Research

Potential Safety Effects of Dynamic Signing at Rural Horizontal Curves

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16. Abstract (Limit: 200 words)

This research explores the potential safety effects of dynamic signing at rural horizontal accomplishes this by asking two key questions. First, is there a relationship between a vehicle's speed on the approach to a curve and the ability to successfully navigate the curve? Second, is there a difference between static and dynamic signing in the ability to or reduce the speed of high-speed vehicles?

Researchers assembled an off-the shelf hardware and software package and deployed it at a four=degree curve along CSAH 54 in rural Dakota County. If purchased new, the package would cost about $50,000; however, an agency could deploy the components necessary to perform dynamic curve warning (a changeable message sign and radar unit) for approximately $10,000.

The field t4est collected vehicle speed data for about 2,600 vehicles. In addition, researchers tracked and videotaped 600 vehicles. The data suggests, and statistical tests confirm, that the initial speed of a vehicle before entering a curve does have a statistically significant effect on the probability of successfully navigating through the curve. The data also indicated that the overall effect of the dynamic curve warning system on vehicle speed that the static curve warning sign and the dynamic system significantly improved the ability of the high-speed vehicles to successfully navigate through the curve.

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POTENTIAL SAFETY EFFECTS OF DYNAMIC SIGNING AT RURAL HORIZONTAL CURVES

Final Report

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Table of Contents

List of Figures

List of Tables

ACKNOWLEDGMENT

Executive Summary

The results of previous research and a preliminary analysis of local crash data indicate that single vehicle run-off the road crashes are one of the most significant safety issues in rural areas and that the number / frequency of these types of crashes is higher in the vicinity of isolated horizontal curves. The data also suggests that excessive speed and the increased driver effort needed to successfully navigate curves are likely contributing factors in most crashes.

In order to address these key factors effecting rural safety, the Minnesota Department of Transportation (MnDOT) and the Minnesota Local Road Research Board (LRRB) retained BRW, Inc. to conduct a research project investigating the ability of using advanced technologies to lower vehicle speeds and improve vehicle navigation through horizontal curves.

The primary objective of the research is to determine the potential safety effects of dynamic signing at rural horizontal curves. It is proposed to accomplish this research by answering two key questions. First, is there a relationship between a vehicle's speed on the approach to a curve and the ability to successfully navigate the curve? Second, is there a difference between static and dynamic signing in the ability to reduce the speed of high-speed vehicles?

Consideration was given to using crash data as part of the analytical process. However, it was determined that the number of crashes at any one curve, even over an extended period, would be too small to draw statistically reliable conclusions. Therefore, it was decided to use vehicle speed and navigation as the measures of effectiveness because of the ability to generate a large enough database to produce statistically reliable results during a limited test period.

Following a review of candidate rural curve locations and an inventory of available technologies, a package of off-the-shelf hardware and software was assembled. The basic components of the package included a closed-circuit TV camera, a VCR and a personal computer mounted on a standard ADDCO trailer, and a "Brick" changeable message sign and radar unit. This package was then deployed in a four-degree curve along Dakota County State Aid Highway (CSAH) 54 in Ravenna Township (approximately five miles southeast of Hastings). The total cost of the hardware and software package, if purchased new, is approximately $50,000. However, an

agency could deploy the components necessary to perform dynamic curve warning (a changeable message sign and radar unit) for approximately $10,000.

The field test was conducted over a four-day period in August 1999, during which time speed data was collected for over 2,600 vehicles and almost 600 vehicles were tracked through the curve and captured on videotape. This data suggests and statistical tests confirm that the initial speed of a vehicle prior to entering a curve does have a statistically significant effect on the probability of successfully navigating through the curve. The data also indicated that the overall effect of the dynamic curve warning system on vehicle speeds is relatively small. However, the dynamic system had a much greater effect on high-speed vehicles than the static curve warning sign and the dynamic system significantly improved the ability of the high-speed vehicles to successfully navigate through the curve.

1.0 Introduction

The results of previous research and a preliminary analysis of local crash data indicate that single vehicle run-off-the road crashes are the most common type of crash on rural roadways. As a result, this type of single vehicle crash is one of the most significant safety issues in rural areas. In addition, the data also suggests that the number / frequency of these crashes is higher in the vicinity of isolated horizontal curves than on tangent sections of comparable roadways. It appears that this is probably a result of the increased level of effort needed to successfully navigate the curve and the fact that excessive speed is cited on many of the crash reports suggests that speed may be one of the primary contributing factors.

Safety design practices suggest that the first step in addressing roadway navigation and the associated run-off-the road issues is to keep the vehicles on the road. Traditional methods in the traffic engineers toolbox for accomplishing this include: providing pavement markings, wide shoulders, and static curve warning signs. There is, however, little or no information that documents the effectiveness of these devices.

Some recent research has suggested that the application of advanced technologies has had a more positive effect on driver behavior than static signs and markings. As a result, the Minnesota Department of Transportation (MnDOT) and the Minnesota Local Road Research Board (LRRB) retained BRW, Inc. to conduct a research project consisting of developing a dynamic curve warning system and then deploying the system along a typical two-lane roadway in a rural environment.

In order to accomplish the research, BRW contracted with ADDCO to assist with the development and deployment of the actual hardware and software package and with Professor Gary Davis (at the University of Minnesota) to assist with the evaluation of the research results.

The primary objective of the research is to determine the potential safety effects of dynamic signing at rural horizontal curves. It is proposed to accomplish this research by answering two questions. First, is there a relationship between a vehicle's speed on the approach to a curve and

the ability to successfully navigate the curve? Second, is there a difference between static and dynamic signing in the ability to reduce the speed of high-speed vehicles?

Consideration was given to using crash data as part of the analytical process. However, a preliminary investigation determined that the number of crashes at any one curve, even over an extended period, would be too small to draw statistically reliable conclusions. Therefore, it was decided to use vehicle speed and navigation as the measures of effectiveness because of the ability to more easily generate a large enough database to produce statistically reliable results during a limited test period.

The work tasks included in the project consist of the following items:

- Conducting a literature search to document the results of previous studies.

- Conducting a survey of practice of local agencies to: identify their concerns about safety issues at horizontal curves on two-lane rural roadways, potential candidate locations for conducting the field testing, and current best design practices.

- Designing the hardware and software package to conduct the research using the standard ADDCO Smart Work Zone Portable Tower Platform. The key components of the package included a Personal Computer, Closed Circuit TV, VCR, Doppler Speed Radar and a "Brick" Dynamic Message Sign.

- Evaluating candidate horizontal curve locations along two-lane rural roadways and then selecting a site for deployment.

- Collecting the field data, which consisted of:

    1. Speed information for a random distribution of northbound vehicles along County State Aid Highway (CSAH) 54 in Ravenna Township (Dakota County)

2. Documenting the change in speed as the vehicles approached the curve as a function of the type of warning message (static versus dynamic)

3. Documenting whether or not the vehicles successfully navigated the curve (stayed within the northbound lane).

- Analyzing the data to determine the overall effectiveness of the various signs

- Determining the statistical reliability of the results

It should also be noted that the research effort was coordinated with a Technical Advisory Panel consisting of the following traffic engineering professionals:

- Richard Beck, MnDOT Traffic Engineering Research Engineer
- Michael Weiss, MnDOT Traffic Signing Engineer
- Peter Sorenson, Dakota County Traffic Engineer

2.0 Literature Search

A literature search was conducted using the Transportation Research Information System (TRIS), Institute of Transportation Engineers (ITE), Federal Highway Administration (FHWA), and Intelligent Transportation Systems America (ITS America) sources. The purpose was to document previous research findings relating to potential safety effects of dynamic signing at rural horizontal curves and to substantiate the relevant conclusions of those studies.

2.1 Research Articles

Research revealed five reports and/or articles that pertained to dynamic signing at rural horizontal curves. The articles are identified below and the key findings are summarized in the following section.

1. Chowdhury, Mashur A., Davey L. Warren, Howard Bissell, and Sunil Taori, *Are the Criteria for Setting Speed Advisory Speeds on Curves Still Relevant?*, ITE Journal, February, 1998.

2. McGee, Hugh W. and Rodney R. Strickland, *An Automatic Warning System to Prevent Truck Rollover on Curved Ramps*, Public Roads (On-Line), Spring, 1994.

3. Rama-P and Luomo-J, *Driver Acceptance of Weather Controlled Road Signs and Displays*, Transportation Research Board (TRB), 1997, pp. 72-75.

4. Rogerson-P, Trial of a Speed Information Sign, Victoria Roads, Australia, 1991, pp. 91.

5. Taniguch-E, Hayama-A, Morikawa-K, and Sugawara-K, *Deployment of Automatic Incident Detection Systems in Expressways*, ITS America, Washington D.C., 1996, pp.203.

2.2 Summary of Articles

1. "Are the Criteria for Setting Speed Advisory Speeds on Curves Still Relevant?"

An advisory speed plate often supplements warning signs when a comfortable speed is less than the speed limit. The advisory speed is intended to inform unfamiliar drivers of a possible hazardous situation and recommend a comfortable and safe speed to navigate the curve.

This study selected 28 test sites on two-lane highways in four states. The study found that the criteria for determining advisory speeds are not valid for modern vehicles. At most curves, posted advisory speeds were not only well below the prevailing traffic speed, but also below the recommended values as suggested by the two criteria – namely the ball-bank indicator and the Traffic Control Devices Handbook (TCDH) nomograph. The two criteria were found to be outdated and based on field measurements made over 50 years ago. This indicated serious deficiency in the advisory speeds posted on curves. The evidence was sufficient to expect very little compliance from drivers. The study verified that expectation. It found that the posted advisory speeds do not have the desired affect on motorists. Overall, drivers were advised to slow down an average of 15 miles per hour; however, the actual speed drop averaged only six miles per hour. The advisory speed and test sites were thus exceeded on average by nine miles per hour.

2. "An Automatic Warning System to Prevent Truck Rollover on Curved Ramps"

Truck crashes on urban freeways occur more frequently at interchanges -- particularly on curved exit ramps -- than at any other location. One way to prevent, or at least reduce, truck rollover crashes on curved exit ramps would be to install an automatic warning system on these ramps to help truck drivers take preventative action. The system warns drivers when the truck, based on its load conditions and speed, would roll over if its speed were not reduced.

6

As a truck travels through a curved ramp, its speed and the ramp's curvature and superelevation cause a level of lateral acceleration on the truck. The maximum level of lateral acceleration beyond which a truck will rollover is called the rollover threshold (RT). To help prevent the possibility of a rollover, an *inroad detection-warning system* that depends on a "intelligent highway" was developed.

An inroad detection-warning system would include detector hardware, a controller for processing the electronic data, and a warning system. For an inroad detection-warning system to operate effectively, it should capture certain vehicle parameters as a minimum – vehicle type, such as truck or non-truck; speed and deceleration profile; and weight. An electronic controller is needed to accept the electrical charges according to a prescribed logic for identifying a truck that is exceeding the rollover threshold, and send a signal to activate the warning device. The warning device would consist of a static warning sign with a supplemental fiber optic sign with the message "TRUCKS REDUCE SPEED."

Based on plans, specifications, and cost estimates, it was found that a single-lane ramp would cost $100,000 and for a dual ramp $160,000. These costs include engineering design, materials, installation, and annual maintenance and operations costs. The benefits from the warning system are a reduction in truck rollover crashes and associated costs. These costs are the dollar values assigned to the fatalities, injuries, vehicle property damage and cargo loss, possible damage to the highway facility appurtenances, motorist delay, and traffic control and clean up caused by the crash. A cost of $15,470 per truck crash was developed.

From the data that was gathered, it appears that an effective automatic truck warning system could be cost effective if applied at ramps with a history of truck rollover crashes of at least one every five years.

3. "Driver Acceptance of Weather-Controlled Road Signs and Displays"

This study was designed to investigate driver acceptance of weather-controlled road signs and displays on Finland's southern coast where road condition changes are particularly frequent and rapid. There were 36 variable speed limit signs and five variable message displays to warn about hazardous conditions on the 14-kilometer long experimental road section. Local weather and road surface conditions were monitored automatically from road weather stations; the information gathered was used for determining appropriate speed limits, as well as controlling variable "SLIPPERY ROAD" signs and temperature displays. Three, four, eleven, and thirteen months after the introduction of this new road section, 590 drivers were interviewed. The results showed that a high percentage of the drivers were able to recall the variable signs. Furthermore, 81 percent of the drivers said that the posted speed limit was appropriate, and 95 percent of the drivers stated that the variable speed limits were useful. However, only a relatively small proportion of drivers indicated that the "SLIPPERY ROAD" sign or temperature display influenced their behavior. The main implication of this study is that the concept of weather-controlled road signs and displays is a promising one. However, objective data will need to be collected in order to estimate the effects of the weather-controlled road signs and displays and to evaluate the profitability of the system.

4. "Trial of a Speed Information Sign"

The Speed Management Strategy Implementation Committee of Victoria, along with representatives from VIC ROADS, the Victoria Police Department, and the Transport Accident Commission proposed a speed study trial in 1998. The study was performed to determine the effect of two electronic signs displaying, "DRIVERS NOT SPEEDING LAST WEEK -- %," on vehicle speeds. The signs were placed facing both directions of traffic on Beach Road, near the junction with New Street, in Sandringham from March 19 to May 21, 1990. Vehicle speed was measured using

8

Golden River Traffic Classifiers. The trial was based on the premise that reduced speeds would result in fewer injury and total crashes.

It was found that when the sign was operational, fewer vehicles exceeded the speed limit of 60 kilometers per hour. The greatest effect was the reduction in the percentage of vehicles exceeding 90 kilometers per hour. However, as in previous studies, vehicle speeds increased again upon removal of the sign. It was recommended that this sign not be used again unless the procedure is simplified in a cost-effective way and the associated factors are investigated.

5. "Deployment of Automatic Incident Detection Systems in Expressways"

This paper describes the evaluation of automatic incident detection systems by image processing and the future deployment of systems for traffic surveillance and traffic control systems on the expressways. Automatic incident detection systems have been installed and operated at several sites, such as sharp curves and tunnels of expressways, in Japan. The objectives of the systems are: 1) automatic and quick detection of incidents such as traffic accidents and stopped vehicles; 2) transmission of information to traffic control centers and drivers in following vehicles. Based on the experience of operation on expressways, the systems have good accuracy for automatically detecting incidents on roadways; and warning to the drivers in following vehicles is effective in reducing vehicle speed and avoiding secondary rear end collisions. Currently, the systems are only installed in sharp curves and tunnels in Japan, and information is provided by variable message signs; but in the future the system may cover whole areas of urban expressways and information could be transmitted to drivers by a road-vehicle communication system like VICS. Therefore, the authors discuss future planning of development of the systems in urban expressways. They focus on the possibility of substitutes for conventional loop coil or ultra sonic traffic detectors and the effects of quick detection of incidents on road traffic (e.g. prompt action in rescuing injured persons and quick removal of a stopped

9

vehicle to minimize the congestion due to the incident). The also discuss the cost/benefit relationship on the deployment of the systems in urban expressways.

2.3 Conclusions of the Published Research

- The majority of the speed advisory plates that are in place today are not valid for modern vehicles. The posted advisory speeds were well below the prevailing traffic speed, and also below the values suggested by the ball-bank indicator and the TCDH nomograph. In addition, the speed advisory plates did not achieve the desired results. The observed speed reductions at the test sites averaged only 40 percent of what was recommended by the advisory plate.

- Dynamic speed signs appear to have a greater effect on driver performance and awareness than static signs.

3.0 Survey of Agencies

The purpose of this chapter is to document and summarize the results that were found from the surveys that were distributed by MnDOT's Office of Traffic Engineering to local road authorities in order to determine the potential safety effects of dynamic signing at rural horizontal curves. The purpose of the survey was to solicit information regarding:

- Identification of safety issues at rural horizontal curve locations

- Identification of "typical" types of advance warning devices currently deployed by particular jurisdictions (e.g. static signs, sign mounted flashers, speed advisories, etc.)

- Identification of potential problem curve locations (route system, route number, reference point, etc.)

- General impressions of potential uses, applications, and advantages/disadvantages of a dynamic curve warning system

The responses to the surveys that were returned are summarized below. A copy of the survey that was distributed is included in Appendix A.

3.1 Survey Response

Mn/DOT distributed the survey form entitled "Dynamic Signing at Rural Horizontal Curves" to 126 city engineers and 87 county engineers throughout the state of Minnesota. Of the 126 surveys sent to the city engineers, 26 completed surveys were returned, giving a response rate of 21 percent. For the county engineer responses, 65 were received, giving a response rate of 75 percent.

3.2 Summary of Response Data

The types of warning devices that are currently used at horizontal curves by city and county engineers are shown in Figure 3-1. All of the city agencies and most of the county agencies (96.9 percent) that responded use at minimum an advance curve warning sign. The speed advisory plate is the next most utilized warning device (in conjunction with the curve sign) at 57.7 percent for city agencies and 92.3 percent for county agencies.

In the matter of the agencies having any warrants or guidelines for the installation of curve warning signage, approximately 70 percent of the city agencies and 80 percent of the county agencies use the Minnesota Manual on Uniform Traffic Control Devices as a reference guide. The other agencies either have no warrants or guidelines or follow their own policies regarding the installation of warning signage.

Figure 3-2 shows other methods that are used by both city and county agencies to address hazardous curve locations. For both city agencies and county agencies, improving the geometrics of the horizontal curve is the most utilized method for addressing safety issues at horizontal curves. However, improving the geometrics of the roadway can be very costly; therefore, the city and county agencies choose to install additional signage and implement pavement markings as the next most utilized and cost effective methods for addressing safety issues at horizontal curves

To determine the condition of the shoulders along a horizontal curve, city and county agencies were asked to describe the type and width of the shoulders that are typically constructed along the roadways for which they are responsible. For the city agencies, the shoulders are typically paved and are four to six feet wide. For the county agencies, the shoulders are typically gravel and the majority are four to six feet wide along the horizontal curve.

Figure 3-3 shows some factors that the agencies believed contributed to a vehicle going off of the roadway along a horizontal curve. For both the city and county agencies, vehicle speed and pavement / weather conditions were the two most common factors contributing to vehicle navigation problems. Two other factors that were cited by both the city and county agencies were driver error and alcohol use.

The number of crashes that the agencies believed would need to occur in order for the curve to be considered hazardous is shown in Figure 3-4. For both the city and county agencies, two crashes per year was the most common answer. Some of the respondents stated it depends on the severity and type of crash and on the Average Daily Traffic (ADT) of the roadway to determine if the curve could be considered hazardous.

Each agency was asked if they thought that a dynamic warning system would be useful in the reduction of crashes involving vehicles running off of the roadway, and the majority of the city agencies said yes. However, the county engineers were almost evenly split in their response (Figure 3-5).

When the surveys were returned, most of the agencies chose to utilize the last section to give general impressions of potential uses, applications, and advantages/disadvantages of a dynamic warning system. Some of the comments that were made include:

- The sign may make people aware of their speed which may result in a lowering of that speed thus improving safety
- Need a cost/benefit analysis to determine if installing the sign is beneficial
- The cost of installation and maintenance would be high
- The sign may be distracting
- The sign could attract drivers to the area to "test" the sign (i.e. travel at higher speeds to activate the sign)
- Potential liability if the sign failed to activate
- ADT's do not warrant it

3.3 Conclusions

- All of the city (100 percent) and the majority of the county agencies (96.9 percent) that responded use a curve warning sign at horizontal curves. A speed advisory plate is generally used in conjunction with the curve warning sign.

- Most city (66.7 percent) and county agencies (82.4 percent) follow the warrants and/or guidelines in the MMUTCD for the installation of curve warning signs.

- Geometric improvements are the number one method that both city and county agencies use to address hazardous curve locations. However, if cost is an issue, the agencies will install additional signage and/or implement pavement markings as the next best alternatives to address these hazardous curves.

- For both the city and county agencies, vehicle speed was chosen as the main factor contributing to vehicle navigation problems in horizontal curves.

- In determining the number of crashes per year that would need to occur in order for the curve to be considered hazardous, the answers given were varied. For both city (46.2 percent) and county (26.2 percent) agencies, the highest response was two crashes per year that would need to occur for the curve to be considered hazardous. Other factors that may be needed to be taken into consideration are the crash history of the horizontal curve and ADT of the roadway.

- Approximately two-thirds of the city agencies agreed that a system that would provide a warning message if a driver were exceeding some predetermined criteria would be useful in the reduction involving vehicles running off of the road. The county agencies were evenly split as to the potential usefulness of the dynamic warning sign.
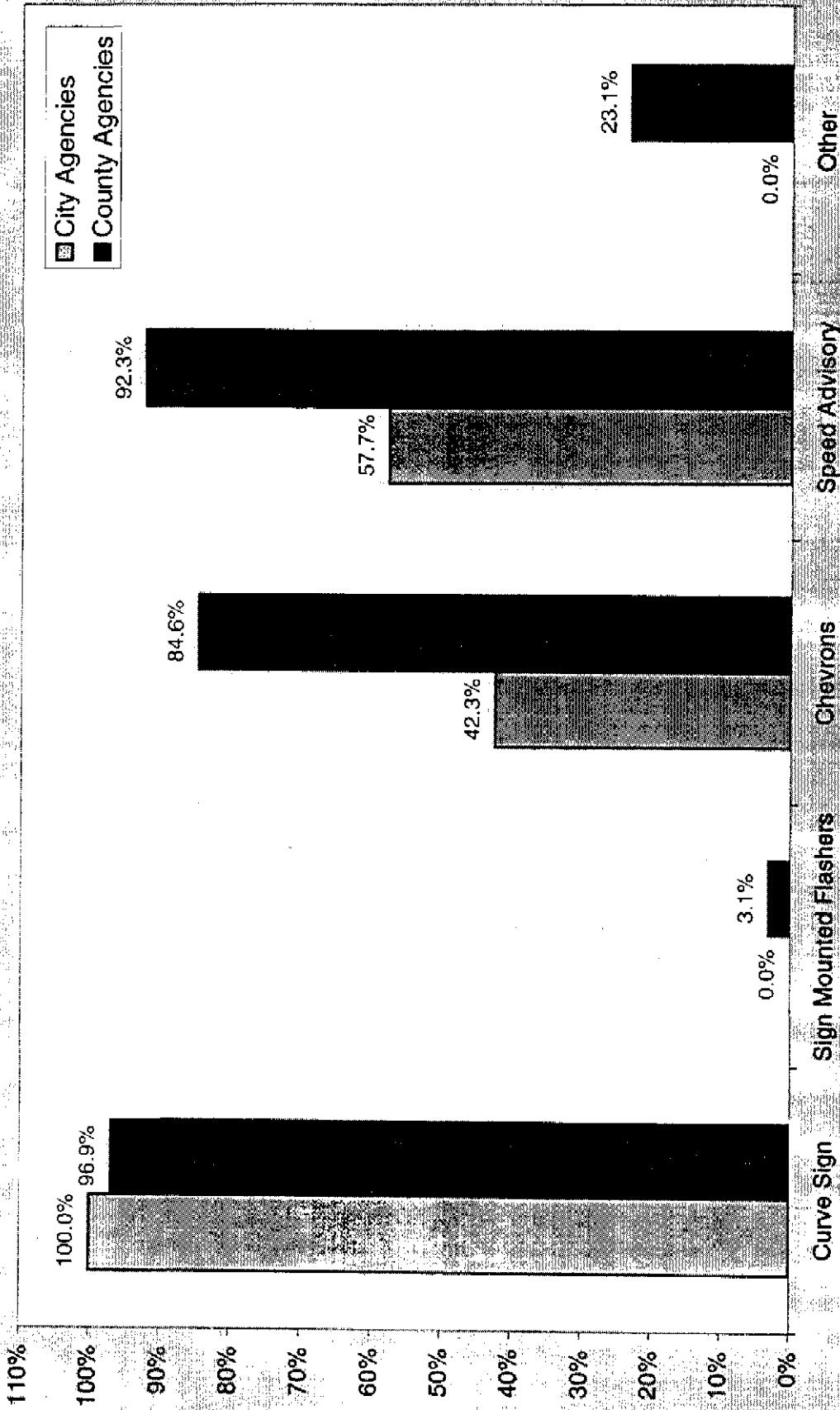
Figure 3-1
Warning Devices Currently Used In Practice

Legend: City Agencies, County Agencies

Curve Sign: 100.0%, 96.9%
Sign Mounted Flashers: 0.0%, 3.1%
Chevrons: 42.3%, 84.6%
Speed Advisory: 57.7%, 92.3%
Other: 0.0%, 23.1%

Survey of Agencies

15
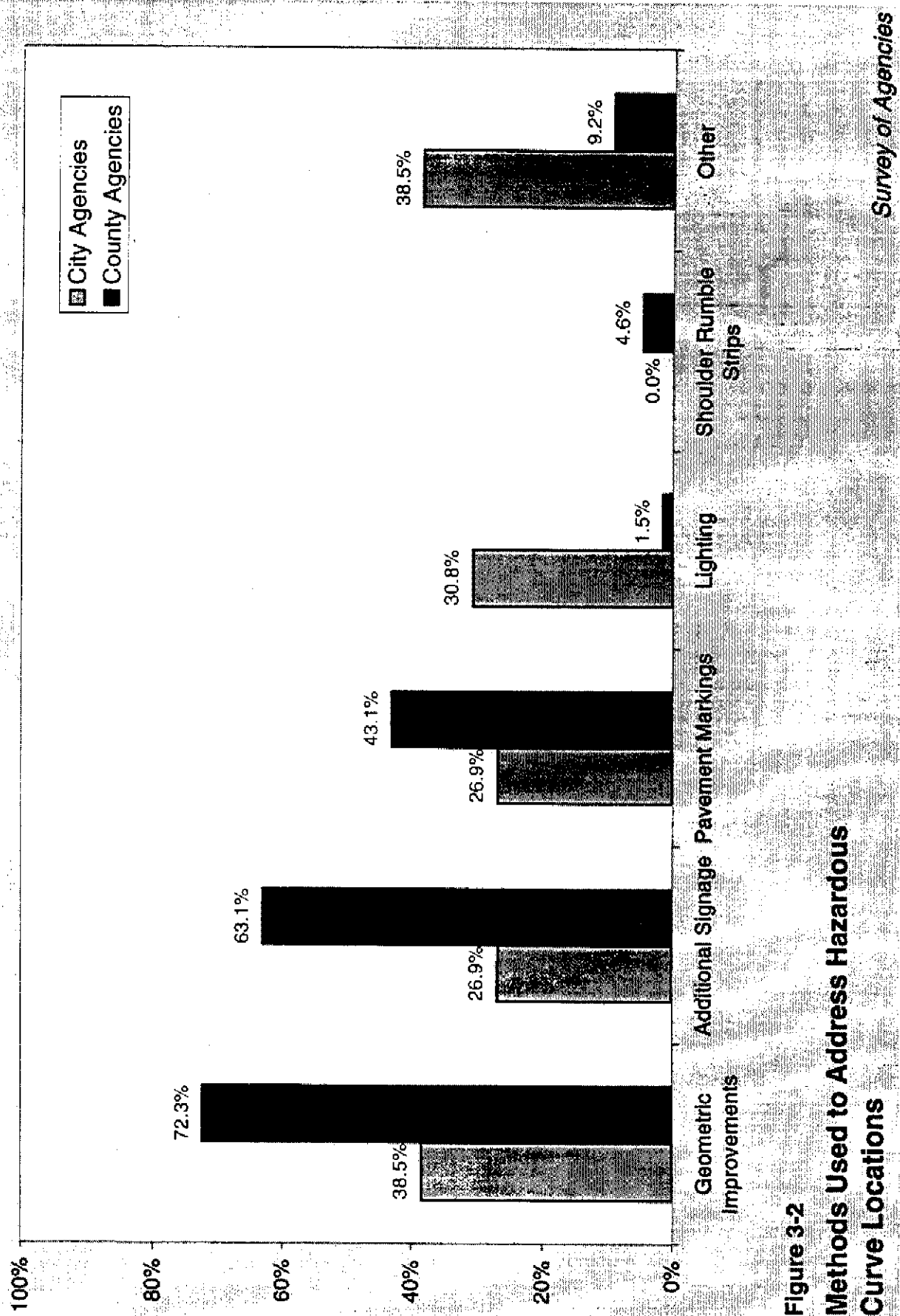
Figure 3-2
Methods Used to Address Hazardous Curve Locations

Legend: City Agencies, County Agencies

Geometric Improvements: City 38.5%, County 72.3%
Additional Signage: City 26.9%, County 63.1%
Pavement Markings: City 26.9%, County 43.1%
Lighting: City 30.8%, County 1.5%
Shoulder Rumble Strips: City 0.0%, County 4.6%
Other: City 38.5%, County 9.2%

Survey of Agencies

16
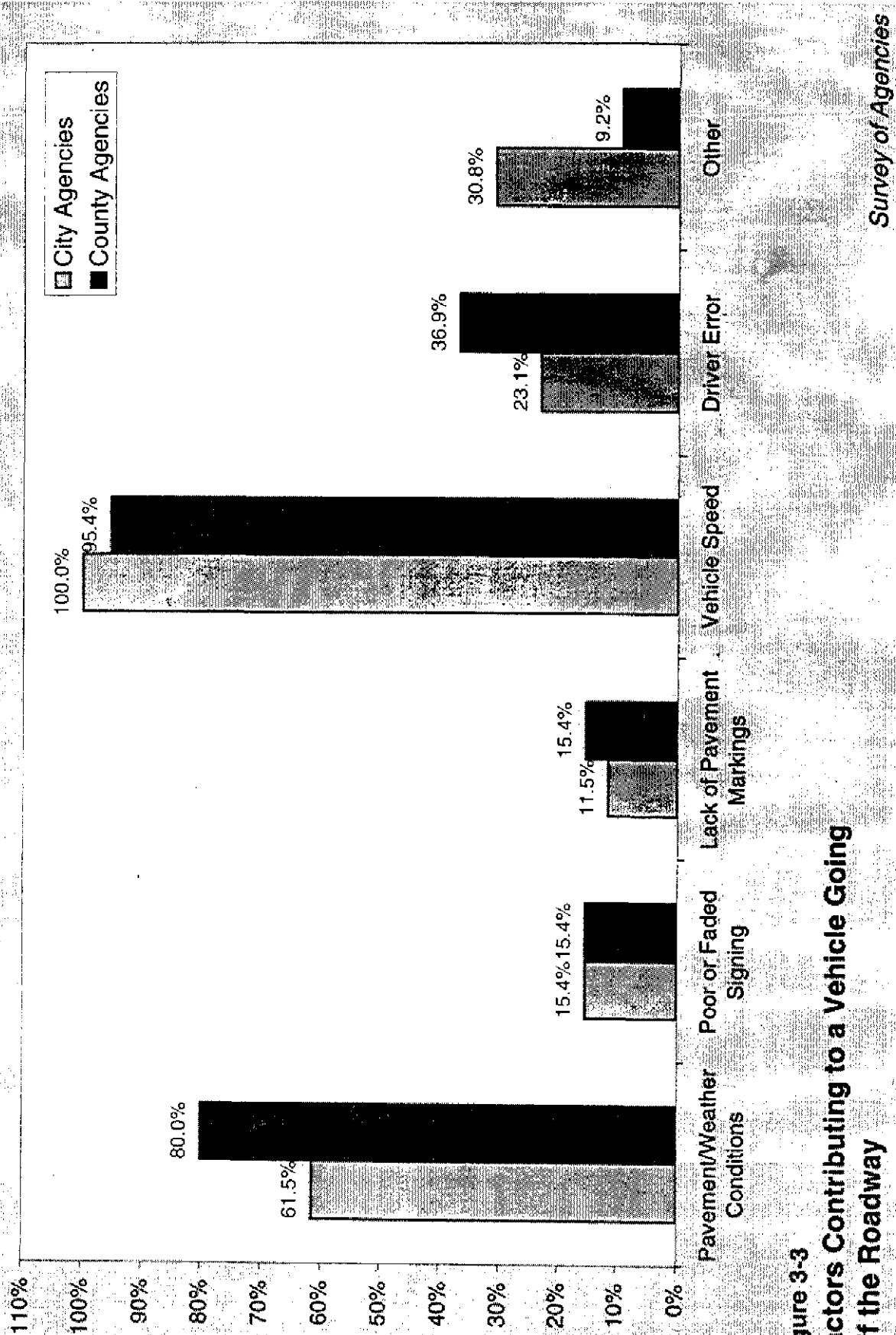
Figure 3-3
Factors Contributing to a Vehicle Going Off the Roadway

Legend: City Agencies, County Agencies

Pavement/Weather Conditions: 61.5%, 80.0%
Poor or Faded Signing: 15.4%, 15.4%
Lack of Pavement Markings: 11.5%, 15.4%
Vehicle Speed: 100.0%, 95.4%
Driver Error: 23.1%, 36.9%
Other: 30.8%, 9.2%
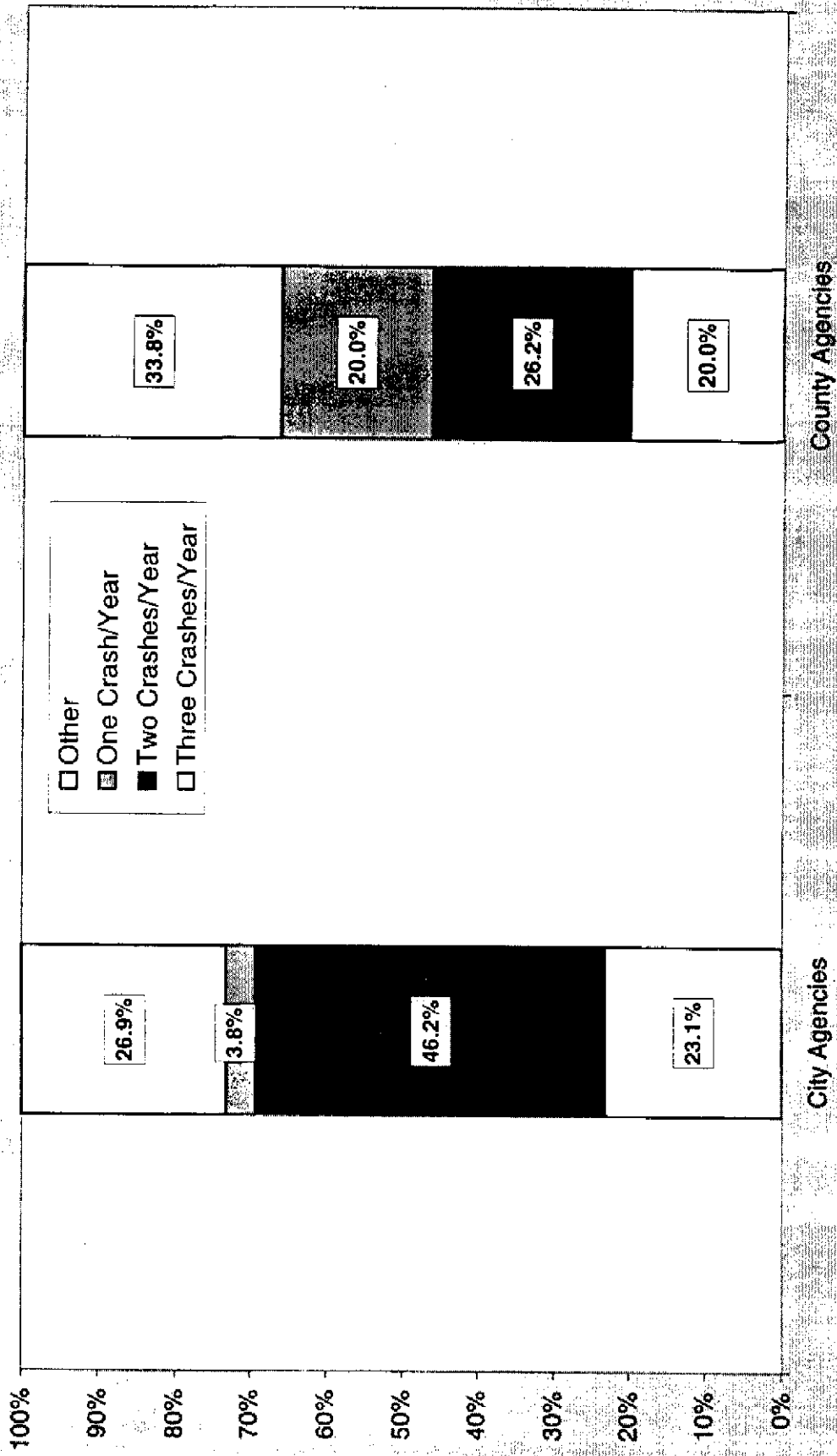
Survey of Agencies

Figure 3-4

Number of Crashes to Consider a Curve Hazardous

18

Figure 3-5
Use of a Dynamic Warning System

Survey of Agencies

4.0 Description of Equipment, Software, and Data Collection

The purpose of this chapter is to detail the equipment and software that was used to collect data and describe the process by which it was collected.

4.1 Equipment Description

The system used to collect the data for the test consisted of the following major components (Figure 4-1 shows a schematic of how the equipment was deployed.):

1. Trailer Mounted Equipment:

- 386 Industrial Personal Computer (PC)

  This unit consisted of: ISA style passive backplane Industrial PC with a 386 - 40 mhz processor and 2 megabytes of memory; hard disk; floppy disk; two serial RS - 232 ports; and a special digital output interface board which allows for digital control of the Industrial VCR. One of the RS - 232 serial ports is used to drive the Video Text writer which allows a program on the PC to write data onto the VCR Video tape. The other serial port is connected to the Doppler speed radar unit for input of speed data to the program and is also connected to the dynamic sign to command which messages to display on the ADDCO BRICK Sign.

- Pelco SpectraDome II Closed-Caption Television (CCTV) Camera

  The Pelco SpectraDome II is a sealed, full color, pan/tilt/zoom NTSC video camera with several advanced features. In this application, a TV monitor was connected to the video output from the camera during initial setup and the camera was aimed using a laptop computer with a serial RS - 422 connection to the camera unit. Once the camera is setup, it will always return to the original position and setup whenever power is applied to the unit. The camera was powered from a special 12 - 24 volt DC converter.

- Panasonic Industrial VCR

  This device is a special industrial model VCR designed to operate in a harsh environment and is powered from a 12 volt DC source. The recorder has several features that made it ideal for this test, including: a digital control input to start and stop recording and it is designed to operate in a "Standby" mode for extended periods of time. In this application, the VCR is started and records for 18 seconds each time a vehicle triggers the system via the Doppler Radar. The VCR also writes status information onto the tape such as time and date.

- "PoleWatcher" Video Text Writer

  This device allows the computer to write data such as speed, sign status, and a serial number that allows later correlation between computer speed data and video images onto the videotape.

- ADDCO Smart Zone Portable Tower Platform

  This device is the heart of the system. It provides 12 volt DC power to the electronics in the test via a battery / solar power system employing 8-75 watt solar panels and 32-6 volt heavy duty lead acid batteries. In addition to the power source, it also provides a 35-foot high platform for the CCTV camera on the extended tower. This whole system is mounted on a skid that is totally self-sufficient and designed for the roadside environment. The skid is then mounted on a trailer for ease of transport. The whole system is designed to be set-up in less than 2 hours on site by a two-person crew.

- Misc. Line Driver and Power Supplies

  These devices provide the support needed for the various interconnected devices on the system. The power supply portion was an inverter to change the 12 volt DC power to 115 volt AC for transmission over the approximate 600 feet between

22

the Sign Post Mounted devices and the Trailer mounted components. At the Sign Post location, the 115 volt AC power is converted back to 12 volt DC for use by the Doppler Speed Radar and the ADDCO BRICK Sign. This conversion to 115 volt AC for transmission was performed to allow smaller interconnecting cables between the two major sub-systems. The power draw of the sign and radar is such that large cables for power would be required if power transmission were done at 12 volt DC.

The line driver portion provides for extended distance transmission of the serial data to and from the Sign and Radar.

Figure 4-2 shows a picture of the trailer-mounted equipment and its location in regard to the CSAH 54.

2. Sign Post Mounted Equipment:

• ADDCO 6 BRICK Dynamic Message Sign

This is a standard ADDCO High Density BRICK Modular Sign consisting of six BRICKS mounted in a horizontal configuration of three wide by two high. The sign is powered from 12 volt DC. Communication to the sign is at 9600 baud.

For this test the sign displayed three different messages:
1. BLANK SIGN – NO MESSAGE
2. CURVE AHEAD
3. CURVE AHEAD – REDUCE SPEED (sequential message)

• Doppler Speed Radar with Serial Speed Output (RS - 232)

The Doppler Speed radar is a commercial unit intended to measure vehicle speed and output a simple three-digit indication of speed anytime the speed changes. This output is RS - 232 at 9600 baud. The computer via its serial port monitors

this data. The radar's field of view was approximately from 700 feet away from the sign to 15 to 50 feet in front of the sign.

Figures 4-3 and 4-4 illustrate the ADDCO 6 BRICK Dynamic Warning Sign and the Doppler Speed Radar.
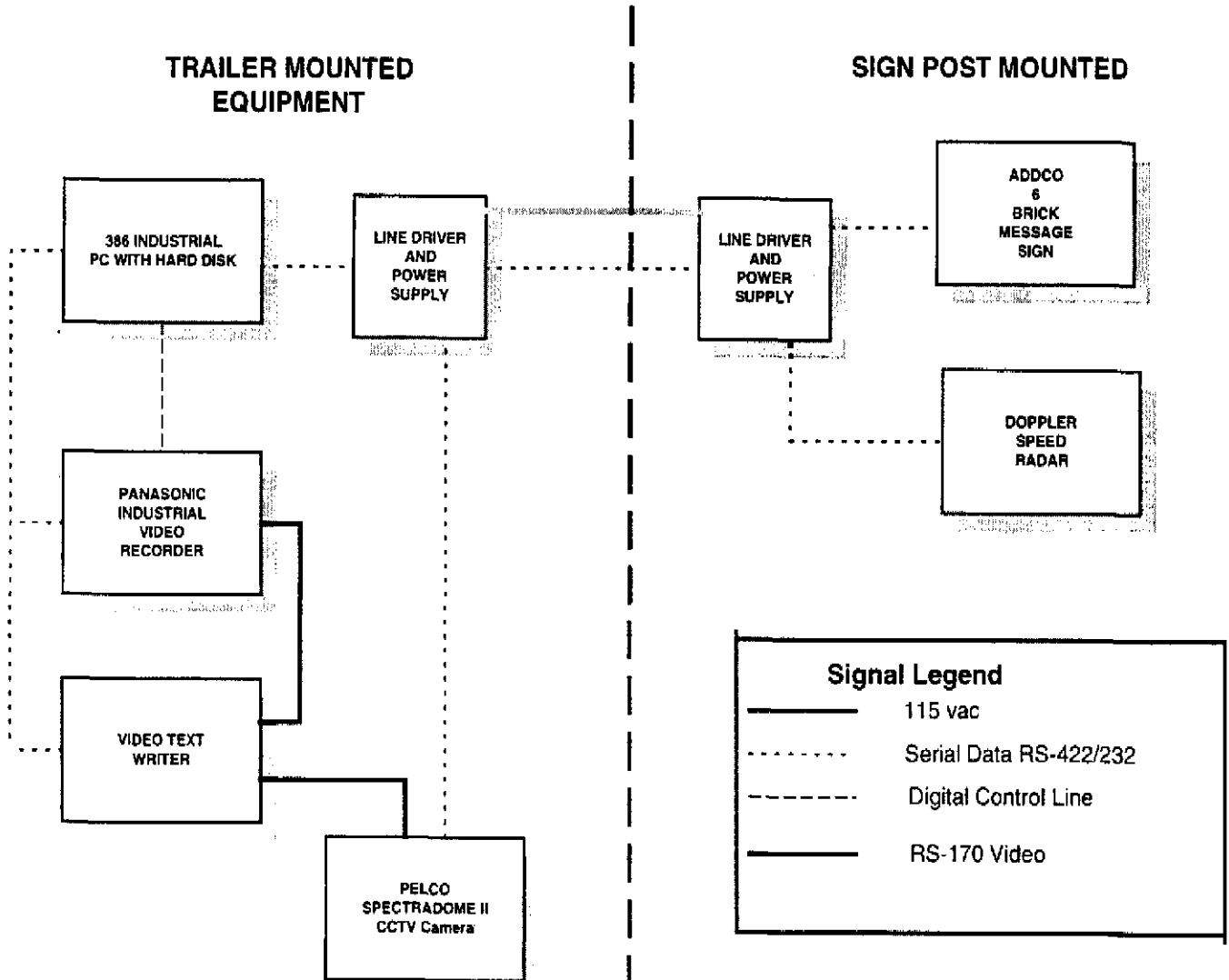
Figure 4-1: Block Diagram of Deployed System

Closed - Caption
Television Camera

Extended Tower

Solar Panels

Personal Computer,
Industrial VCR,
Line Driver, and
Power Supplies

32 Heavy Duty Lead
Acid Batteries

Underground cable
to dynamic warning
sign

Figure 4-2: Trailer mounted Equipment

Static Curve Warning Sign
and Speed Advisory Plate

Radar

Dynamic
Warning Sign

40

Figures 4-3 and 4-4: Photo of Dynamic Warning Sign and Radar

Radar

4.2 Software and Data Collection

When this particular study was in the initial planning phase, it was first determined that data would need to be collected in two-week time periods in order to determine if the dynamic sign had any effect on the vehicles entering the curve. This meant that for two weeks data would be collect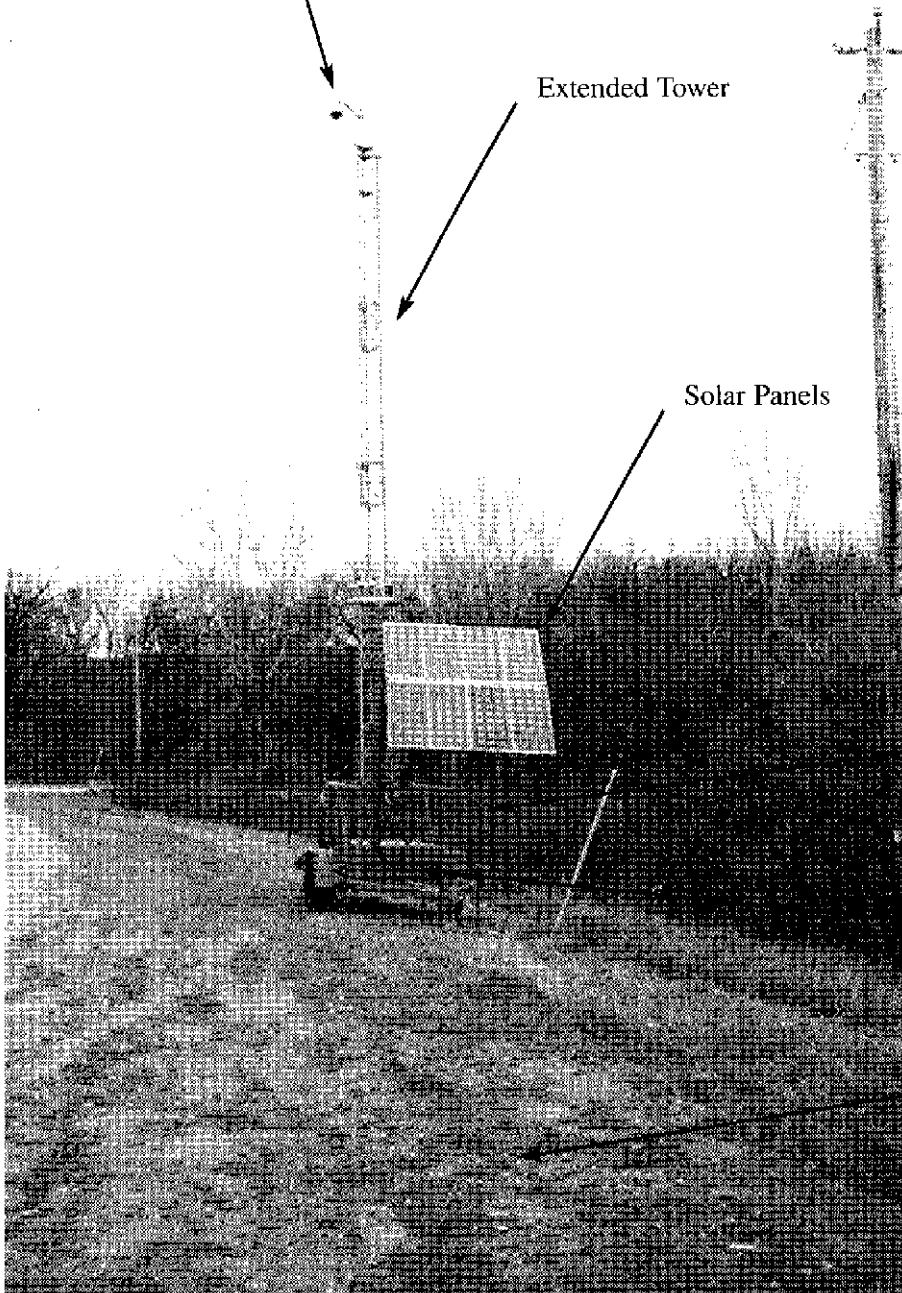ed with the dynamic sign turned completely off. For another two weeks, data would be collected with the "CURVE AHEAD" message on the dynamic sign; and for another two weeks, data would be collected with the "CURVE AHEAD, REDUCE SPEED" message on the dynamic sign (The data was only collected for those vehicles that were traveling at or above 53 mph). Upon completing this data collection over a month and a half time period, there would have been a massive amount of data to analyze. However, it was determined that this large amount of data was unnecessary and that a statistically reliable sample size was all that was needed. Therefore, the method of data collection was modified as described below.

The data used for the analysis was collected on the following days and times:

- August 23, 1999, 3:00 PM to 8:00 PM
- August 26, 1999, 2:00 PM to 8:00 PM
- August 30, 1999, 9:00 AM to 6:00 PM
- September 1, 1999, 7:30 AM to 7:00 PM

The weather for these days was partly cloudy with high temperatures between 70 and 85 degrees Fahrenheit (This information was retrieved from the University of Minnesota Climatology Working Group Internet site). Due to the inability of the camera to "see" at night, nighttime data was not analyzed because it could not be determined if a vehicle was on or crossing over the centerline into the oncoming lane of traffic.

The following is a description as to how the data was collected.

1. At midnight each day, the computer creates a new data file on disk for the coming day.

2. If the time of day is between 6:00 AM – 10:00 AM or 11:00 AM - 2:00 PM or 4:00 PM - 7:00 PM, it will illuminate the dynamic sign with the message "CURVE AHEAD."

3. If the RADAR detects any vehicle traveling at 53 mph or faster, it will start the VCR and record the view for 18 seconds. During recording, the VCR will have the date and time; the SERIAL NUMBER for the current recording interval; the Vehicle Speed that the vehicle tripped the RADAR; the current vehicle speed; and a code indicating the status of the sign: 1 = "CURVE AHEAD," 2 = CURVE AHEAD - REDUCE SPEED," and 3 = No Message - BLANK on the video image. In addition to recording this data on the video image, the computer also writes this data to the disk file at a rate of two samples per second.

4. For each vehicle that is detected by the radar and activates the VCR, the computer selects a random number. If the vehicle that is detected has the particular random number that the computer has chosen, the "CURVE AHEAD - REDUCE SPEED" message will be displayed. Therefore, if condition 2 above is true and condition 3 above is true and the particular vehicle meets a random number that is generated each time condition 3 is met above, the computer will tell the dynamic sign to then display the sequential message "CURVE AHEAD - REDUCE SPEED" for 10 seconds.

When the VCR is activated due to a vehicle traveling at or above 53 mph, the computer also writes the collected information to a disk. The data file on the disk contains the following:

- An integer time stamp from the computer in number of seconds since midnight
- The current speed from the radar in MPH
- The speed at which the vehicle first was recorded during this sample (initial speed)

- The frame serial number (sequential for each sample period, starts at 1 at midnight)

- The current sign message code: 1 = "CURVE AHEAD," 2 = "CURVE AHEAD - REDUCE SPEED," and 3 = No Message - BLANK

A sample of the data is included below.

33039,56,53,1,1

33039 -	seconds from midnight
56 -	current speed in MPH
53 -	initial speed in MPH
1 -	frame (on video tape) serial number
1 -	sign = CURVE AHEAD

This data will have a sample every three seconds during the time the vehicle was in the radar field of view. This is how the speed deltas were determined.

5.0 Project Location and Existing Roadway Design

The purpose of this chapter is to document and summarize the decisions that were made regarding choosing the best location of where to install the dynamic curve warning sign.

5.1 Project Location

Through several meeting and discussions with members on the advisory panel, it was determined to install the dynamic warning system on CSAH 54 (Ravenna Trail) in Dakota County southeast of Hastings, Minnesota. Figure 5-1 shows the general location of CSAH 54 in relation the Twin Cities Metropolitan area. CSAH 54 has the following characteristics:

- It is a two-lane county state-aid highway with a rural roadway classification
- It has a posted 55 mph speed limit
- It had a 1996 Average Daily Traffic (ADT) of approximately 3,250 vehicles.

Figure 5-2 shows the location of where the dynamic warning sign was installed on CSAH 54 and the location of the static warning signs that are currently in place in the surrounding area. The dynamic sign was placed for northbound traffic alongside a static curve warning sign with a speed advisory plate of 40 mph (Figure 5-3). The sign was placed at this location on CSAH 54 for several reasons:

- There is adequate sight distance for the radar and video equipment to be able to detect vehicles approaching and traveling through the horizontal curve.

- The equipment trailer that houses the solar panels, batteries, computer equipment, and the video camera and recorder could be safely placed outside of the clear zone along the side of the roadway.

31

- The roadway, at this location, traverses through both a horizontal and a vertical curve.

- CSAH 54 is used by people who do not frequently travel on the roadway. There is a casino located approximately 20 miles southeast of Hastings. Therefore, people living in the Twin Cities area have the option of using CSAH 54 as a possible route to travel to the casino.

5.2 Existing Roadway Design

Figure 5-4 shows the plan and profile views of this location on CSAH 54. The horizontal curve was designed using a radius of 819 feet, a curve length of 780 feet, and a degree of curvature of 7°00'. The as-built superelevation for the horizontal curve was approximately 5%. The vertical curve has a length of 1200 feet and has grades of –7.0% to 4.1% (traveling northbound). Figures 5-5 and 5-6 show photographs of the study location.

The design of both the horizontal and vertical curves is consistent with MnDOT guidelines for rural county highways.

N
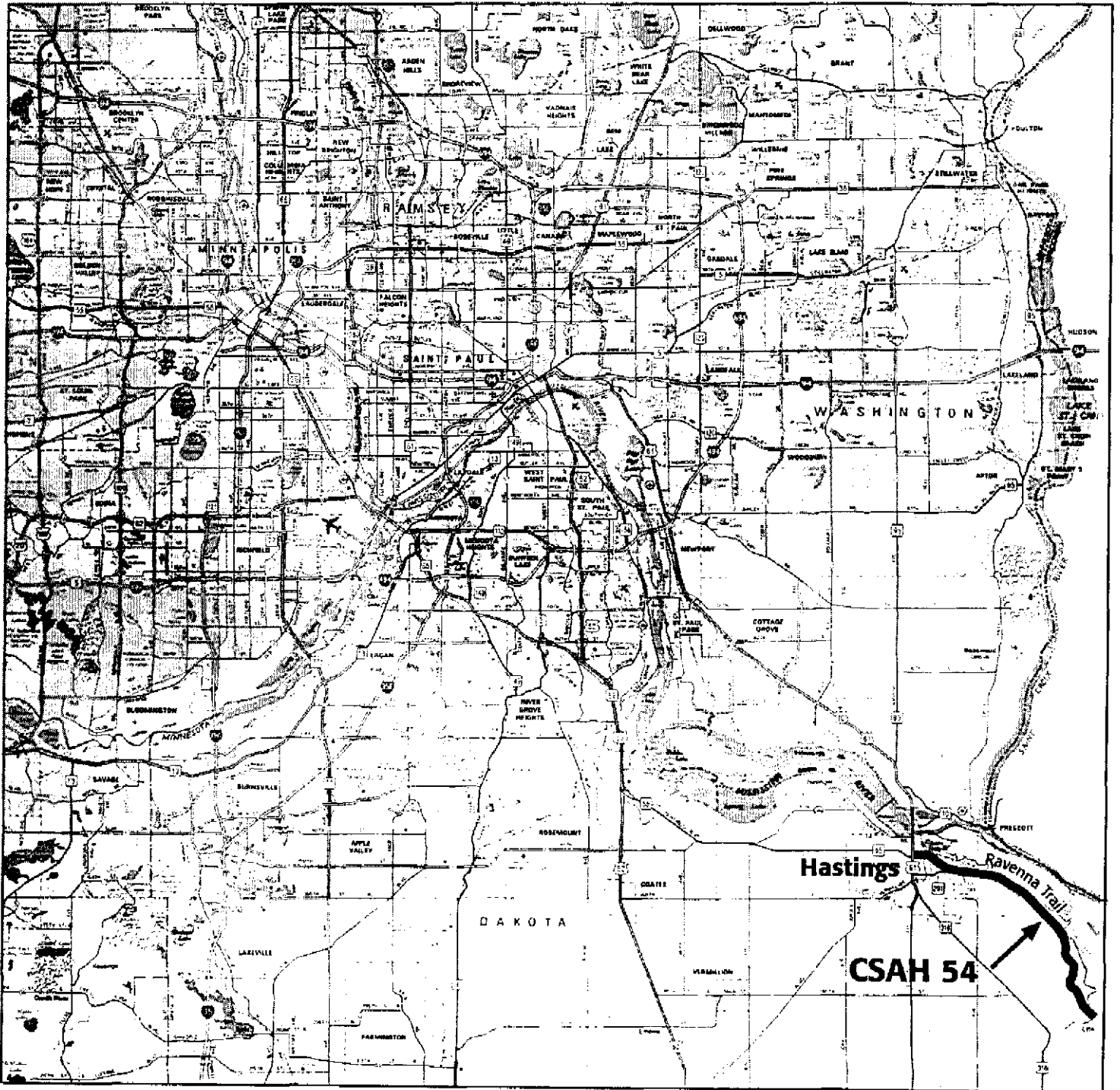
Figure 5-1
Metro Location

175th St

50 m.p.h.

Backbird Trail

CSAH 54

45 m.p.h.

50 m.p.h.

Horizontal
Curve
Location

Hardware skid

650'

CMS

40 m.p.h.

45 m.p.h.

185th St

Ravenna Trail

Six Chevrons
120'-160'

45 m.p.h.

CSAH 54

NEXT
2
MILES

N
W — E
S
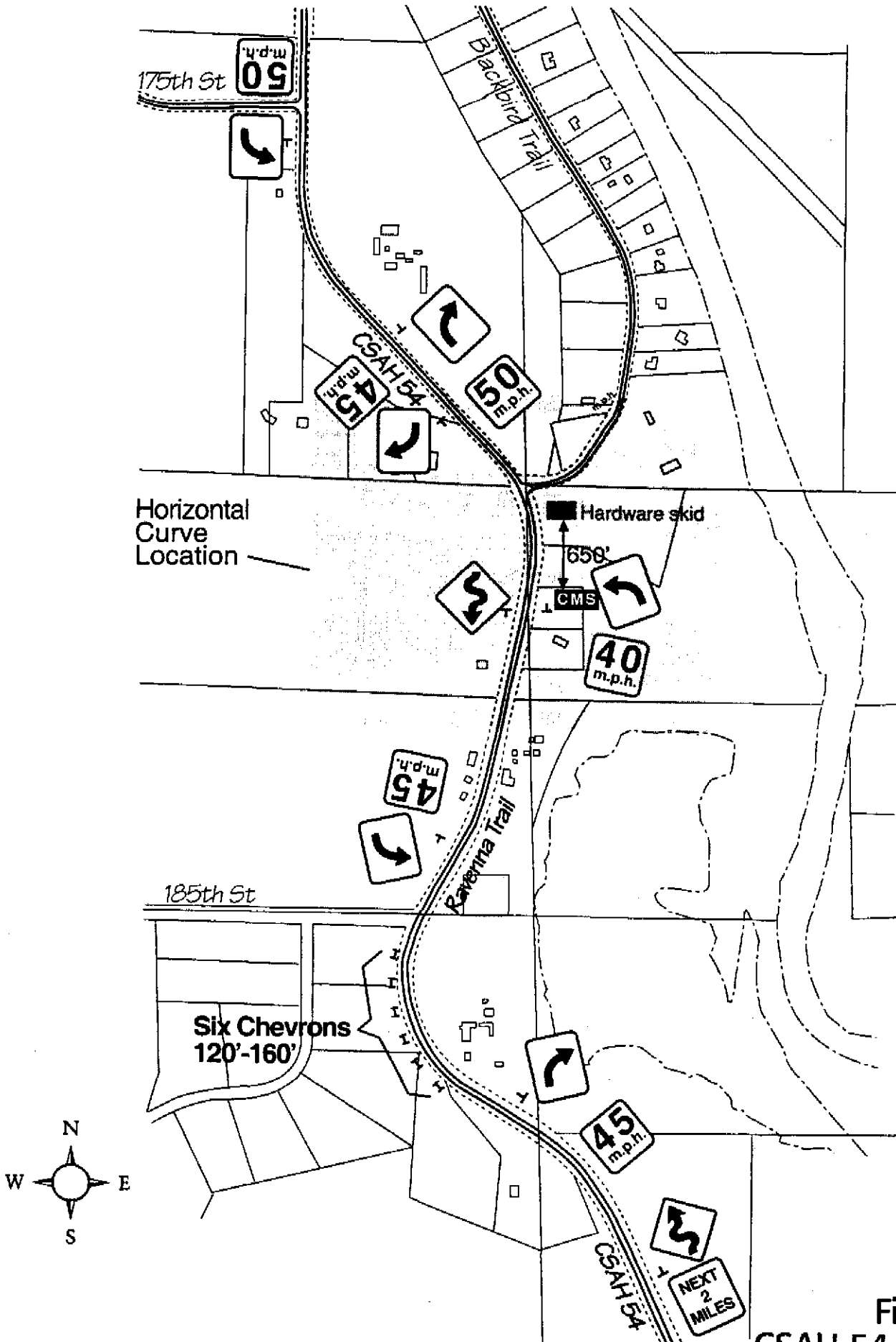
Figure 5-2
CSAH 54 Location

34

Sections 7 & 8
T114N, R16W
Ravenna Township

650'

Hardware Skid-Video
Camera & VCR

Inplace Advance Curve Warning
Sign & Speed Advisory Plate

CMS Changeable Message
Sign & Radar

N

CSAH 54

Blackbird Trail

Ravenna Trail
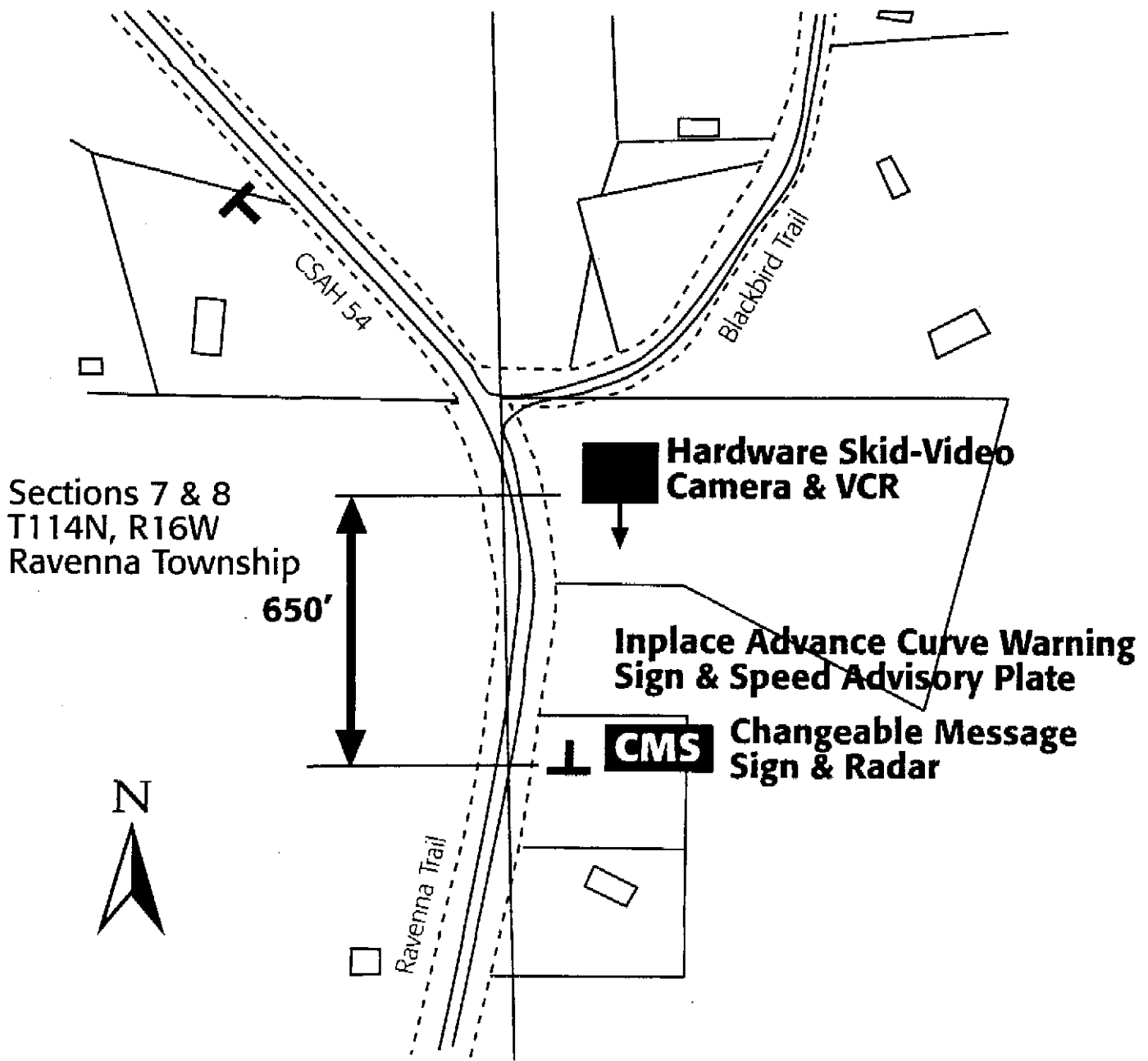
Figure 5-3
Site Location

Plan View

Profile View

Figure 5-4
Plan and Profile Views

Figures 5-5 and 5-6: Photographs of Existing Horizontal and Vertical Curve

6.0 Analysis of Field Data and Results

The purpose of this chapter is to document and summarize the data that was collected regarding: the ability of a vehicle to successfully navigate through a horizontal curve at a particular speed and the effectiveness of a dynamic (variable) message sign on reducing the speed of vehicles approaching the horizontal curve.

6.1 Correlation Between Speed and Successful Navigation

In examining the data that was recorded onto a videocassette and saved on disk for the four day test period described in Section 4.2, there were a total of 2,650 vehicles that activated the dynamic "system" by traveling at or above the set s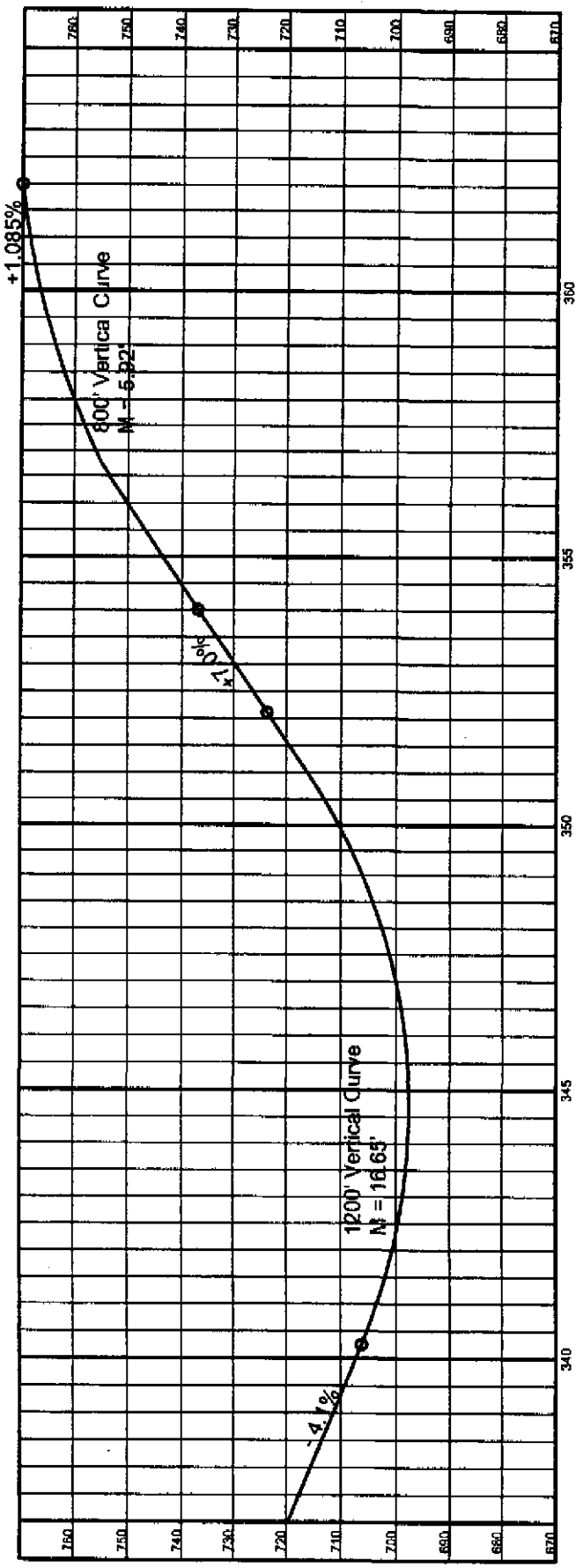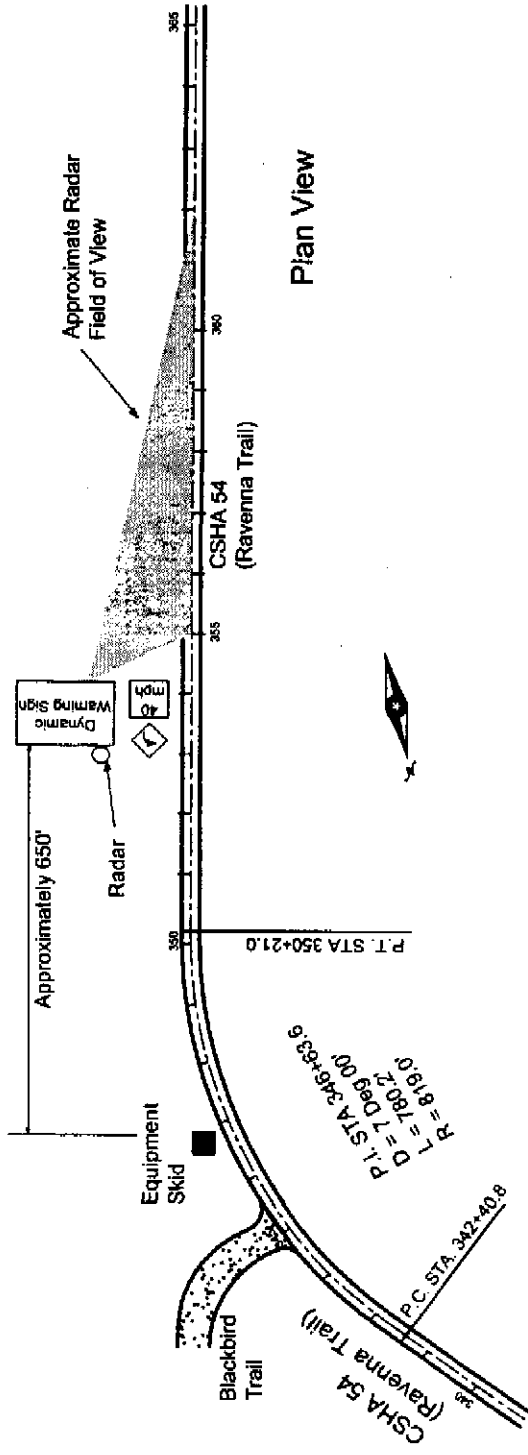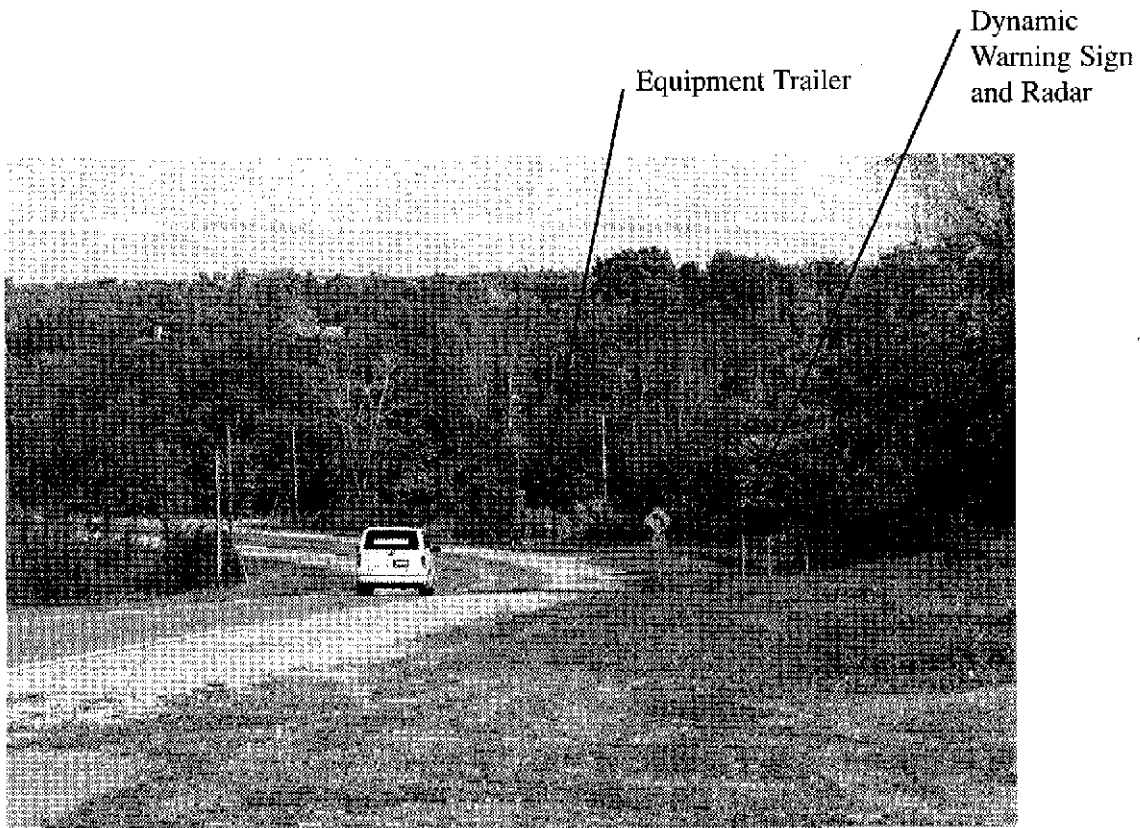peed threshold of 53 mph. In order to be able to distinguish speed data between vehicles, each vehicle that activated the system was given its own unique serial number. This unique number was saved on both the disk and on the video image.

The 2,650 vehicle speed data was divided into two separate categories.

1. Vehicles with an initial speed at or below the speed limit (55 mph)
2. Vehicles with an initial speed greater than the speed limit

There were 1,321 vehicles recorded that were traveling at or below the speed limit and 1,329 vehicles traveling above the speed limit. Because the VCR only started recording vehicles that had an initial speed at or above 53 mph, there was only a 53 to 55 mph speed range for vehicles that had an initial speed at or below the speed limit.

Although the data was automatically saved to a disk that could be loaded into a spreadsheet-like software program, an individual had to watch the videotapes in order to be able to determine if a particular vehicle successfully navigated through the horizontal curve. The definition of "successful navigation" that is used for this report is "Any vehicle that, as they are traveling through the horizontal curve, remains within their lane

39

lines (between the shoulder line and the centerline)." If a particular vehicle travels on or over the centerline, it is considered an unsuccessful navigation. Figures 6-1 through Figure 6-4 show examples of unsuccessful navigations of the curve.

The database consisted of 2,650 vehicles for which there was both speed data and video documenting navigation through the curve. All 2,650 vehicles were used in the speed data analysis because it was a relatively simple task. However, evaluating the navigation information on the videotape required a significantly greater level of effort. Therefore, it was decided to limit the analysis of vehicle navigation to a statistically reliable sample of the data. It was determined that for the data to be statistically reliable there would need to be at minimum 150 vehicles in each speed category (less than or equal to 55 mph and greater than 55 mph). To choose an unbiased statistically random sample, approximately every fourth data entry was chosen, which lead to a sample size of approximately 660 vehicles. Because some of the data had to be disregarded due to erroneous results, there were a total of 589 vehicles observed traveling through the horizontal curve. Of these 589 vehicles, 249 vehicles were observed traveling at or below 55 mph and 340 vehicles were observed traveling above 55 mph (Table 6-1). Figure 6-5 shows a graphical representation of the data with 99-percentile confidence intervals applied. For vehicles with an initial speed at or below the speed limit, approximately 20 percent were unable to successfully navigate through the curve. However, for vehicles with an initial speed above the posted speed limit, approximately 40 percent were unsuccessful in navigating through the curve. The statistical analysis indicates that the difference between successful navigation of vehicles traveling at or below the speed limit and vehicles traveling above the speed limit is significant at the 99 percent confidence interval.

To be able to determine which vehicles were less likely to be able to successfully navigate through the horizontal curve, the data was further divided into several categories.

- Vehicles approaching the horizontal curve with and initial speed of 65 mph or greater.

40

- Vehicles with a low (final recorded) speed of 40 mph or less.
- Vehicles with an initial speed of 55 mph and a decrease in speed of 15 mph or greater.

Figure 6-6 shows the number and percent of vehicles with an initial speed less than 65 mph or greater than and equal to 65 mph that were successful and unsuccessful in their navigation through the curve. Although there were only 33 vehicles observed traveling with an initial speed at or above 65 mph, approximately 45 percent of these vehicles were unable to successfully navigate through the curve compared to 30 percent for vehicles that were traveling less than 65 mph. The difference between vehicles with an initial speed less than 65 mph and vehicles traveling at or above 65 mph is statistically significant at a 90 percent confidence interval.

There is an existing 40 mph speed advisory plate attached to the static curve warning sign. To determine if vehicles that obeyed the speed advisory plate were able to successfully navigate through the curve, the data was divided into vehicles with a final speed at or below 40 mph and vehicles with a final speed greater than 40 mph. For vehicles that were traveling at a low (final recorded) speed equal to or less than 40 mph, approximately 20 percent were unable to successfully navigate the curve compared to 33 percent for vehicles that were traveling above 40 mph upon entering the curve (Figure 6-7). Even though there was a relatively small sample of vehicles traveling at or below 40 mph, the differences were significant at the 95 percent confidence interval.

Figure 6-8 shows the number and percent of vehicles that had an initial speed at or above 55 mph and that had a decrease in speed of 15 mph or greater when the radar gave its final reading. If a vehicle decreased its speed by a minimum of 15 mph, that vehicle successfully navigated the curve approximately 70 percent of the time. However, if a vehicle did not decrease its speed by a minimum of 15 mph, the vehicle was able to successfully navigate the curve only 60 percent of the time. A statistical analysis indicates that this difference is significant at the 90 percent confidence interval. Upon further examination of the data, it was found that the average last speed recorded by the

radar for vehicles that had a decrease in speed of 15 mph or greater was 40.5 mph. However, for vehicles that did not decrease their speed by 15 mph, the average last recorded speed was 60.0 mph. This was a difference of approximately 20 mph which lead to a 10 percent better chance to successfully navigate the curve.

6.2 Effectiveness of Dynamic Warning System

As stated above, to determine the effectiveness of the dynamic sign on reducing the speed of vehicles entering the horizontal curve, three scenarios were examined.

1. Static CURVE AHEAD warning sign and speed advisory plate only (dynamic sign is blank)
2. Static sign with "CURVE AHEAD" message on the dynamic sign
3. Static Sign with the sequential "CURVE AHEAD, REDUCE SPEED" message on the dynamic sign.

Table 6-2 and Figure 6-9 show the differences in the decrease in speeds for each sign scenario. The sequential message displayed on the dynamic sign caused the largest decrease in speed of 12.3 mph from highest speed to lowest speed. However, this was only a 0.8 mph greater reduction from the static sign only scenario (11.5 mph).

Figure 6-10 shows a plot of maximum speed versus change in speed for each sign scenario. At speeds greater than approximately 60 mph, the dynamic sign messages cause a greater decrease in the speed of the vehicles approaching the curve. At 75 mph, a vehicle that sees the static sign only will decrease their speed by 20 mph (to the speed limit); whereas, a vehicle that sees either of the dynamic warning signs will decrease their speed by 25 mph (under the speed limit). There was an approximate 5 mph greater decrease in speeds between the dynamic warning sign messages and the static curve warning sign at 75 mph.

The effectiveness of the three sign scenarios versus the successful navigation through the horizontal curve was also examined (Figure 6-11). Approximately 35 percent of the vehicles that observed only the static sign were unable to successfully navigate through the horizontal curve compared to only 26 percent for the vehicles observed the sequential "CURVE AHEAD, REDUCE SPEED" dynamic message. A statistical analysis indicated that this difference of 9 percent was significant at a 90 percent confidence interval. The "CURVE AHEAD" dynamic message also decreased the percent of vehicles that were unable to successfully navigate the curve; however, that difference was not statistically significant.

6.3 Statistical Analyses

A comprehensive statistical analysis was performed to determine if the results are statistically reliable. Three of these tests include:

- Logistic Regression Analysis
- Null Hypothesis
- Confidence Intervals

The logistic regression analysis was used to model the relationship between initial speed and the probability of an unsuccessful navigation. This method is frequently used in medical and health science research to model, for example, the relationship between the dose of a toxin and the probability of dying.

The null hypothesis was used to determine if initial speed has an effect on the probability of a vehicle being unable to successfully navigate through the curve. An acceptance of the null hypothesis would imply that initial speed would have no effect on the probability of an unsuccessful navigation. However, a rejection of the null hypothesis would imply that initial speed does have an effect on the probability of an unsuccessful navigation.

Confidence intervals were also used to determine the statistical reliability of the data. A confidence interval is an interval constructed around the observed sample average such that any given vehicle, in a particular category, will fall in this range. For example, if there is a 95 percent confidence interval applied to the initial speed data of a vehicle, we are 95 percent *confident* that the next vehicle's initial speed will be in this interval.

Appendix B contains the calculations that were made for the logistic regression analysis and the null hypothesis.

6.4 Summary of Results

The results of the correlation between speed and successful navigation of the curve are summarized below.

1. The speed data for 2,650 vehicles was divided into two categories.
   - Vehicles with an initial speed at or below the speed limit of 55 mph (1,321 vehicles)
   - Vehicles with an initial speed greater than the speed limit (1,329 vehicles)

2. The data suggests and the statistical tests confirm that the initial speed of a vehicle does have a statistically significant effect on the probability of successfully navigating through the curve.

3. There was an approximate 20 percent greater chance for vehicles with an initial speed at or below the speed limit to be able to successfully navigate the curve than for vehicles with an initial speed above 55 mph. The statistical analysis indicates that the difference is significant at the 99 percent confidence interval.

4. Although there were only 33 vehicles observed traveling with an initial speed at or above 65 mph, approximately 45 percent of those vehicles were unable to

successfully navigate through the curve compared to 30 percent for vehicles that were traveling with an initial speed less than 65 mph. The 15 percent difference is statistically significant at a 90 percent confidence interval.

5. There is a 13 percent better chance for a vehicle that was traveling at a low (final recorded) speed equal to or less than 40 mph to be able to successfully navigate the curve than for a vehicle traveling above 40 mph upon entering the curve. Even though there was a relatively small sample of vehicles traveling at or below 40 mph, the differences were significant at the 95 percent confidence interval.

The results of the effectiveness of a dynamic warning system are summarized below.

1. The sequential message displayed on the dynamic sign (CURVE AHEAD, REDUCE SPEED) caused the largest decrease in speed of 12.3 mph from highest speed to lowest speed. However, this was only a 0.8 mph greater reduction from the static sign only scenario (11.5 mph).

2. At speeds greater than approximately 60 mph, the dynamic sign messages cause a greater decrease in the speed of the vehicles approaching the curve than the static sign.

3. Approximately 35 percent of the vehicles that observed only the static sign were unable to successfully navigate through the horizontal curve compared to only 26 percent for the vehicles that were exposed to the sequential "CURVE AHEAD, REDUCE SPEED" dynamic message. A statistical analysis indicated that this difference of 9 percent was significant at a 90 percent confidence interval.
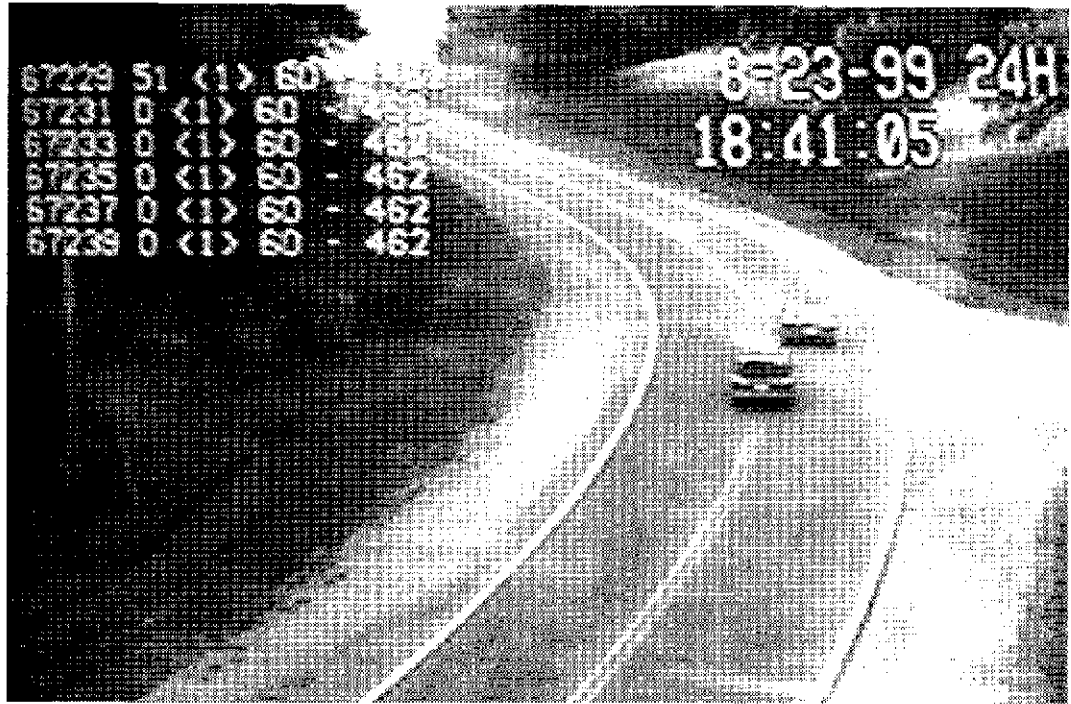
Figure 6-1
Example of an Unsuccessful Navigation (on centerline)

Figure 6-2
Example of an Unsuccessful Navigation (over centerline)

Figure 6-3: Example of An Unsuccessful Navigation (From Videotape)

Figure 6-4: Examples of Unsuccessful Navigations (From Videotape)

Table 6-1
Successful Navigation of Horizontal Curve

	Number of Observations	Successful Navigation of Curve		Unsuccessful Navigation of Curve	
		Number	Percent	Number	Percent
Lower Speed Vehicles (<= 55 mph)	249	198	79.5%	51	20.5%
Higher Speed Vehicles (> 55 mph)	340	210	61.8%	130	38.2%
Total	589	408	69.3%	181	30.7%
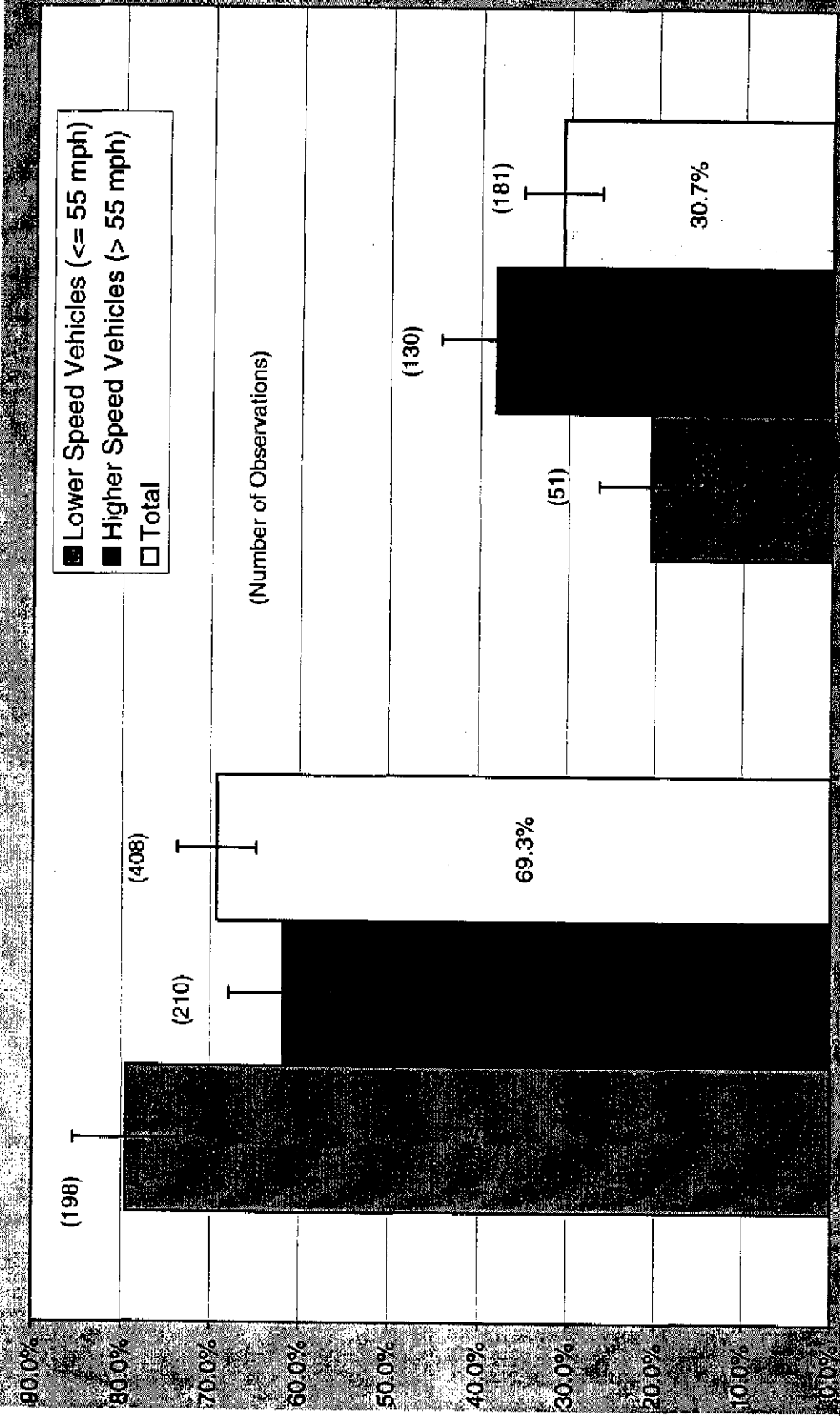
Figure 6.5: Successful Navigation With 99% Confidence Interval

Legend:
- Lower Speed Vehicles (<= 55 mph)
- Higher Speed Vehicles (> 55 mph)
- Total

(Number of Observations)

Total bars: (408) 69.3%, (181) 30.7%
Higher Speed: (130), (51)
Lower Speed: (210), (198)

Y-axis: Successful Navigation of curve

X-axis: 0.0% to 90.0%

Figure 6-6
Initial Speed >= 65 mph with a 90% Confidence Interval

Figure 6-7
Low Speed <=40 mph with a 95% Confidence Interval

Figure 6-8 Decrease in Speed >= 15 mph with a 90% Confidence Interval (For Vehicles With an Initial Speed At or Above 55 mph)

Table 6-2
Speed Reduction on Approach to Horizontal Curve

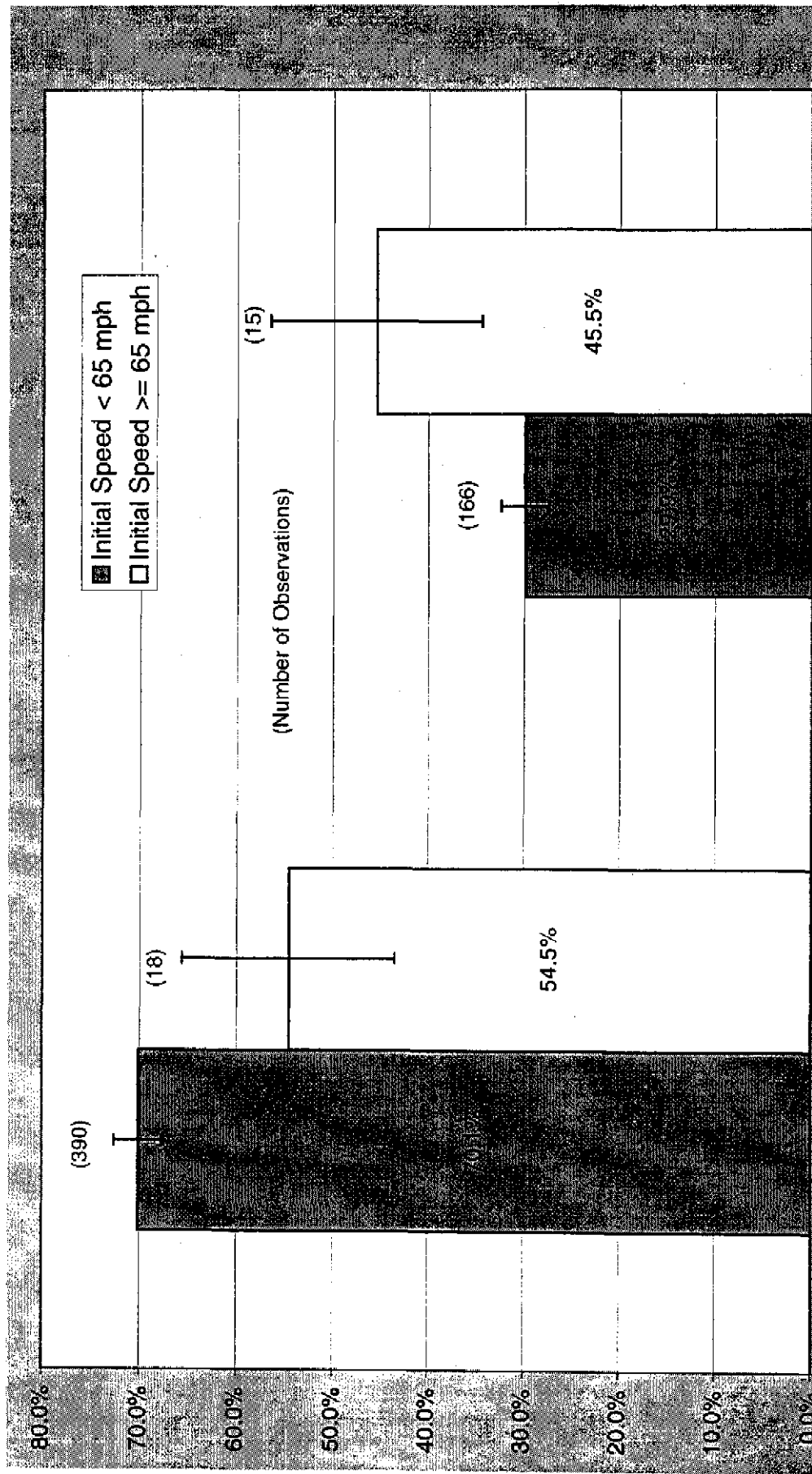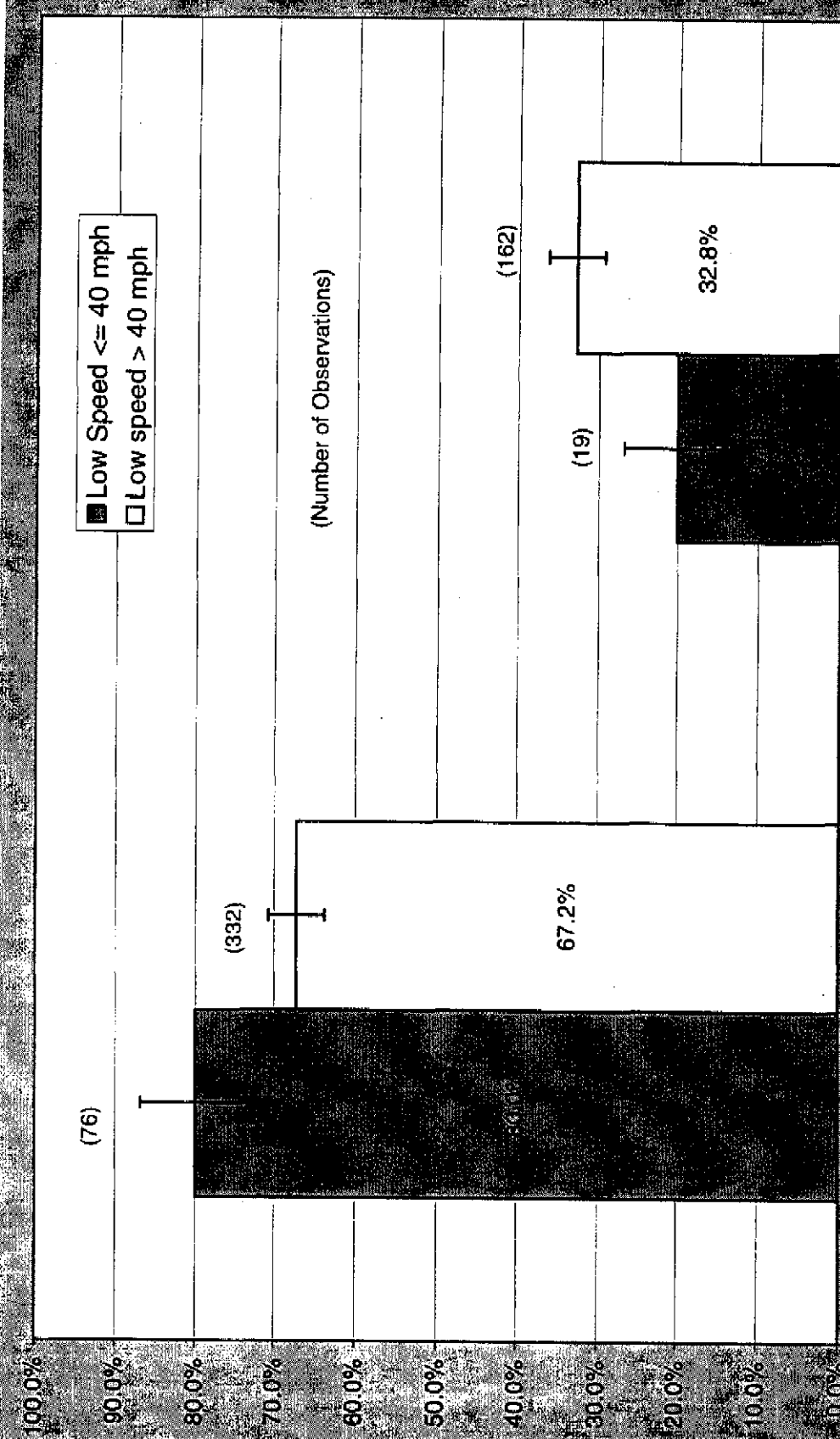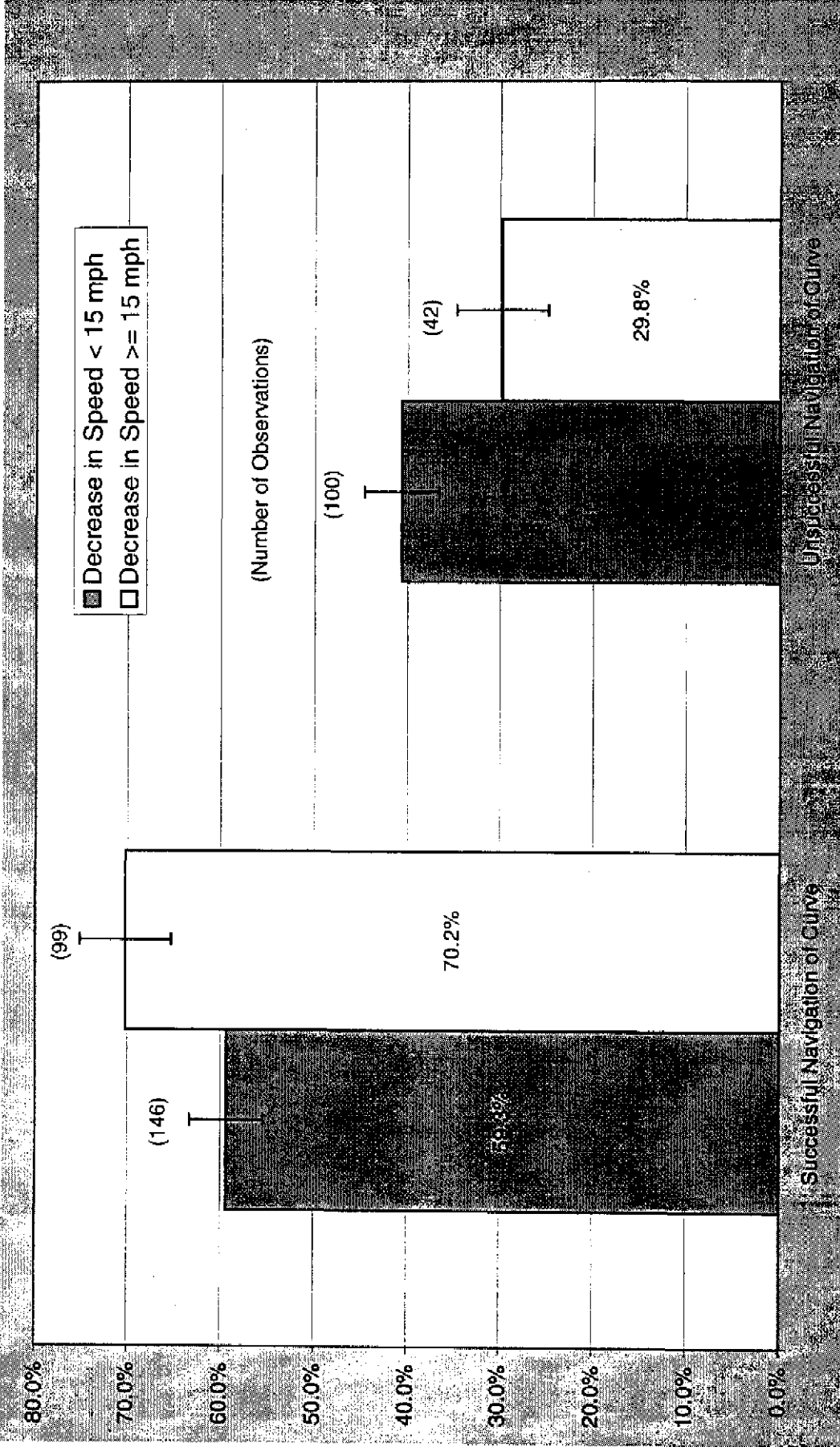| Sign Category	Number of Vehicles	Average Initial Speed (mph)	Average Highest Speed (mph)	Average Lowest Speed (mph)	$\triangle_1$ (mph)	$\triangle_2$ (mph)
1	733	56.9	58.4	46.4	10.6	12.1
2	759	57.0	58.5	46.2	10.8	12.3
3	1533	56.7	58.0	46.5	10.2	11.5

Sign Category
1 - Static Curve Ahead Warning Sign + LED "CURVE AHEAD" Message
2 - Static Curve Ahead Warning Sign + Alternating LED "CURVE AHEAD" / "REDUCE SPEED" Message
3 - Static Curve Ahead Warning Sign

$\triangle_1$ - Difference between Average Initial Speed and Average Lowest Speed

$\triangle_2$ - Difference between Average Highest Speed and Average Lowest Speed

Miles Per Hour (MPH)

Legend:
- 1 - Static Curve Ahead Warning Sign + LED "CURVE AHEAD" Message
- 2 - Static Curve Ahead Warning Sign + Alternating LED "CURVE AHEAD" / "REDUCE SPEED" Message
- 3 - Static Curve Ahead Warning Sign

Ave Initial Speed: 56.9, 57.0, 56.7
Ave High Speed: 58.4, 58.5, 58.0
Ave Low Speed: 46.4, 46.2, 46.5
Ave Initial Speed - Ave Low Speed: 10.6, 10.8, 10.2
Ave High Speed - Ave Low Speed: 12.1, 12.3, 11.5

Axis values: 70.0, 60.0, 50.0, 40.0, 30.0, 20.0, 10.0, 0.0

Figure 6-9
Speed Values on the Approach to the Horizontal Curve
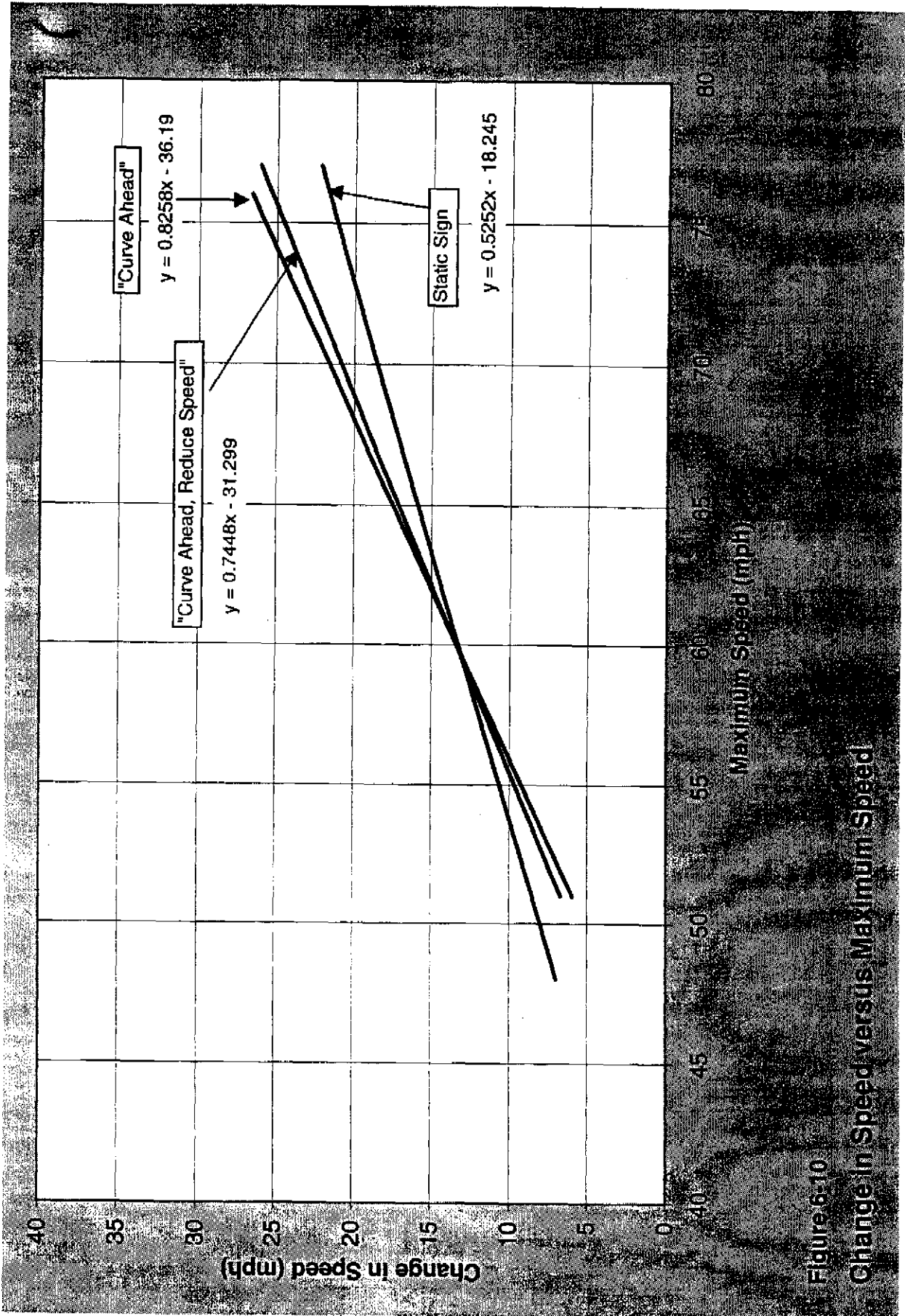
Figure 6-10
Change in Speed versus Maximum Speed

56
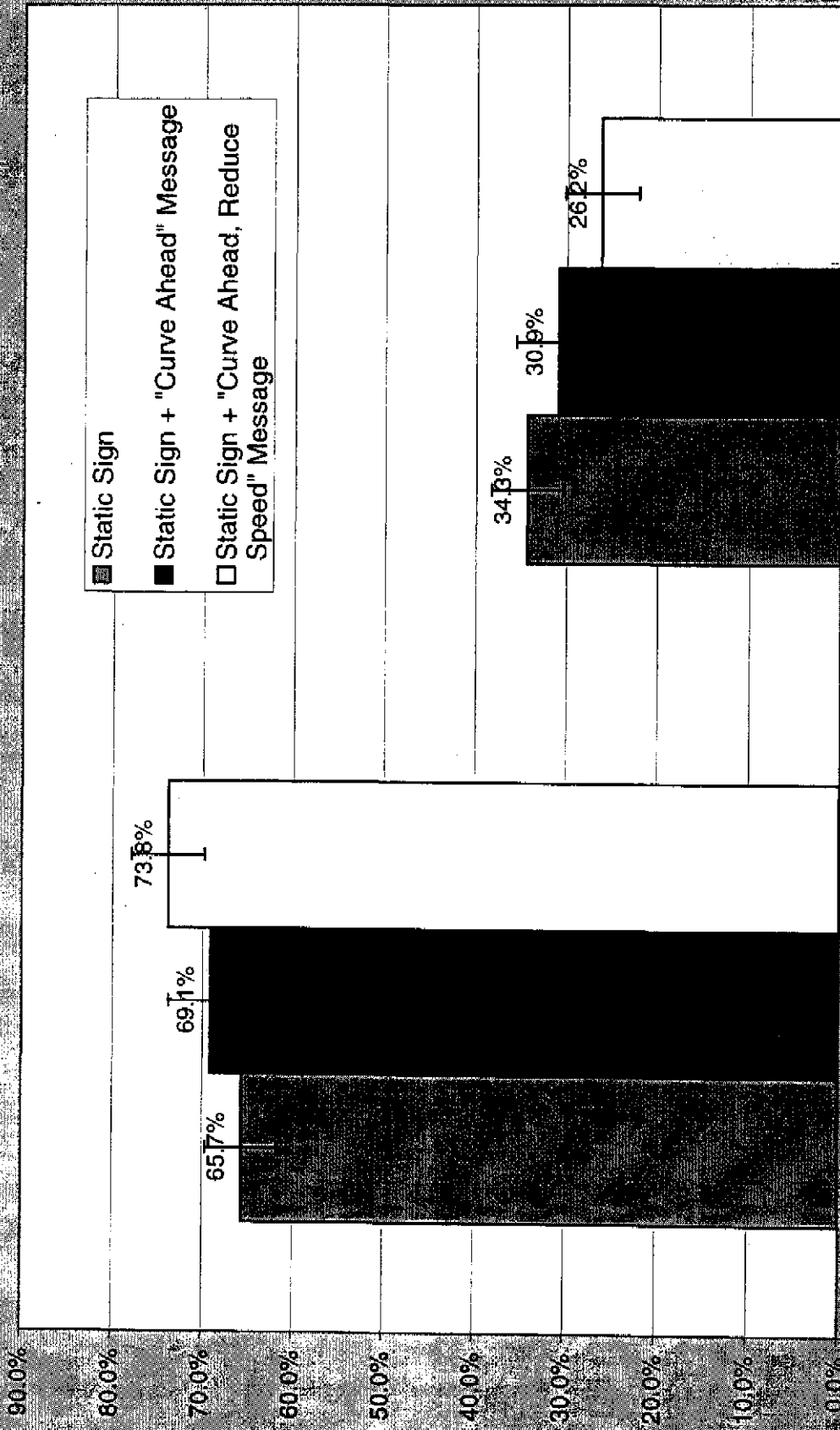
Figure 6-11. Comparison of the Effectiveness of the Warning Signs

Legend:
- Static Sign
- Static Sign + "Curve Ahead" Message
- Static Sign + "Curve Ahead, Reduce Speed" Message

Successful Navigation of Curve:
- 65.7%
- 69.1%
- 73.8%

Unsuccessful Navigation of Curve:
- 34.3%
- 30.9%
- 26.2%

7.0 Conclusions

Literature Search

1. The most common device used by engineers to warn motorists of highway curves is the CURVE AHEAD sign with a speed advisory plate.

2. Most speed advisories are determined by either the ball-bank indicator or the nomograph in the TCDH, and these methods produce results that are not valid for modern vehicles.

3. The use of speed advisories is not very effective in actually reducing vehicles speeds to the posted advisory speed.

4. Dynamic speed signs appear to have a greater effect on driver performance than static signs.

Survey of Practice

5. The most common device used in Minnesota to warn motorists on highway curves is the CURVE AHEAD sign with a speed advisory plate.

6. Most agencies in Minnesota use the guidance in the MMUTCD regarding the design and installation of curve warning devices.

7. Cities and counties do not have a common definition of exactly how many crashes it takes to constitute a hazardous curve. However, the number one mitigative measure is realigning the curve followed by installing additional signs and/or pavement markings if cost is a factor.

8. Most agencies indicated that the dynamic curve warning system would be a useful addition to the safety toolbox.

Equipment

9. The hardware and software necessary to conduct the research was assembled using off-the-shelf technology and devices. The package of hardware and software is totally self-contained and, therefore, could be deployed along any rural roadway.

10. The total cost of the hardware and software package is estimated to be approximately $50,000. However, an agency could deploy the changeable message sign and radar unit (the components necessary to perform dynamic curve warning) for approximately $10,000.

Analysis and Field Data Results

11. Speed data was collected for approximately 2,650 vehicles and almost 600 vehicles were tracked through the curve and captured on videotape.

12. Also, of the 600 vehicles that were tracked through the horizontal curve, 180 were unable to successfully navigate through the curve (regardless of speed). Of these 180 vehicles, 179 were observed driving on or to the left of the centerline (tracking to the inside of the curve), and only one vehicle was observed driving onto the right shoulder (tracking to the outside of the curve).

13. The data suggests and the statistical tests confirm that the initial speed of a vehicle prior to entering a curve does have a statistically significant effect on the probability of successfully navigating through the curve.

14. The overall effect of the dynamic warning system on vehicle speeds was relatively small. However, the dynamic system had a much greater effect on high speed vehicles and significantly improved the ability of these vehicles to successfully navigate through the curve.

APPENDIX A

SURVEY DISTRIBUTED TO
LOCAL ROAD AUTHORITIES

Minnesota Department of Transportation
Survey Form
Dynamic Signing at Rural Horizontal Curves

Agency: _____   Date: _____

Survey Completed By: _____
(*Please print*)   Name   Title

Phone Number_____

Please answer the following questions regarding advance warning signs and design and safety at **rural** horizontal curve locations.

1) What warning devices does your agency currently use at horizontal curves? (Circle all that apply)

a) Curve sign b) Sign mounted flashers c) Chevrons   d) Speed Advisory

        d) Other _____
                Please Describe

2) Does your agency have warrants or guidelines for the installation of curve warning signs, speed advisory signs, or other signage? *If other, please attach copy*

a) MMUTCD   b) No   c) Other

3) If sign mounted flashers are used, how do they operate?

a) Continuously   b) Time of day   c) Other _____
                                    Please describe

4) What other methods have you used to address hazardous curve locations? (Circle all that apply)

a) Geometric improvements
b) Additional signage
c) Pavement markings
d) Lighting
e) Shoulder rumble strip
f) Other _____
                Please describe

5) What kind of shoulder is "typically" used along horizontal curves?

a) Bituminous b) Concrete   c) Gravel   d) Other _____
                             Please describe

6) What is the "typical" width of the shoulders in the curve areas?

a) Less than 4' b) 4' – 6'   c) More than 6'   d) Other _____
                             Please describe

7) What, in your opinion, are contributing reasons a vehicle may go off of the roadway on a horizontal curve?

a) Pavement/weather conditions   b) Poor or faded signing   c) Lack of pavement markings

d) Vehicle speed   e) Other _____   *Please describe*

8) How many crashes on horizontal curves would need to occur in order for the curve to be considered hazardous?

a) 1 per year   b) 2 per year   c) 3 per year   d) Other _____

9) Also needed is a list of potential problem horizontal curve locations for an analysis of the safety impacts of a dynamic advance warning sign. *If more than one, please attach a copy.*

Location: _____

Reference Point: _____

10) Do you believe a system that provides a motorist a warning message if he/she is above what is considered the safe speed limit or driving outside the boundaries of the roadway lane on horizontal curves would be useful in the reduction of accidents involving vehicles running off the road?

a) Yes   b) No

11) What are your general impressions of potential uses, applications, and advantages/disadvantages of a dynamic curve warning sign? (By our definition, a dynamic curve warning sign would be a sign that only activates itself when a vehicle exceeds a set criterion established for the horizontal curve.)

_____

_____

_____

_____

_____

_____

_____

12) Do you want to receive a copy of the Final Report?

a) Yes   b) No

    Questions? Please Contact: Rick Beck
                    Mn/DOT – Office of Traffic Engineering
                    1500 W. County Road B2, Suite 250
                    Roseville, MN 55113
                    (651) 582-1038

APPENDIX B

CALCULATIONS FOR STATISTICAL ANALYSES

Date: December 14, 1999

To: Howard Preston

From: Gary A. Davis

Subject: Logistic Regression Model for Curve Data

Dear Howard,

I've completed and analysis of some of the data Ted sent over. I used data contained in the Excel worksheet 'ini_65.xls' and made to following assumptions:

      (a) the column 'Initial Speed' gave each vehicle's initial speed on approaching the curve

      (b) the column '# of N's' contained the value 1 if the vehicle failed to negotiate the curve properly.

I'll use the term 'encroachment' to refer to an unsuccessful negotiation.

I used logistic regression analysis to model the relationship between initial speed and the probability of encroachment. This is a method frequently used in medical and health science research to model, for example, the relationship between the dose of a toxin and the probability of dying. Technical details can be found in chapters 4 and 13 of the book *Categorical Data Analysis*, by Alan Agresti.

The general form of the model used was

$$Prob[encroachment] = \frac{e^{b_0 + b_1(v - \mu)}}{1 + e^{b_0 + b_1(v - \mu)}}$$

where

      b_0, b_1 = parameters to be estimated

      v = vehicle's initial speed in mph

      μ = mean initial speed in mph

Estimates and standard errors for the model parameters were:

Parameter	Estimated Value	Standard Error of Estimate
b_0	-0.846	0.092
b_1	0.095	0.021
μ	57.4	0.174

Of particular interest is a test of the null hypothesis

$$H_0: b_1 = 0$$

against the alternative

$$H_1: b_1 \neq 0$$

since acceptance of the null hypothesis would imply that initial speed has no effect on the probability of encroachment. A t-test gives

$$t = \frac{\hat{b}_1 - 0}{s_e} = \frac{.095 - 0}{.021} = 4.497$$

Since the probability of obtaining t>4.497 when H_0 is true is less than .001, we reject the null hypothesis and conclude that initial speed has a statistically significant effect on the probability of encroachment.

I'm sending another copy of this report by surface mail, along with MATHCAD documents detailing my calculations. If you have any questions, feel free to contact me.

Logistic Regression Model of Probability of Encroachment As a Function of Initial Speed

ORIGIN $\equiv$ 1

I. Data Input

Read data from file extracted from 'ini_65.xls'

$X := \text{READPRN}\left(\text{curve1}_{txt}\right)$

$N := \text{rows}(X)$

$N = 588 \qquad i := 1 .. N$

$vi := X^{<3>} \qquad\qquad y := X^{<7>}$

vi = initial speed (mph) y = 0, if no encroachment
                                              1, if encroachment

$\text{mean}(vi) = 57.412$

$\text{stdev}(vi) = 4.225$ $\text{mean}(y) = 0.306$

$\text{max}(vi) = 76$

$\text{min}(vi) = 48$ $\sum y = 180$

2. Empirical estimates of speed/encroachment relationship
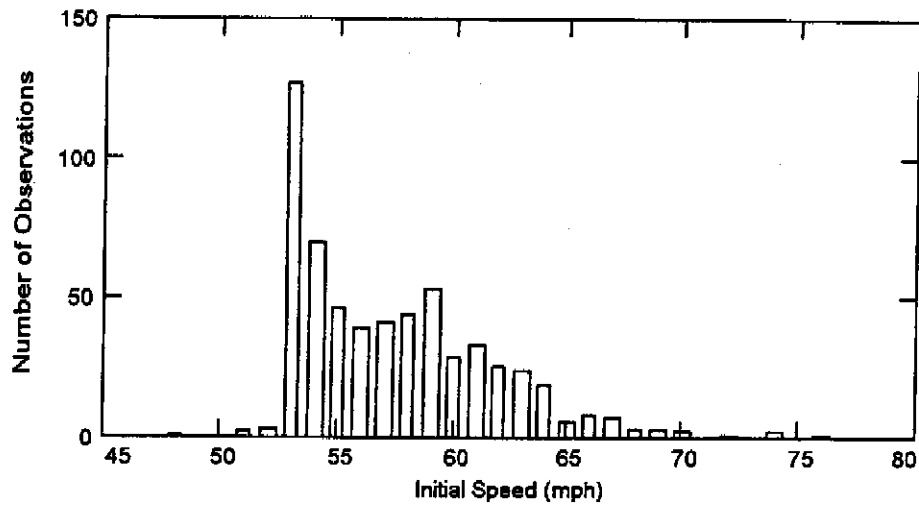
Determine range of initial speeds

$vrange := \text{max}(vi) - \text{min}(vi) \qquad vrange = 28$

$k := 1 .. vrange + 1$

Determine number of observations at each initial speed

$$n_k := \sum_i \text{if}\left[vi_i = \text{min}(vi) + (k-1), 1, 0\right]$$
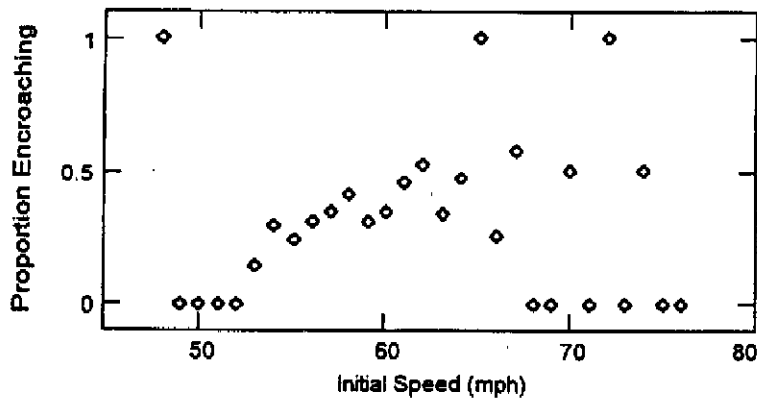
Histogram of initial speed distribution

Determine number of encroaching vehicles at each initial speed

$$x_k := \sum_i \text{if}\left[\left[vi_i = \min(vi) + (k-1)\right] \cdot \left(y_i = 1\right), 1, 0\right]$$

Determine proportion encroaching at each initial speed

$$pe_k := \frac{x_k}{n_k}$$

Plot proportion encroaching at each initial speed

B-4

3. Maximum Likelihood Estimation of Logistic Regression Model

Define independent variable of deviation of initial speed from mean initial speed

$$v_i := vi_i - \text{mean}(vi)$$

Define logistic probability function

$$p(b0, b1, vv) := \frac{\exp(b0 + b1 \cdot vv)}{(1 + \exp(b0 + b1 \cdot vv))}$$

Define log likelihood function

$$\text{loglik}(b0, b1) := \sum_i \left[y_i \cdot \ln\left(p\left(b0, b1, v_i\right)\right) + \left(1 - y_i\right) \cdot \ln\left(1 - p\left(b0, b1, v_i\right)\right) \right]$$

Solve likelihood equations for maximum likelihood estimates of parameters

Initial values $bb0 := .2$ $bb1 := 0$

Log liklihood at initial values $\text{loglik}(bb0, bb1) = -433.306$

Given

$$\sum_i \left(y_i - p\left(bb0, bb1, v_i\right)\right) = 0$$

$$\sum_i \left(y_i - p\left(bb0, bb1, v_i\right)\right) \cdot v_i = 0$$

$$\binom{b0l}{b1l} := \text{Minerr}(bb0, bb1)$$

$$ERR = 9.691 \cdot 10^{-14}$$

Maximum likelihood estimates $b0l = -0.846$ $b1l = 0.095$

Maximum log likelihood $\text{loglik}(b0l, b1l) = -351.805$

Compute Hessian matrix of log likelihood

$$H_{1,1} := -\left[\sum_i p(b0I, b1I, v_i) \cdot (1 - p(b0I, b1I, v_i))\right]$$

$$H_{1,2} := -\left[\sum_i p(b0I, b1I, v_i) \cdot (1 - p(b0I, b1I, v_i)) \cdot v_i\right]$$

$$H_{2,2} := -\left[\sum_i p(b0I, b1I, v_i) \cdot (1 - p(b0I, b1I, v_i)) \cdot (v_i)^2\right] \qquad H_{2,1} := H_{1,2}$$

$$H = \begin{pmatrix} -120.355 & -62.756 \\ -62.756 & -2.259 \cdot 10^3 \end{pmatrix}$$

Compute parameter covariance matrix

$$C := \left[-H^{(-1)}\right]$$

$$C = \begin{pmatrix} 0.008 & -2.342 \cdot 10^{-4} \\ -2.342 \cdot 10^{-4} & 4.492 \cdot 10^{-4} \end{pmatrix}$$

Correlation between parameters

$$r := \frac{C_{1,2}}{\sqrt{C_{1,1} \cdot C_{2,2}}}$$

$$r = -0.12$$

Standard errors

$$s0 := \sqrt{C_{1,1}} \qquad\qquad s1 := \sqrt{C_{2,2}}$$

$$s0 = 0.092 \qquad\qquad s1 = 0.021$$

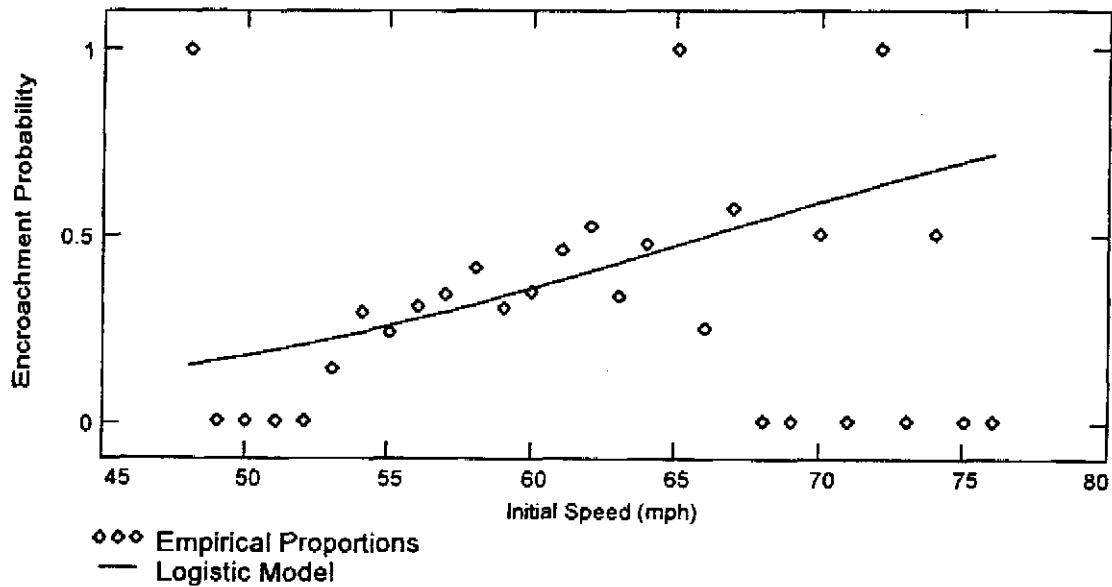t-tests for difference between estimated parameters and zero

$$t0 := \frac{b0I}{s0} \qquad\qquad t1 := \frac{b1I}{s1}$$

$$t0 = -9.209 \qquad\qquad t1 = 4.497$$

4. Compare Logistic Regression Model to Empirical Encroaching Proportions

$$plogit_k := p(b0I, b1I, min(vi) + (k - 1) - mean(vi))$$

Plot empirical and logistic estimates of encroachment probability

○○○ Empirical Proportions
── Logistic Model

5. Plot Logistic Regression Function Over a Wider Speed Range

$j := 1 .. 100$
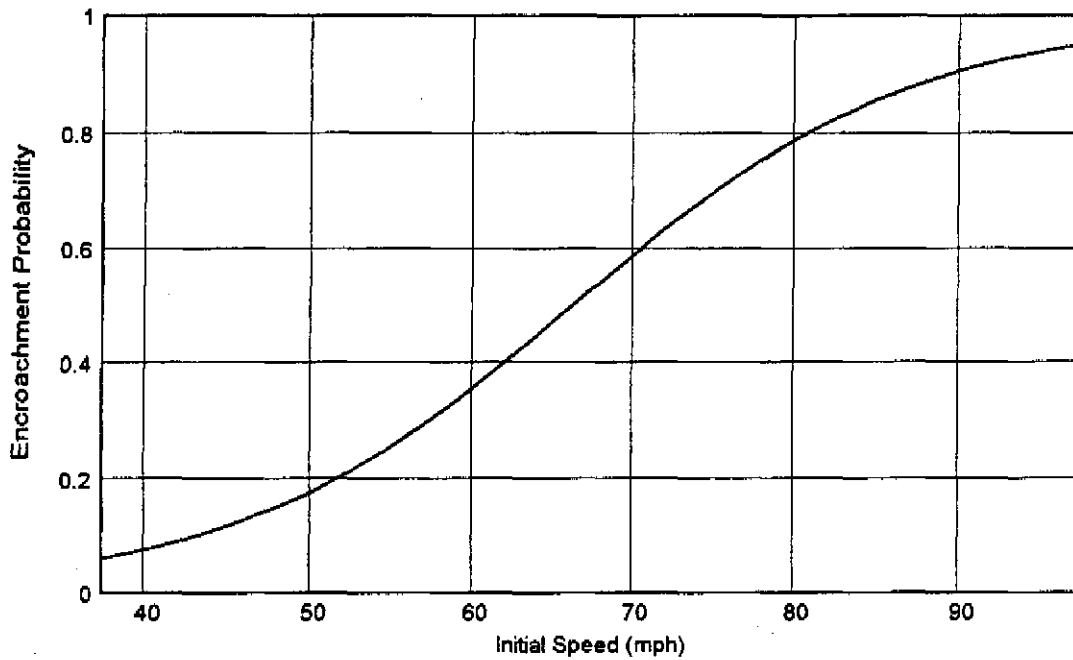
$lower := mean(vi) - 20$ $upper := mean(vi) + 40$

$$delta := \frac{upper - lower}{100}$$

$vplot_j := lower + delta \cdot (j - 1)$

$pv_j := p\left(b0I, b1I, vplot_j - mean(vi)\right)$

November 11, 1999

Dear Howard,

With regard to your data on "Successful Navigation of Horizontal Curves," let p1 denote the probability of an unsuccessful navigation at the lower speed, and p2 denote the probability of an unsuccessful navigation at the higher speed. We would like to test the null hypothesis

> H0: p1=p2

against the alternative

> H1 p1≠p2.

For 2x2 tables, this is most commonly done using the odds-ratio. p1/(1-p1) is the odds of unsuccessful navigation at the lower speed, p2/(1-p2) is the odds of unsuccessful navigation at the higher speed, so the odds ratio is

$$R=[p1/(1-p1)]/[p2(1-p2)] = [p1(1-p2)]/[(1-p1)p2]$$

and one can see that if the null hypothesis is true, R=1.0. Ted sent me the tabulated data

	Unsuccessful	Successful
Lower Speed	31	119
Higher Speed	54	96

The estimated odds ratio for these data is

$$R =[(31)(96)]/[(54)(119)] = 0.463$$

To test the null hypothesis

> H0: p1=p2 → R=1.0

we use the fact that, when the null hypothesis is true, for moderately large sample sizes the natural logarithm of the estimated odds ratio is approximately distributed as a normal random variable, with a mean equal to ln(1.0)=0, and a variance that can be estimated as

$$s^2 = (1/31) + (1/119) + (1/54) + (1/96)$$

The resulting z-statistic is

$$\hat{z} = \frac{\ln\left(\dfrac{(31)(96)}{(119)(54)}\right) - 0}{\sqrt{\dfrac{1}{31} + \dfrac{1}{96} + \dfrac{1}{119} + \dfrac{1}{54}}} = -2.91$$

From a table of probabilities for the standard normal distribution, one can see that if the null hypothesis were true, Probability[$|z| > 2.91$] = .0036. Since this is extremely unlikely, we would reject the null hypothesis, and conclude that $p1 \neq p2$. As for interpreting this result, the estimated probability of unsuccessful navigation of the lower speed vehicles is (31/150)=0.207, while the estimated probability of unsuccessful navigation for the higher speed vehicles is (54/150)=0.360. So while approximately 1 out of 5 lower speed vehicles has trouble with the curve, more than 1 out of 3 higher speed vehicles has trouble.

Confidence intervals for these individual estimates can be computed using the fact that their standard errors can be estimated using the formula $[(p(1-p))/n]^{1/2}$ For the low-speed group, the standard error would be $[(.207(1-.207))/150]^{1/2} = .033$, and a 95% confidence interval for the probability of unsuccessful navigation would be

$$[.207-(1.96)(.033), .207+(1.96)(.033)] = [0.142, 0.272].$$

For the high speed group, the standard error is $[(.360(1-.360))/150]^{1/2} = .039$, and a 95% confidence interval would be

$$[.360-(1.96)(.039), .360+(1.96)(.039)] = [0.284, 0.436].$$

With regard "Speed Reduction on Approach to Horizontal Curve," I would suggest simply computing confidence intervals for various speed reductions and displaying these on a graph. This would required computing estimated standard errors, which cannot be done from the information in the table I received. For a more formal test significant differences, I would recommend using a technique called analysis of covariance. This would involve fitting a linear regression model of the form

$$yi = (b0) \ xi + (b1) \ zAi + (b2) \ zBi + (b3) \ zCi$$

yi = Lowest speed for vehicle i
xi = Initial speed for vehicle i
zAi =   1, for category A vehicles
        0, otherwise
zBi =   1, for category B vehicles,
        0, otherwise
zCi =   1, for category C vehicles
        0, otherwise.
b0, b1, b2 and b3 = regression coefficients.

The coefficient b1 would be the average speed for category A vehicles, after controlling for initial speeds, b2 would give the average speed for category B, after controlling for initial speed, and similarly for b3. Testing whether or not any differences were significantly different from zero would involve comparing the fit of the above model to restricted models embodying the appropriate null hypotheses. This can be done with almost any standard statistics package. I could show Ted how to do this, or if you want to provide me with the original measurements, if could do it for you.