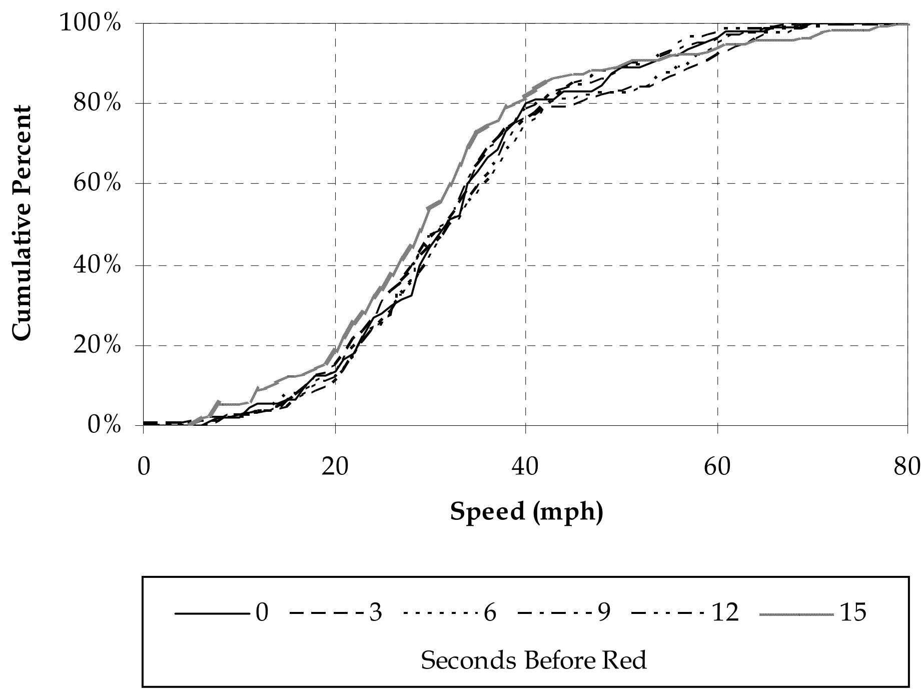

Figure D-46. Cumulative distribution plot for northbound noon peak speeds at the 200 foot detection zone for P6.

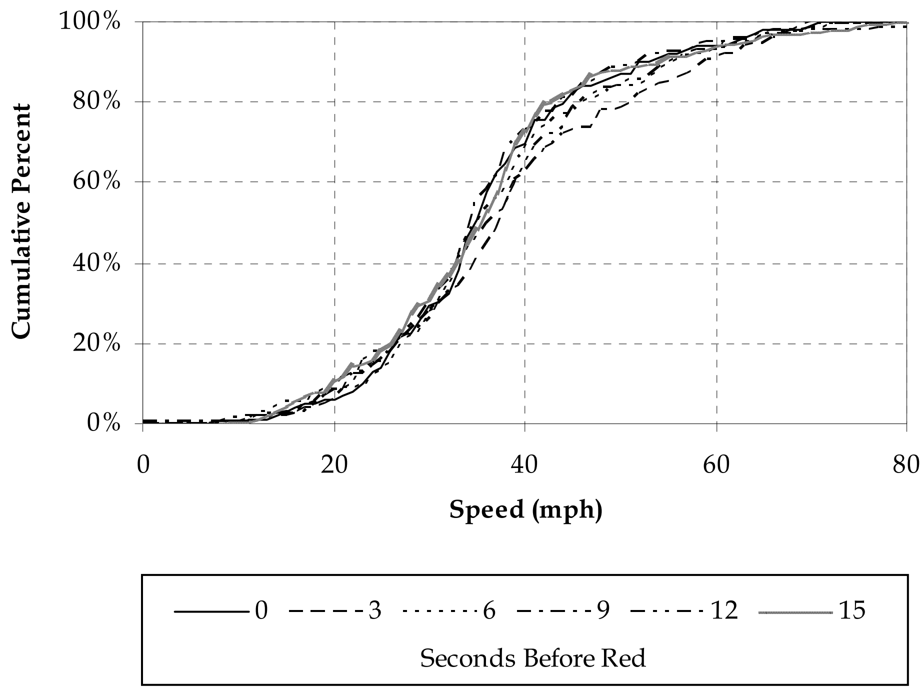

Figure D-47. Cumulative distribution plot for northbound noon peak speeds at the 250 foot detection zone for P6.

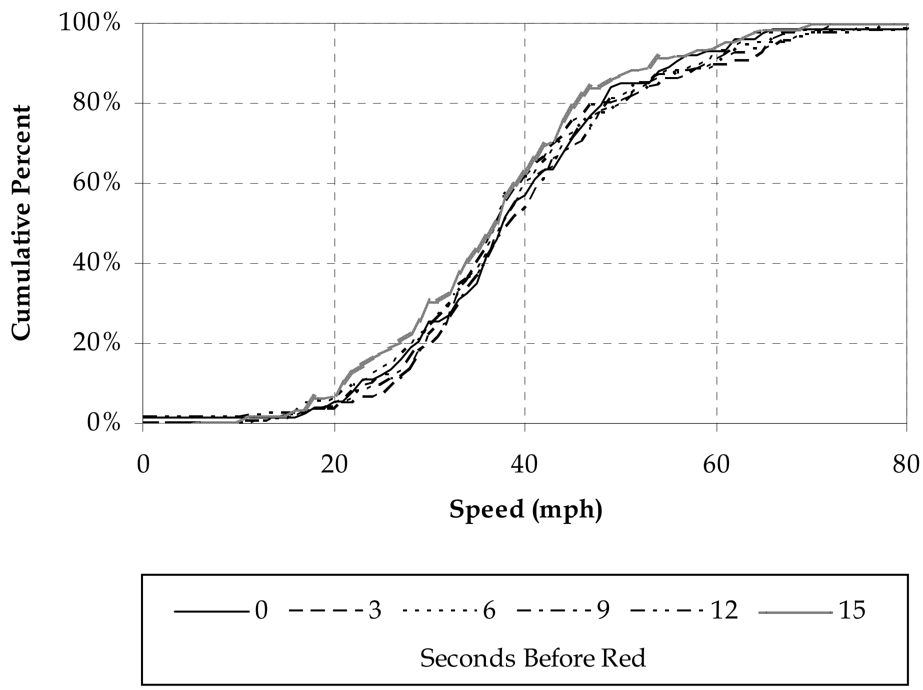

Figure D-48. Cumulative distribution plot for northbound noon peak speeds at the 300 foot detection zone for P6.

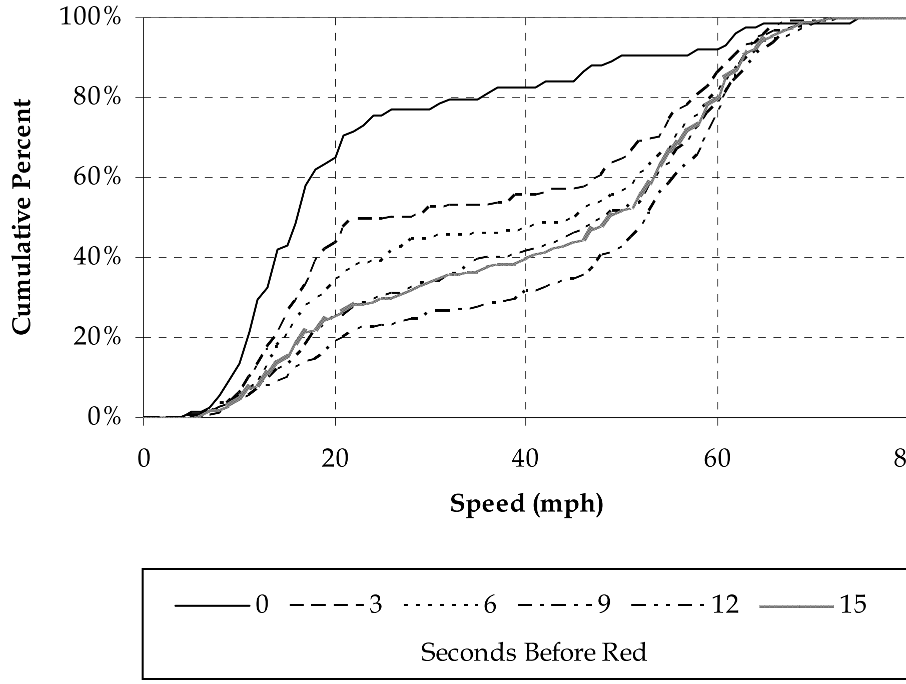

Figure D-49. Cumulative distribution plot for northbound PM peak speeds at the 50 foot detection zone for P6.

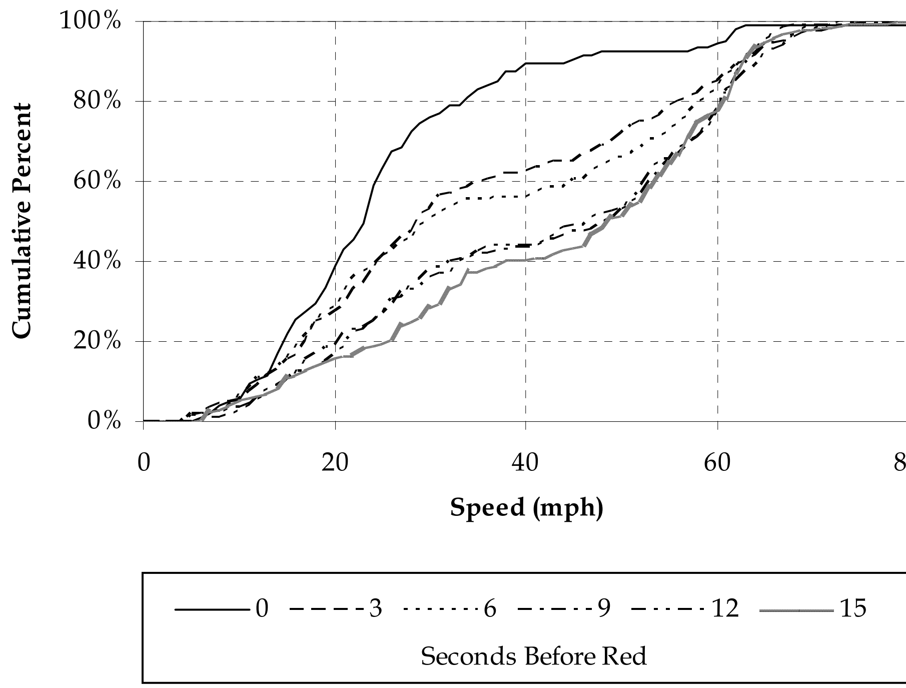

Figure D-50. Cumulative distribution plot for northbound PM peak speeds at the 100 foot detection zone for P6.

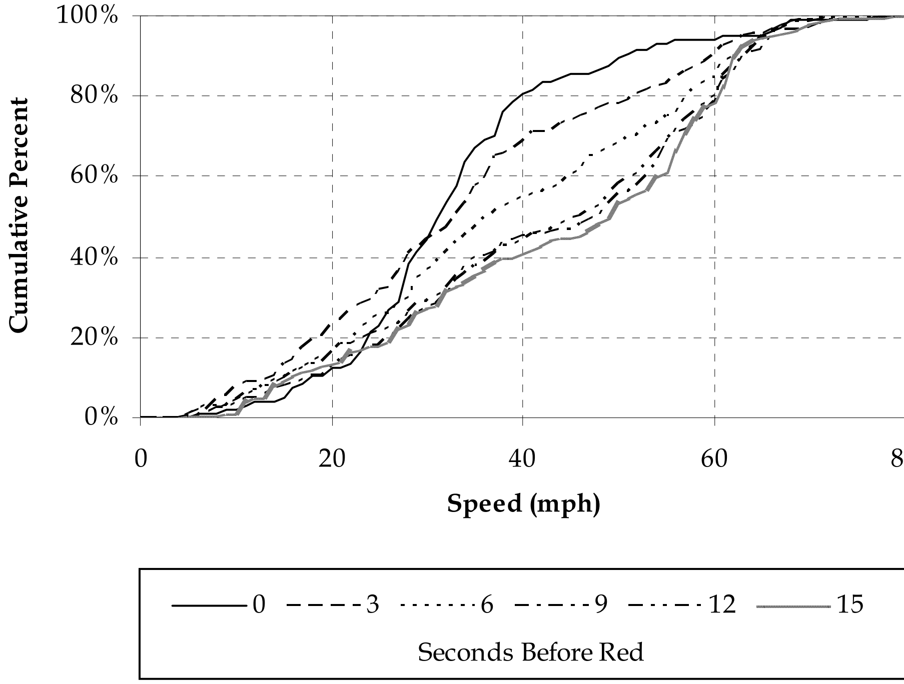

Figure D-51. Cumulative distribution plot for northbound PM peak speeds at the 150 foot detection zone for P6.

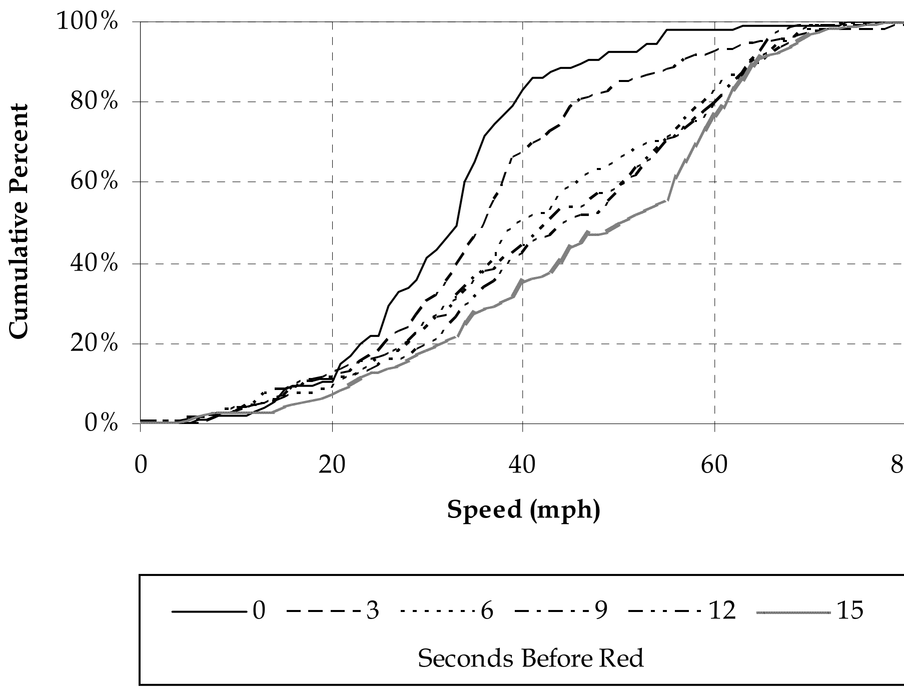

Figure D-52. Cumulative distribution plot for northbound AM peak speeds at the 200 foot detection zone for P6.

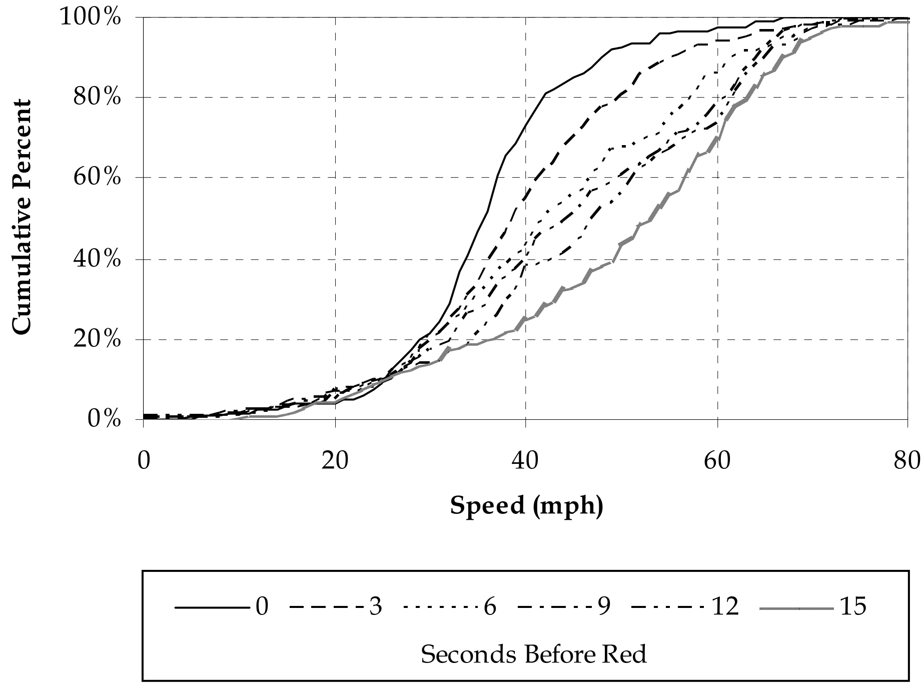

Figure D-53. Cumulative distribution plot for northbound PM peak speeds at the 250 foot detection zone for P6.

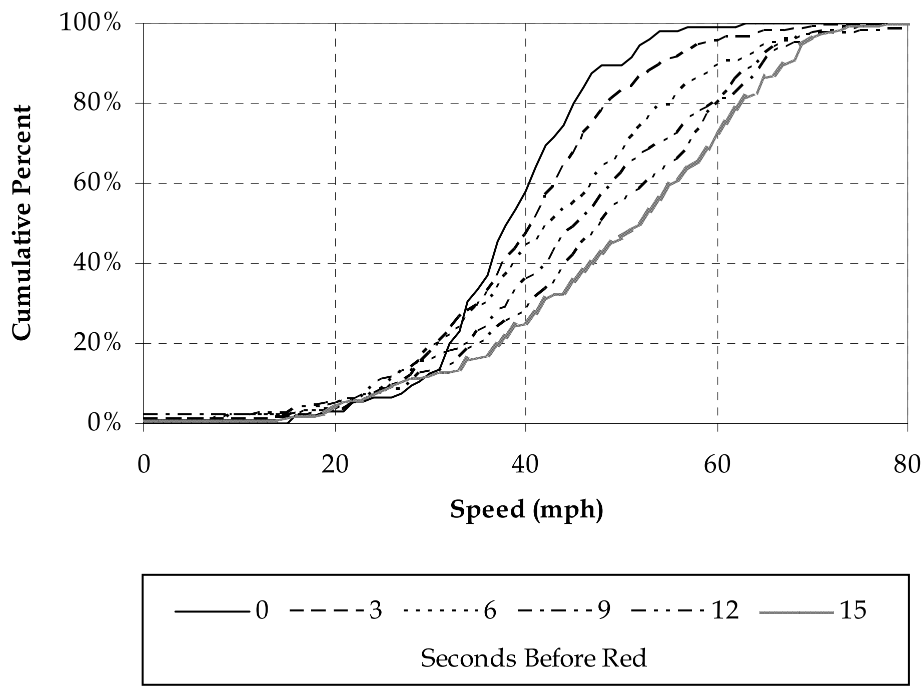

Figure D-54. Cumulative distribution plot for northbound PM peak speeds at the 300 foot detection zone for P6.

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Appendix E. Speed Box Plots

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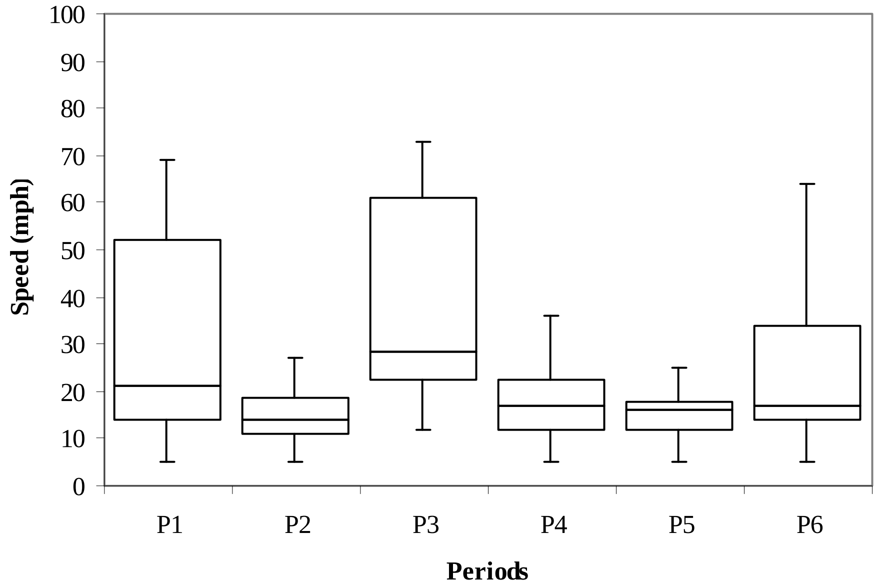

Figure E-1. Box plots of speed data for the northbound 50 foot detection zone during the AM peak for 0 seconds before red.

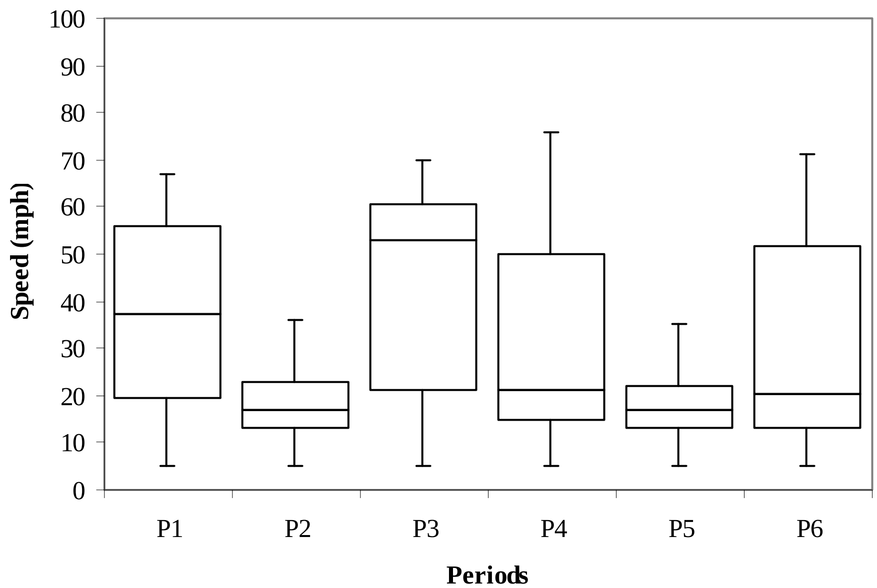

Figure E-2. Box plots of speed data for the northbound 50 foot detection zone during the AM peak for 3 seconds before red.

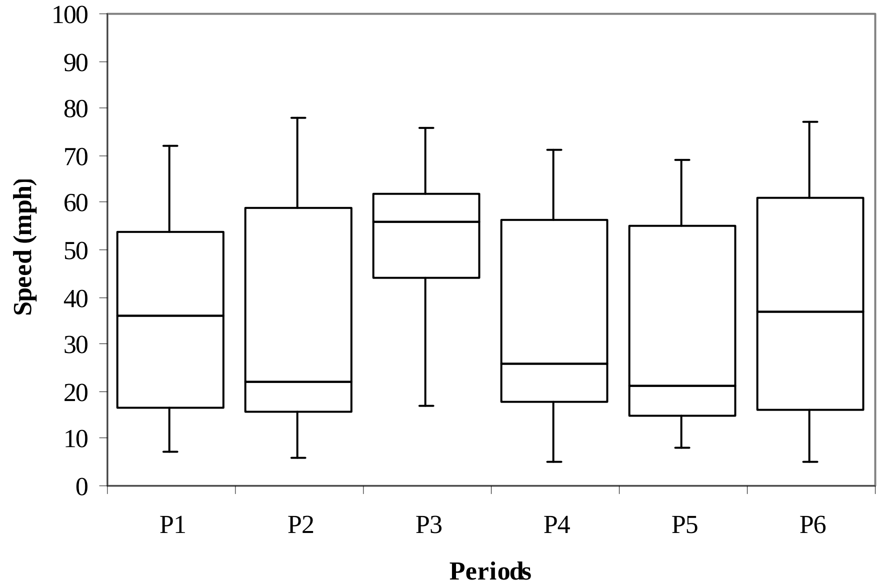

Figure E-3. Box plots of speed data for the northbound 50 foot detection zone during the AM peak for 6 seconds before red.

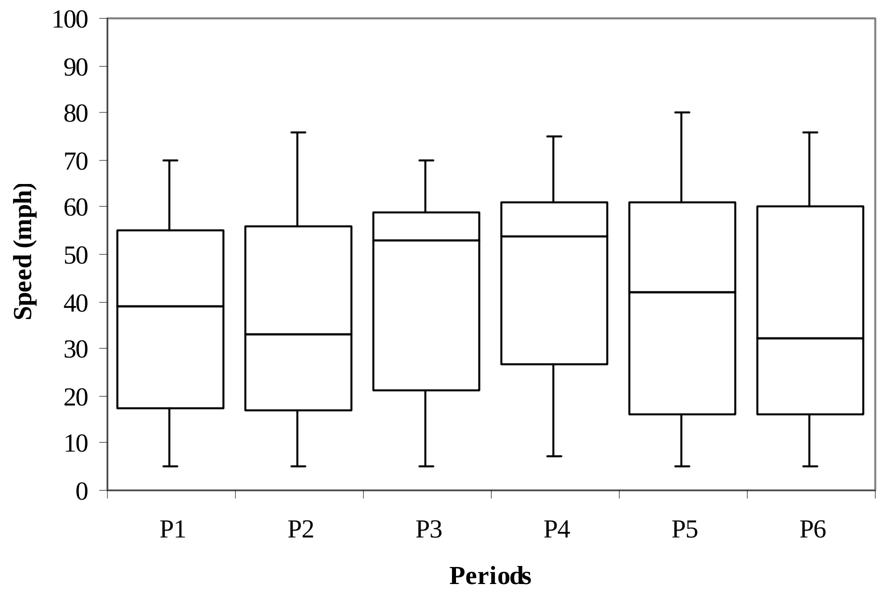

Figure E-4. Box plots of speed data for the northbound 50 foot detection zone during the AM peak for 9 seconds before red.

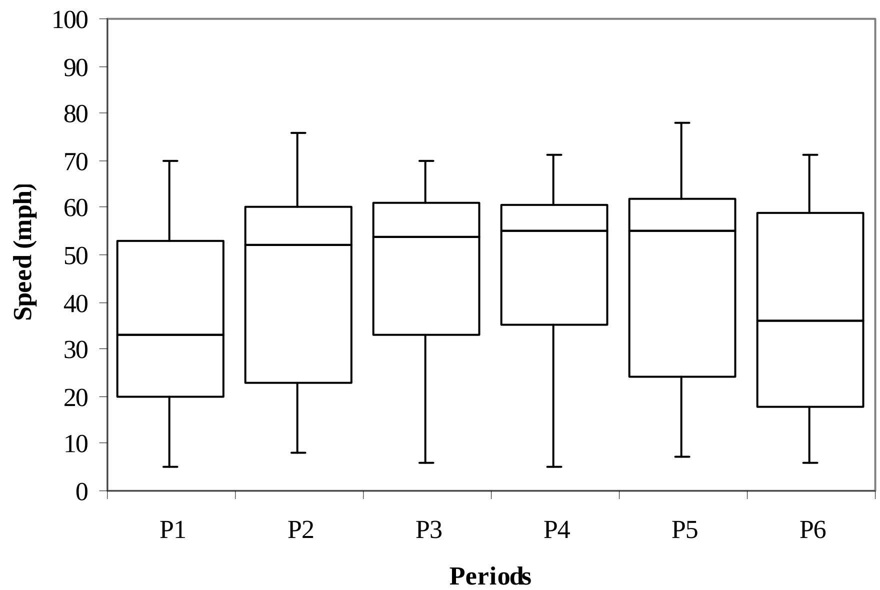

Figure E-5. Box plots of speed data for the northbound 50 foot detection zone during the AM peak for 12 seconds before red.

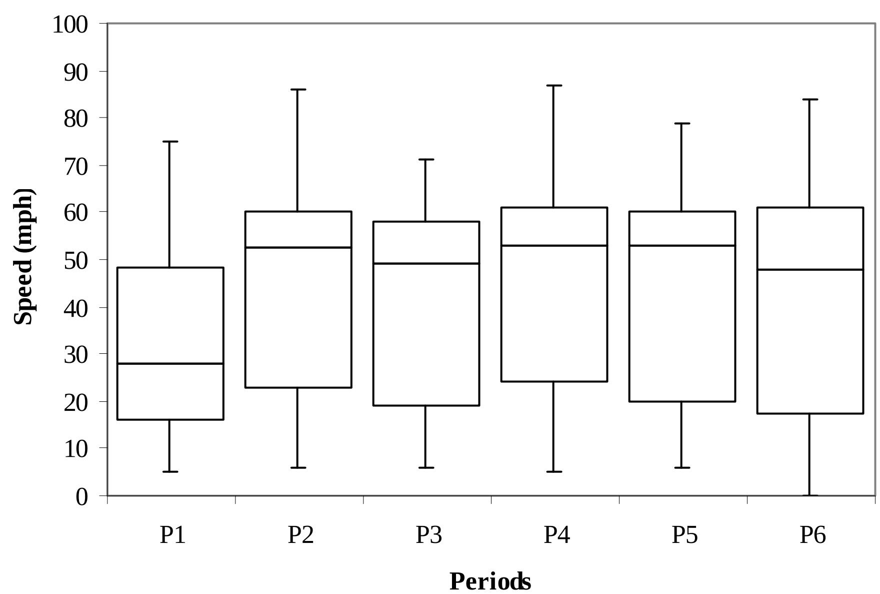

Figure E-6. Box plots of speed data for the northbound 50 foot detection zone during the AM peak for 15 seconds before red.

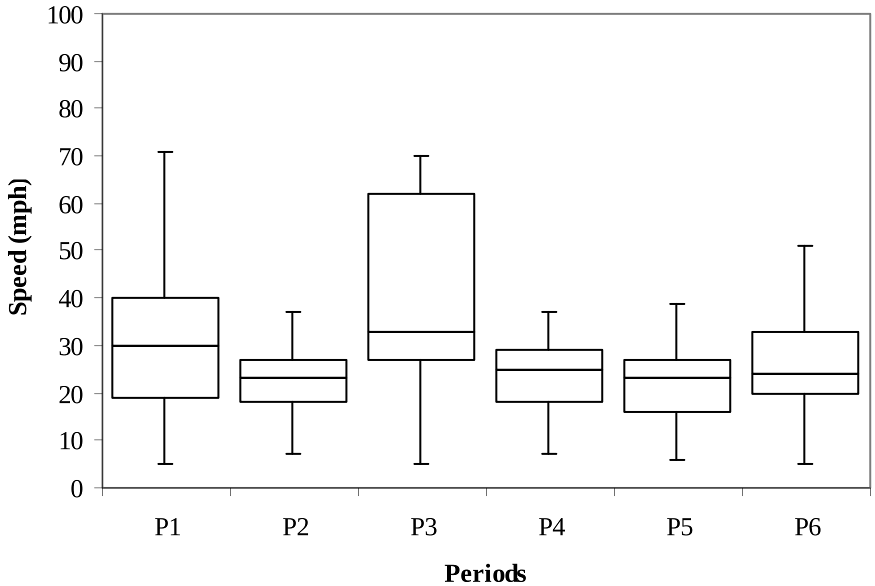

Figure E-7. Box plots of speed data for the northbound 100 foot detection zone during the AM peak for 0 seconds before red.

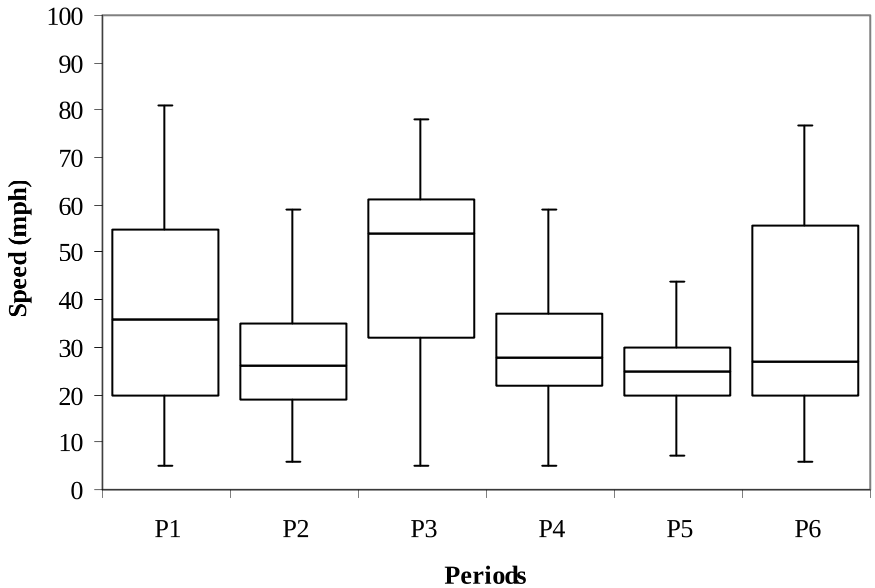

Figure E-8. Box plots of speed data for the northbound 100 foot detection zone during the AM peak for 3 seconds before red.

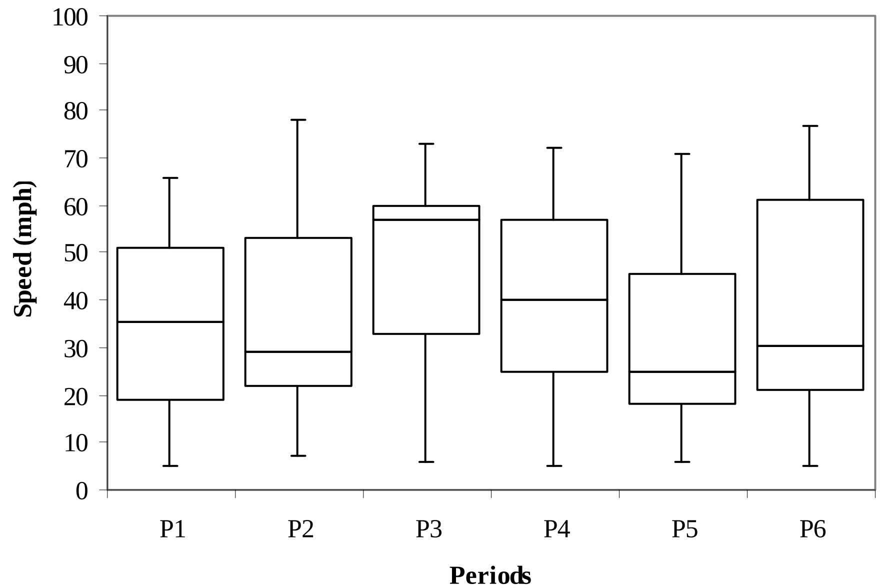

Figure E-9. Box plots of speed data for the northbound 100 foot detection zone during the AM peak for 6 seconds before red.

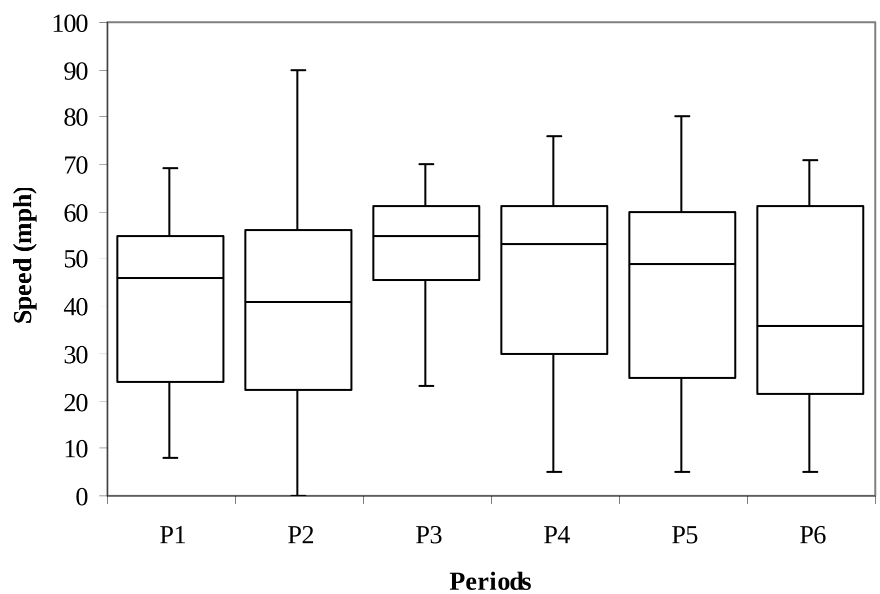

Figure E-10. Box plots of speed data for the northbound 100 foot detection zone during the AM peak for 9 seconds before red.

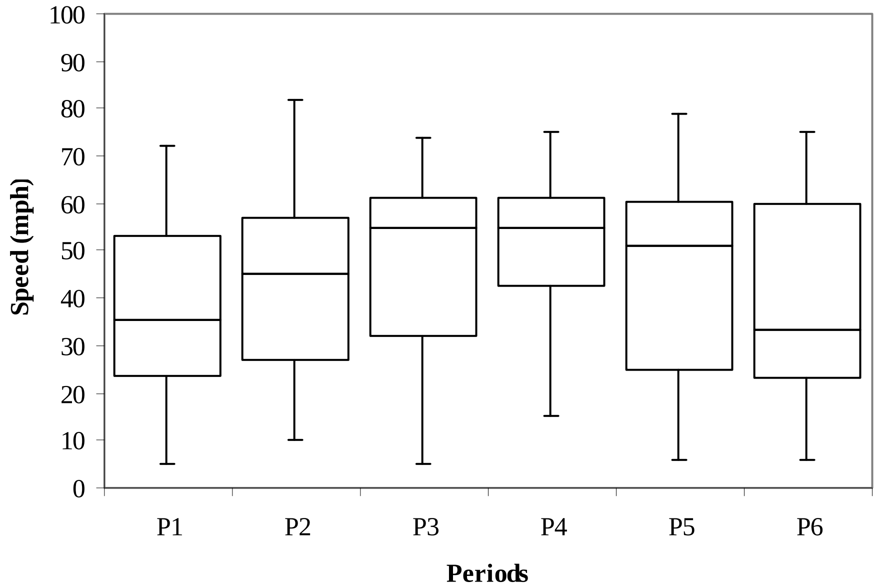

Figure E-11. Box plots of speed data for the northbound 100 foot detection zone during the AM peak for 12 seconds before red.

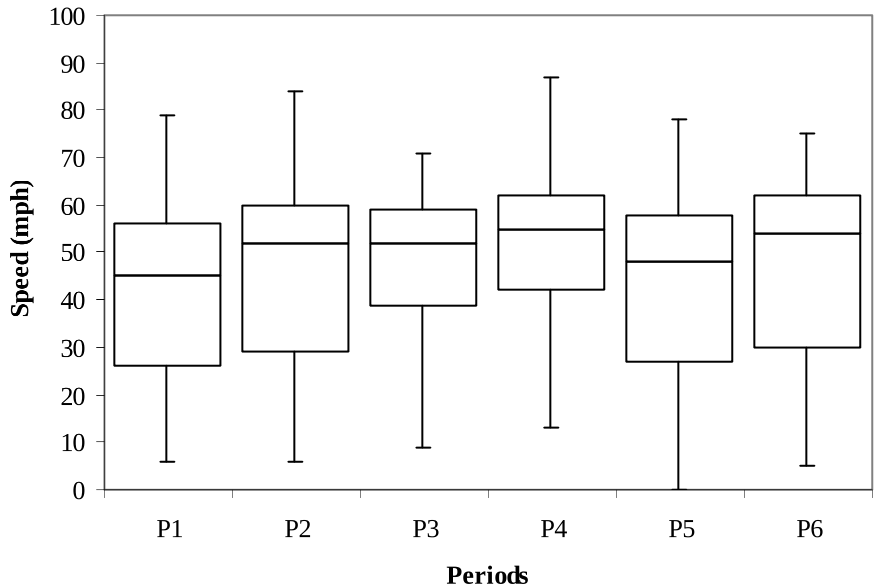

Figure E-12. Box plots of speed data for the northbound 100 foot detection zone during the AM peak for 15 seconds before red.

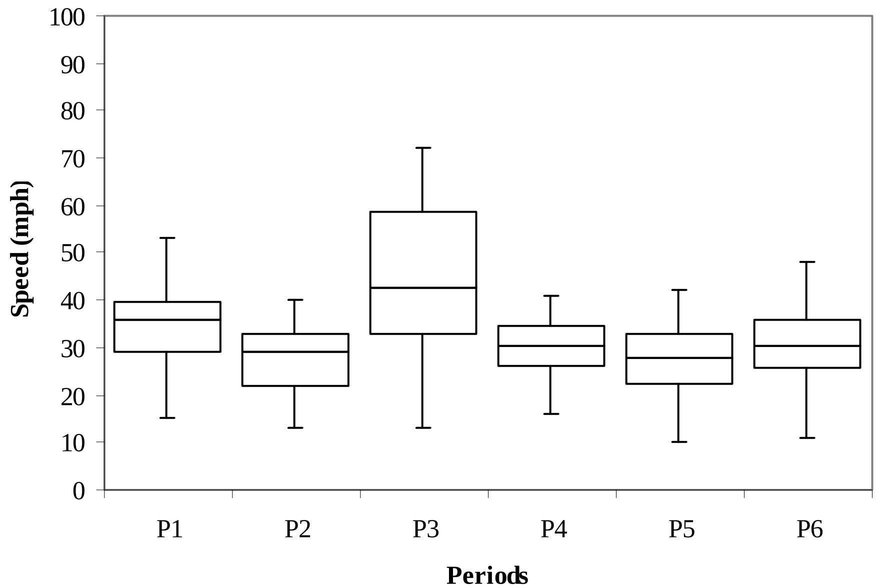

Figure E-13. Box plots of speed data for the northbound 150 foot detection zone during the AM peak for 0 seconds before red.

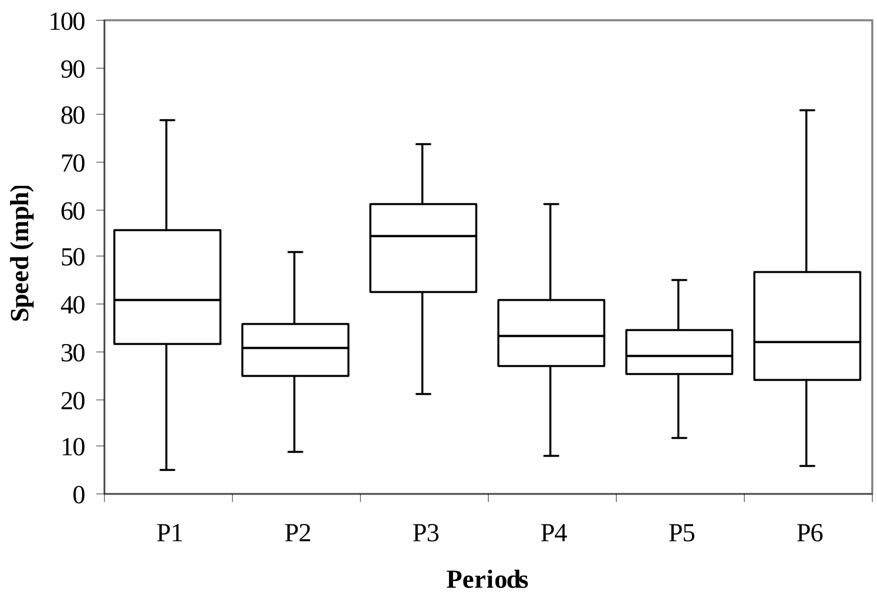

Figure E-14. Box plots of speed data for the northbound 150 foot detection zone during the AM peak for 3 seconds before red.

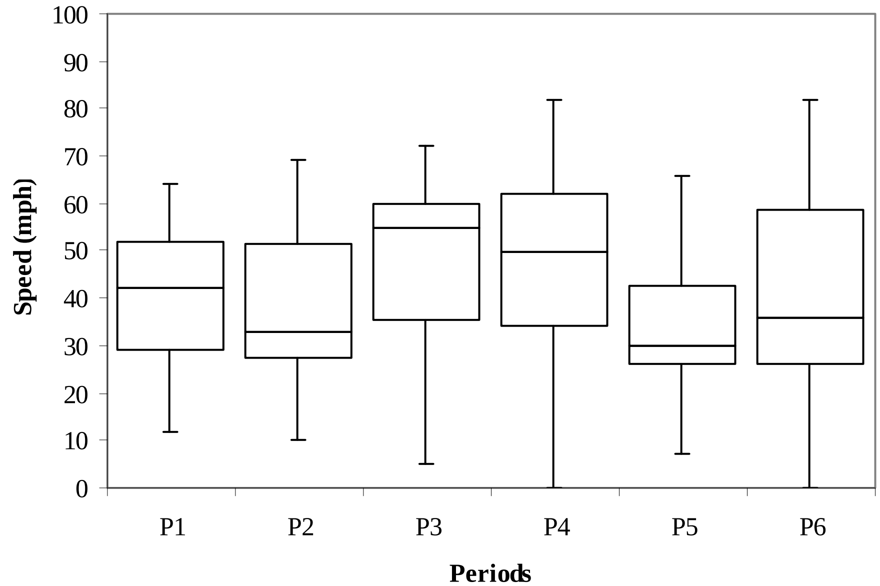

Figure E-15. Box plots of speed data for the northbound 150 foot detection zone during the AM peak for 6 seconds before red.

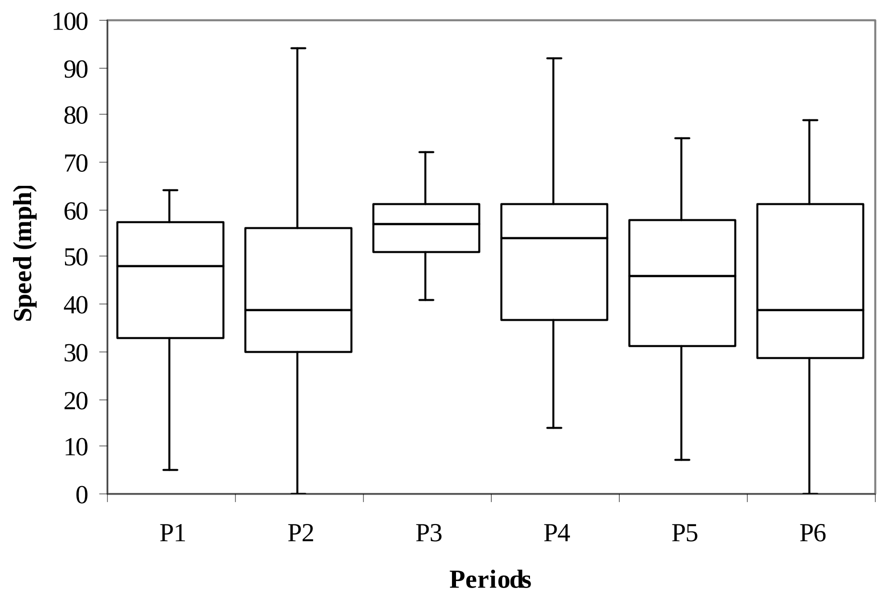

Figure E-16. Box plots of speed data for the northbound 150 foot detection zone during the AM peak for 9 seconds before red.

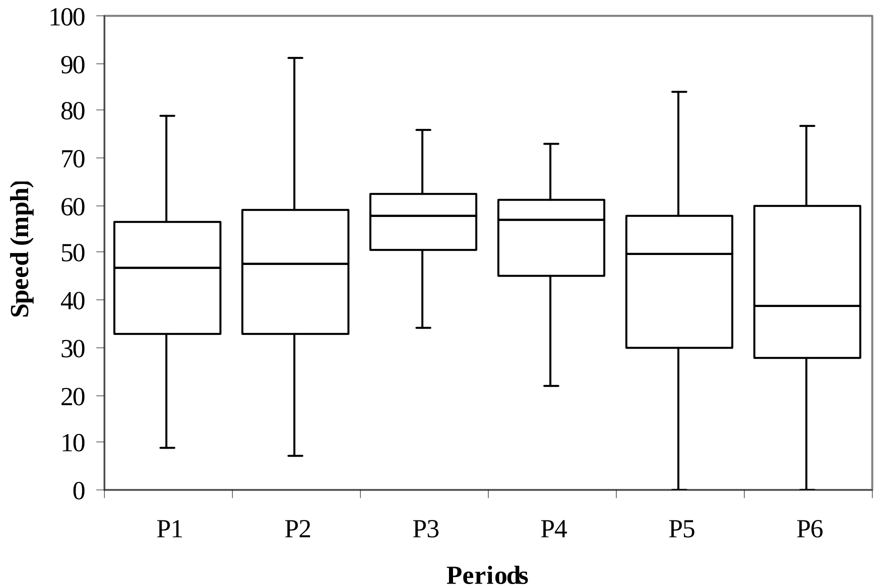

Figure E-17. Box plots of speed data for the northbound 150 foot detection zone during the AM peak for 12 seconds before red.

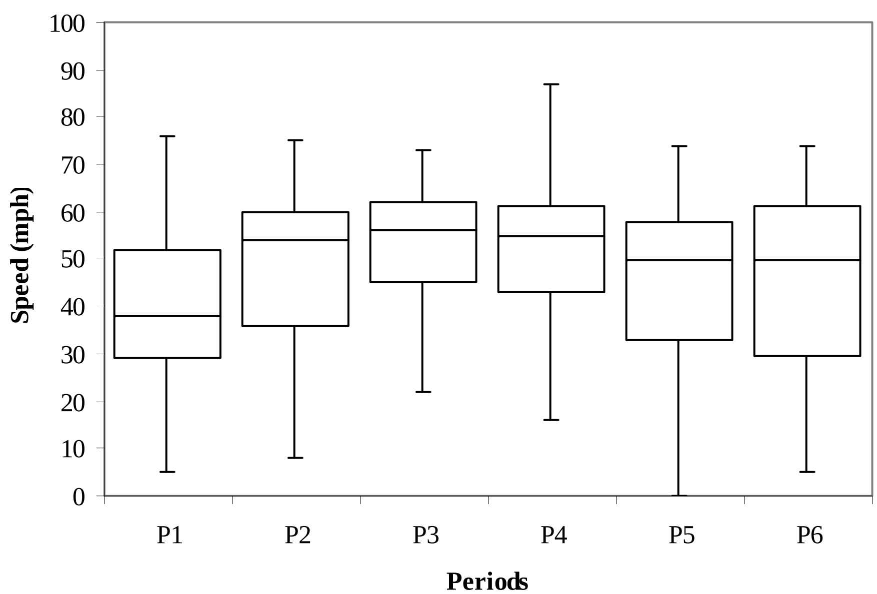

Figure E-18. Box plots of speed data for the northbound 150 foot detection zone during the AM peak for 15 seconds before red.

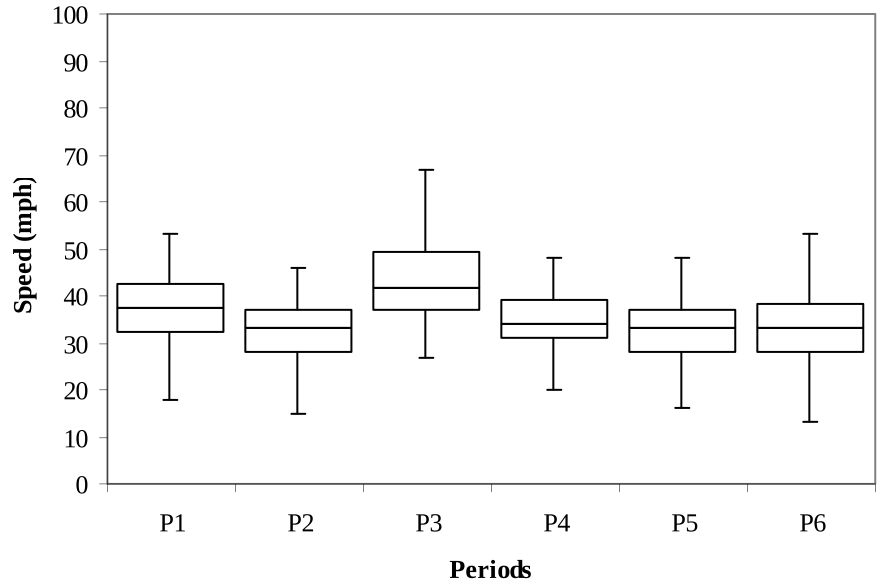

Figure E-19. Box plots of speed data for the northbound 200 foot detection zone during the AM peak for 0 seconds before red.

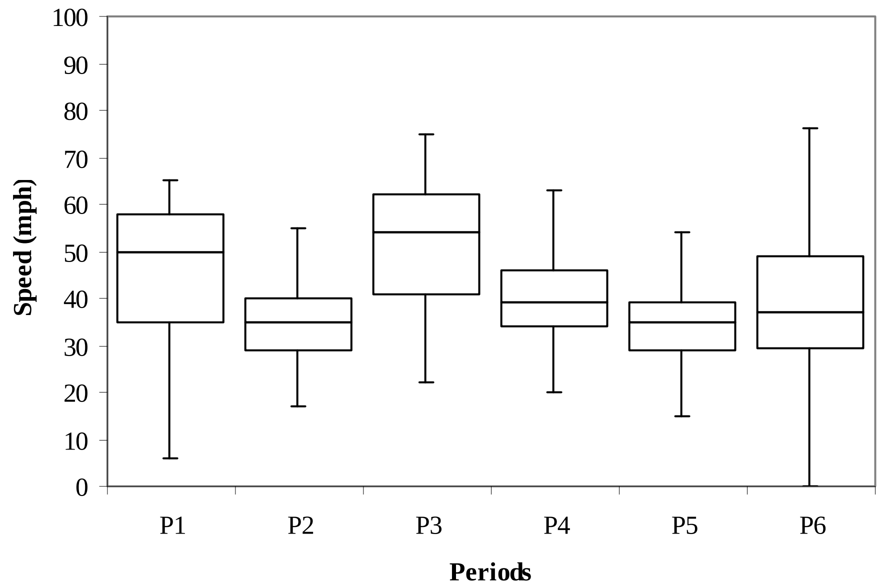

Figure E-20. Box plots of speed data for the northbound 200 foot detection zone during the AM peak for 3 seconds before red.

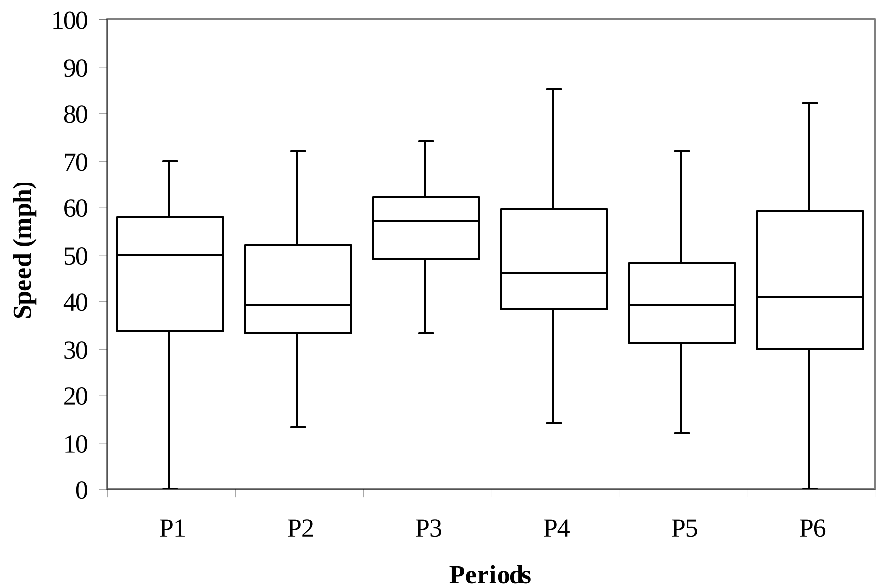

Figure E-21. Box plots of speed data for the northbound 200 foot detection zone during the AM peak for 6 seconds before red.

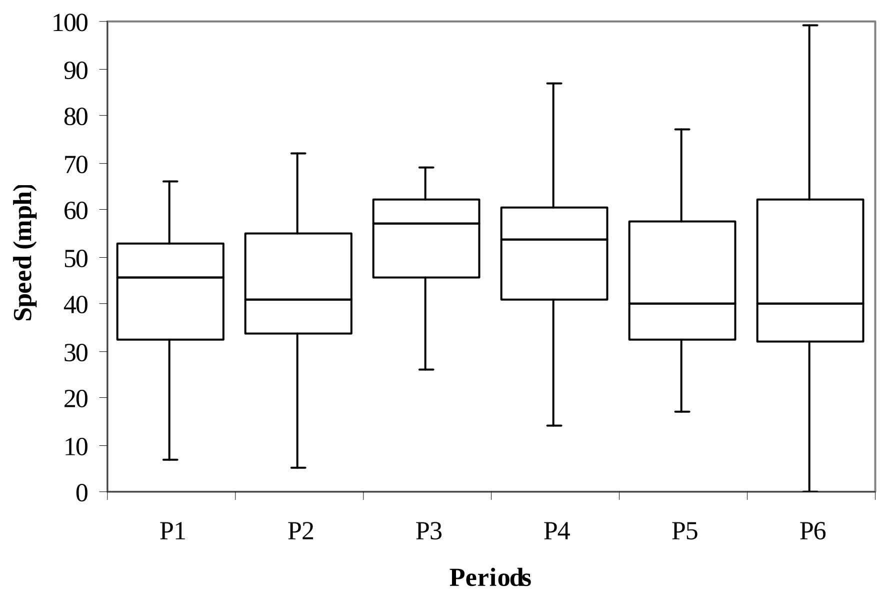

Figure E-22. Box plots of speed data for the northbound 200 foot detection zone during the AM peak for 9 seconds before red.

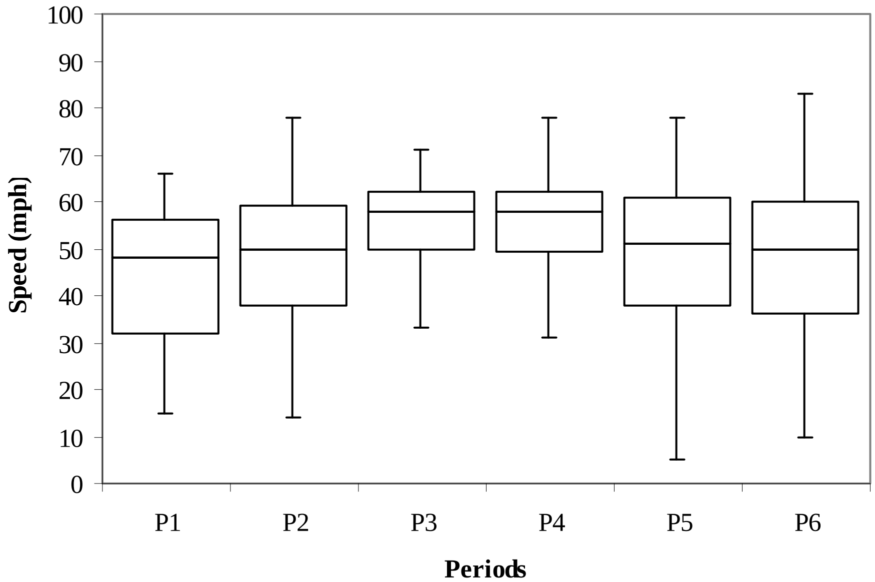

Figure E-23. Box plots of speed data for the northbound 200 foot detection zone during the AM peak for 12 seconds before red.

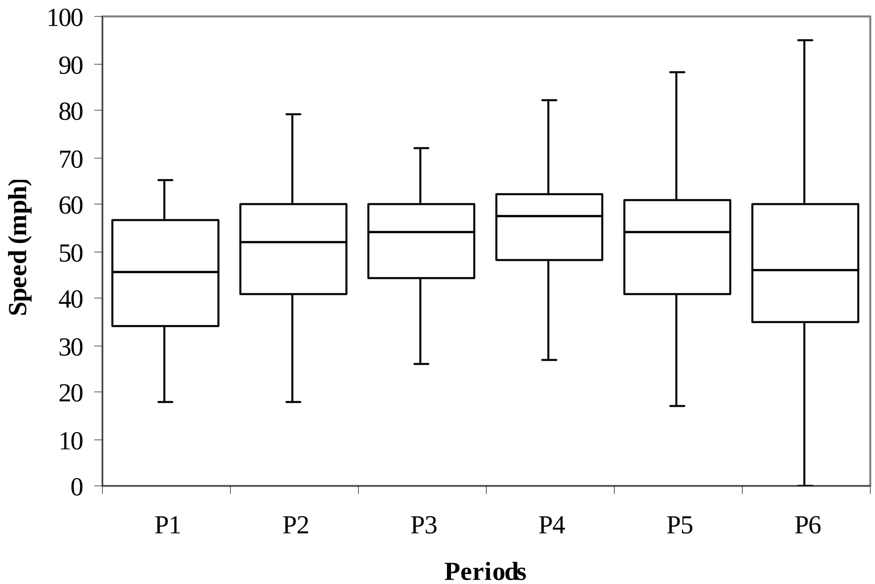

Figure E-24. Box plots of speed data for the northbound 200 foot detection zone during the AM peak for 15 seconds before red.

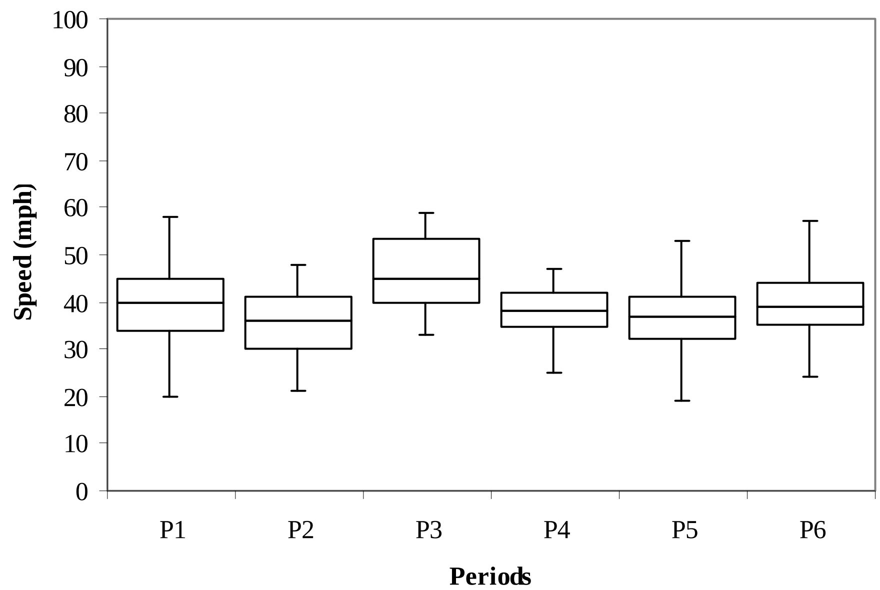

Figure E-25. Box plots of speed data for the northbound 250 foot detection zone during the AM peak for 0 seconds before red.

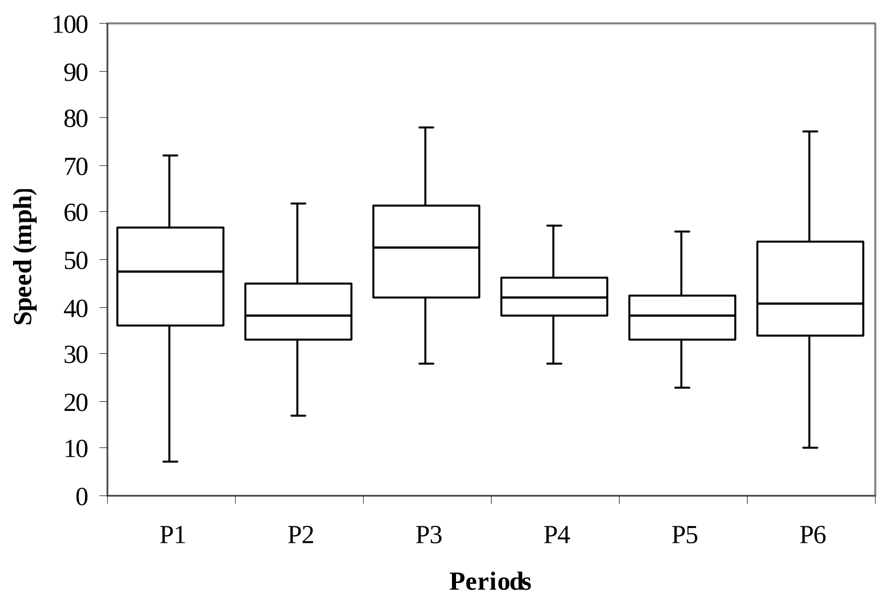

Figure E-26. Box plots of speed data for the northbound 250 foot detection zone during the AM peak for 3 seconds before red.

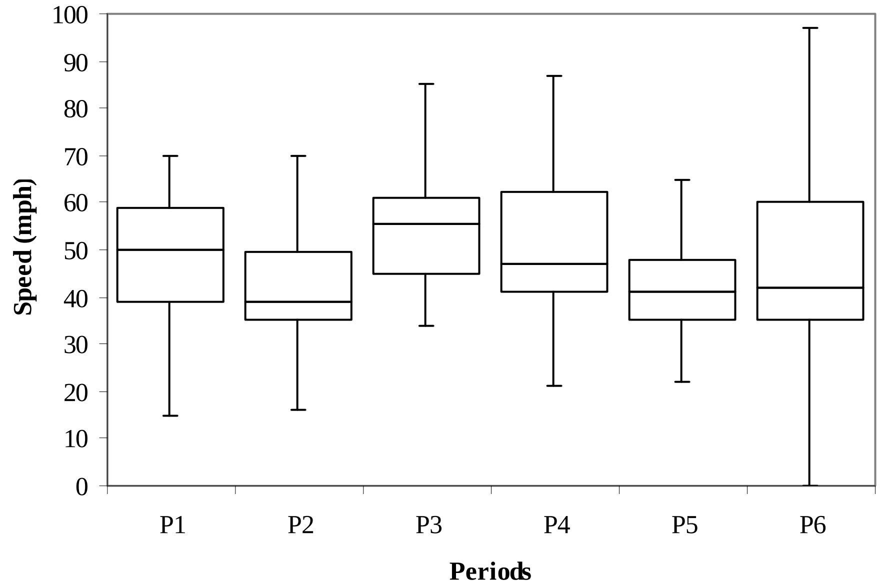

Figure E-27. Box plots of speed data for the northbound 250 foot detection zone during the AM peak for 6 seconds before red.

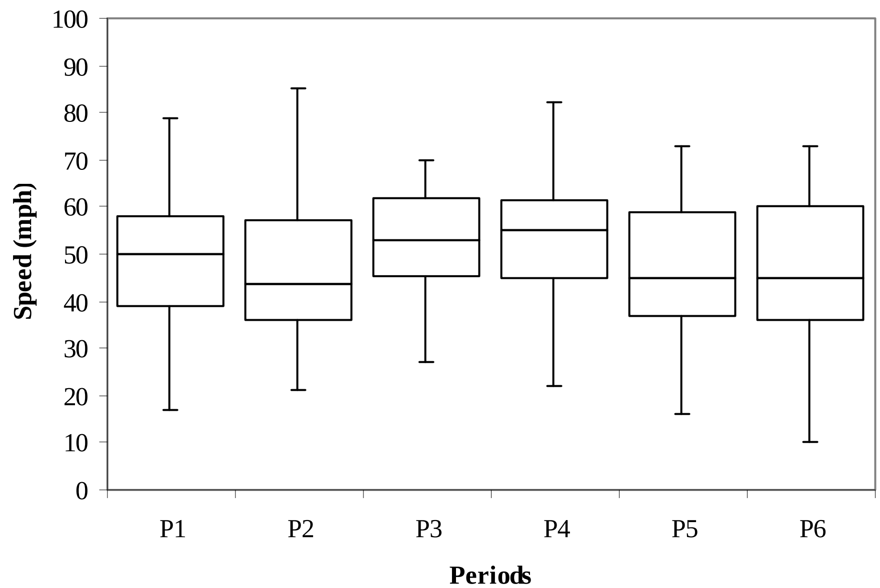

Figure E-28. Box plots of speed data for the northbound 250 foot detection zone during the AM peak for 9 seconds before red.

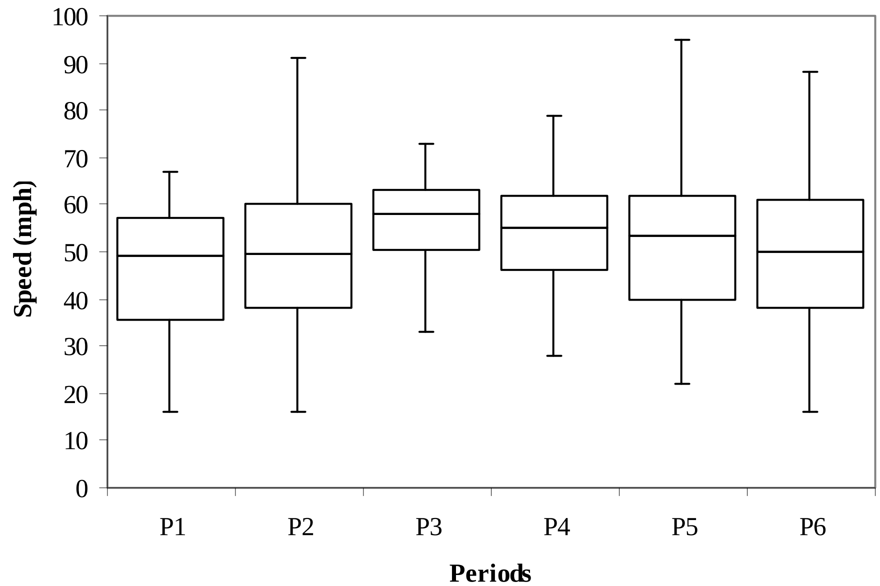

Figure E-29. Box plots of speed data for the northbound 250 foot detection zone during the AM peak for 12 seconds before red.

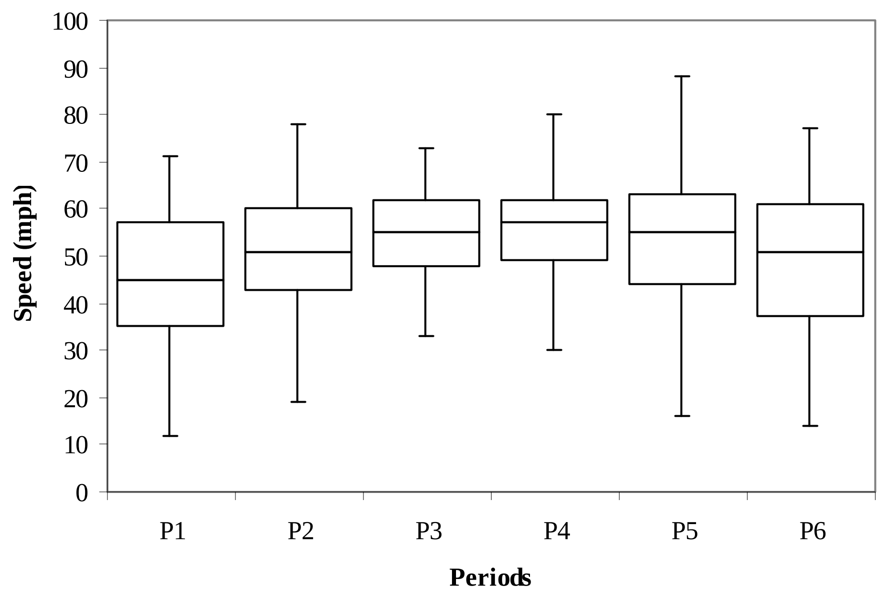

Figure E-30. Box plots of speed data for the northbound 250 foot detection zone during the AM peak for 15 seconds before red.

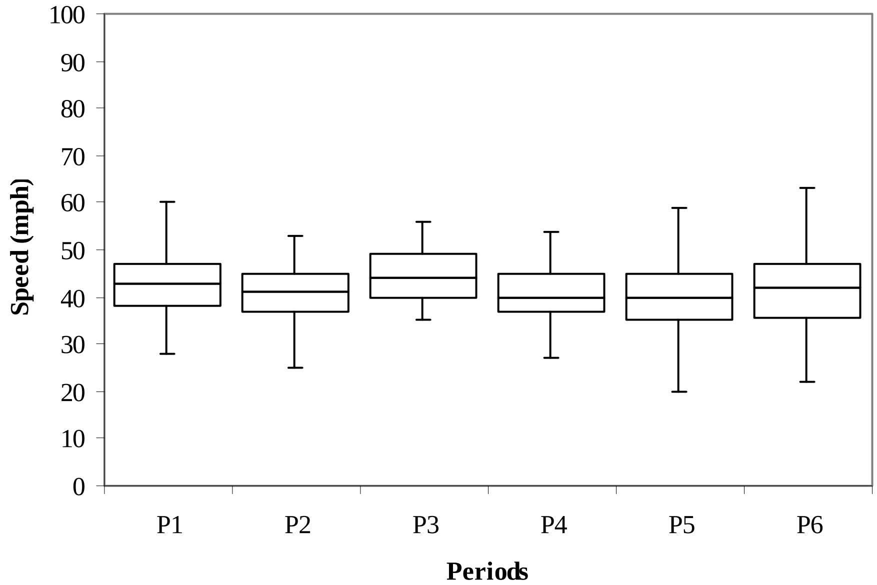

Figure E-31. Box plots of speed data for the northbound 300 foot detection zone during the AM peak for 0 seconds before red.

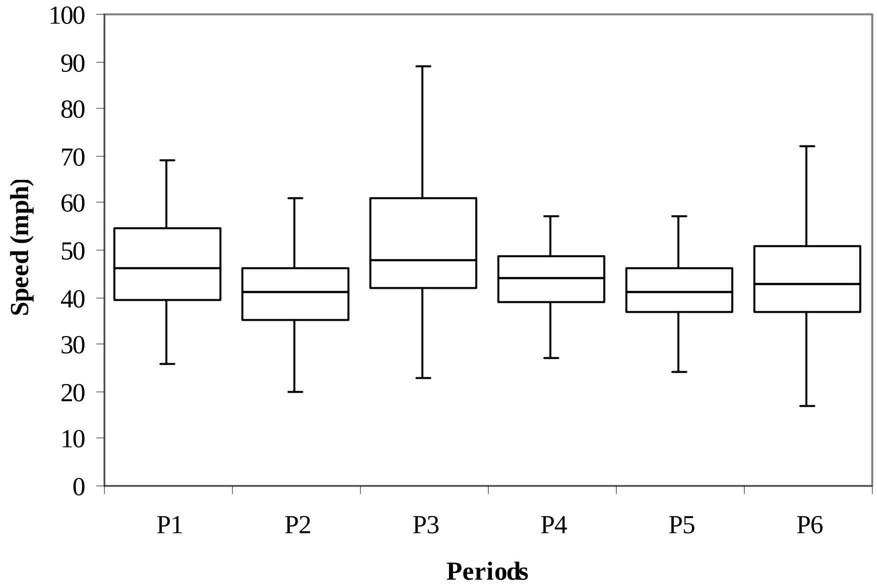

Figure E-32. Box plots of speed data for the northbound 300 foot detection zone during the AM peak for 3 seconds before red.

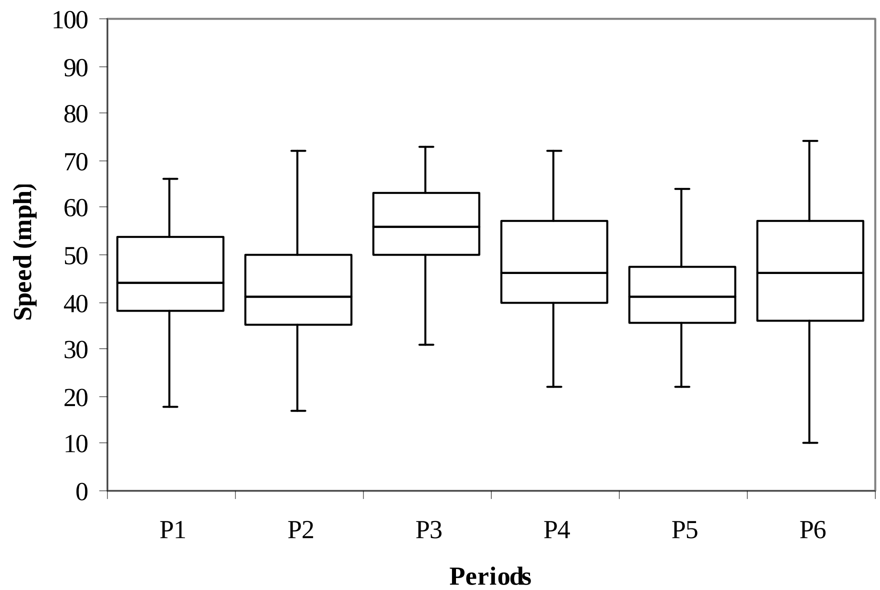

Figure E-33. Box plots of speed data for the northbound 300 foot detection zone during the AM peak for 6 seconds before red.

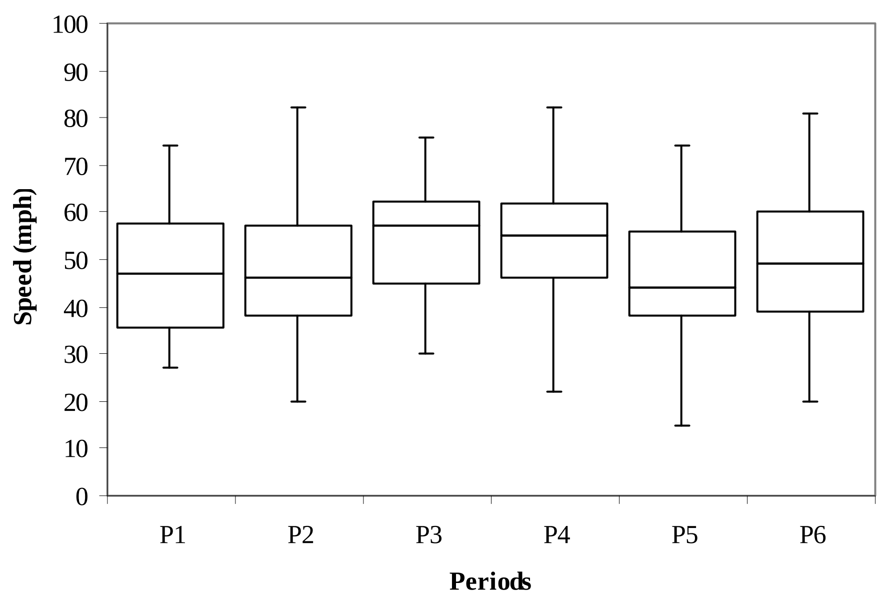

Figure E-34. Box plots of speed data for the northbound 300 foot detection zone during the AM peak for 9 seconds before red.

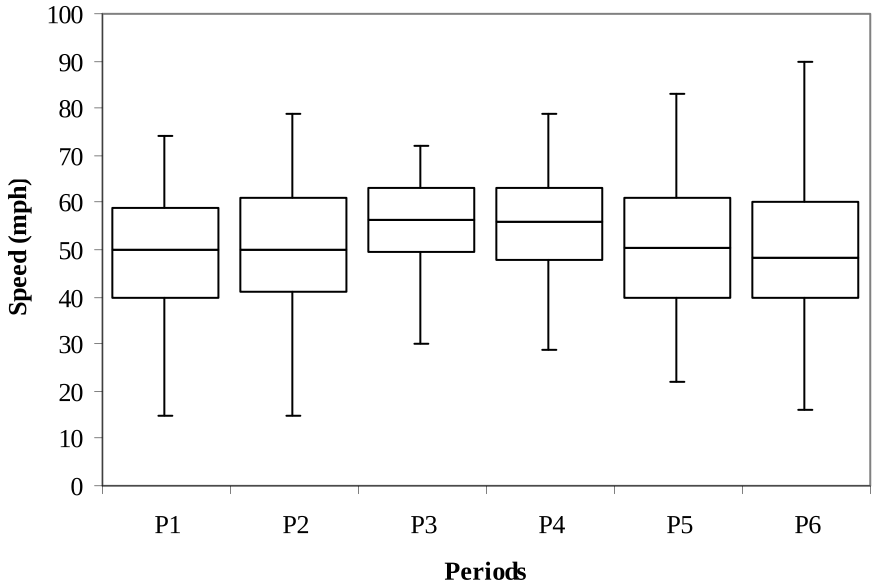

Figure E-35. Box plots of speed data for the northbound 300 foot detection zone during the AM peak for 12 seconds before red.

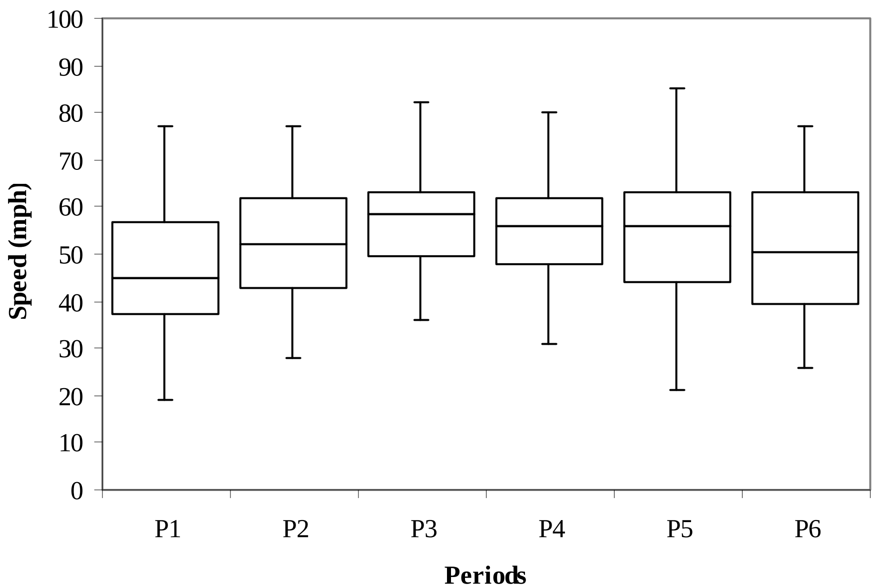

Figure E-36. Box plots of speed data for the northbound 300 foot detection zone during the AM peak for 15 seconds before red.