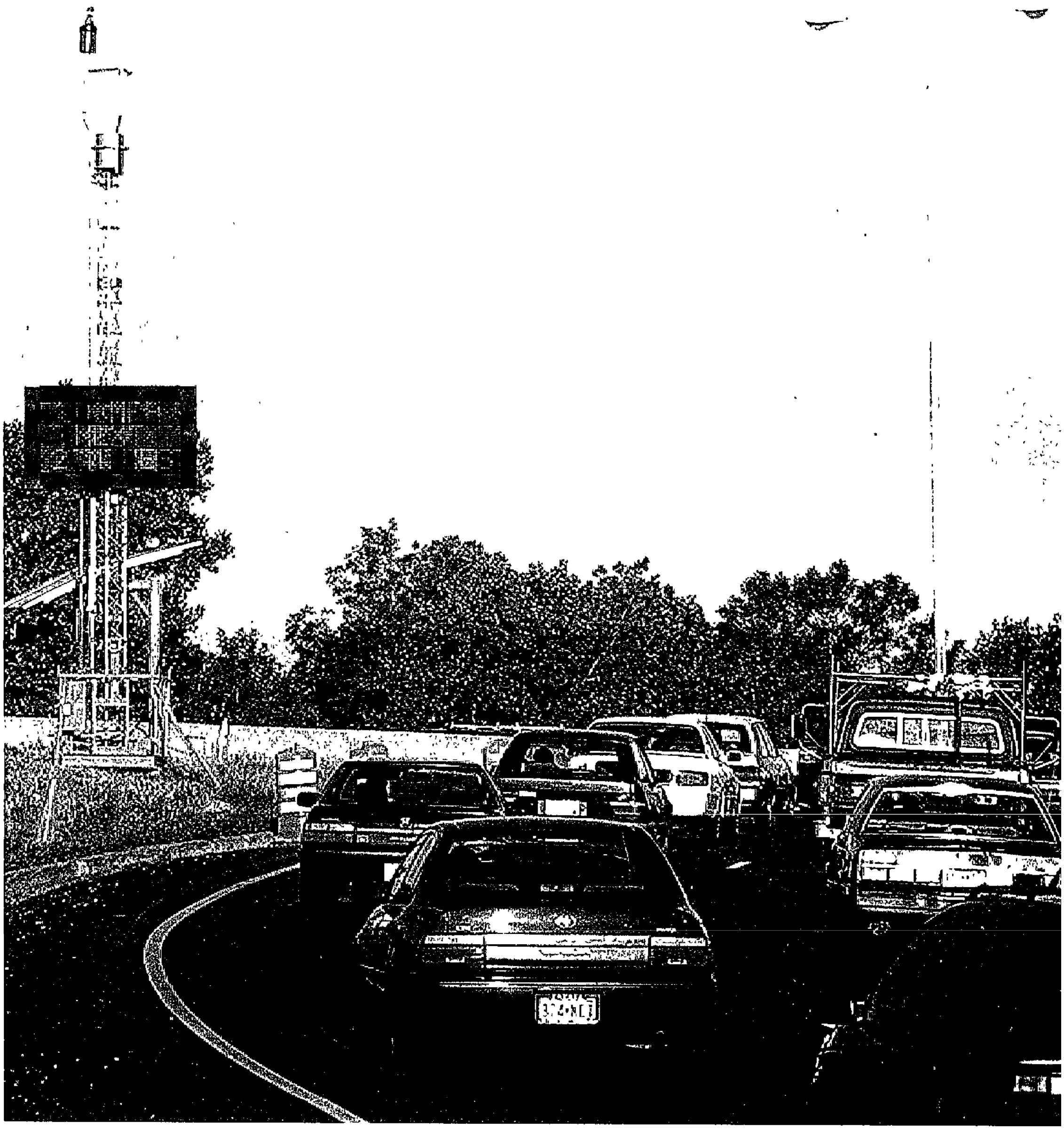
Portable Traffic Management System Smart Work Zone Application

Operational Test Evaluation Report



Minnesota Guidestar

MINNESOTA DEPARTMENT OF TRANSPORTATION

May 1997

PORTABLE TRAFFIC MANAGEMENT SYSTEM

SMART WORK ZONE APPLICATION

OPERATIONAL TEST EVALUATION REPORT

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Prepared For:

MINNESOTA DEPARTMENT OF TRANSPORTATION

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INTRODUCTION

As part of its statewide Intelligent Transportation System (ITS), The Minnesota Department of Transportation (Mn/DOT) sponsored an operational test of the Portable Traffic Management System (PTMS) in a work zone application in cooperation with its private sector partners. The overall goal of the operational test was to provide useful real-time information to motorists about the traffic conditions as they approach and pass through the work zone. The intended purpose of providing the real-time information in the work zone is to improve safety for motorists, improve safety for construction personnel and to minimize the work zone related delays experienced by motorists. As a federally-approved ITS operational test, this independent evaluation was required.

BACKGROUND

The work zone application of the PTMS is the logical extension of the PTMS concept that was originally developed to help handle traffic at major sporting events at the National Sports Center (NSC) and other major events in the Twin Cities. It was intended to provide a means to control periodic traffic congestion problems resulting from major events where the traffic problems are not frequent enough to justify major upgrading of facilities. This portable system was developed as a traffic management system that could be easily moved and adapted to a number of event locations. An operational test was conducted on the original PTMS and the results are summarized in "Portable Traffic Management System, Final Evaluation Report" dated July 13, 1995, by Castle Rock Consultants and available from both Mn/DOT and FHWA.

Following the successful test of the PTMS concept, it was decided that this same basic concept may be applicable to some work zone applications. The intent was to improve the' safety of workers and motorists in work zones and while maintaining adequate traffic flow by providing real-time traffic information to drivers.

The basic PTMS was upgraded using new technologies. These technologies include machine vision (video image processing) and wireless communication systems to provide even more flexibility in obtaining and relaying real-time traffic data.

The goals for the PTMS Work Zone Application Operational Test project were as follows:

- Develop a system that will improve traffic flow through the work zone.
- Develop a system to provide real-time traffic flow information to motorists approaching the work zone.
- Develop a system that will increase safety for motorists and construction personnel.
- Develop a system that is truly portable and adaptable to various construction projects.
- Develop a system that can be integrated with local traffic management systems.
- Develop a system that promotes public acceptance by providing pertinent and true real-time traffic information.
- Develop a cost-effective system.
- Develop the partnerships, both public and private, necessary to enable the successful development and implementation of a PTMS in a work zone application.

The PTMS Work Zone Application was developed through a public/private partnership agreement. Contributions were made by FHWA, Mn/DOT and ADDCO, Inc.

System Design

The PTMS Work Zone Application is an integration of existing and emerging traffic management technologies into a complete portable traffic control system. The system is portable, wireless and able to withstand the elements in the work zone. It provides traffic engineers with data such as speeds, volumes and incident detection so that decisions can be made and communicated to the traveling public. The system consists of four basic subsystems:

- Vehicle Detection/Surveillance
- Traffic Control Center
- Driver Information
- Communications

The PTMS Work Zone Application consists of portable skids housing various sub-systems to serve as work zone nodes. The nodes are placed in strategic locations in the work zone and linked together by spread spectrum radio. The nodes can include both vehicle detection devices and driver information devices. The PTMS skid deployed in the work zone with both types of devices installed is shown in Figure 1in the full report.

The vehicle detection/surveillance subsystem consists of video cameras placed at strategic locations. The portable machine vision provides data such as traffic volume, speed, incident detection and vehicle intrusion into the work zone.

The data from the vehicle detection/surveillance subsystem is transmitted to the Traffic Control Center. The data is reviewed by system operators and traffic control changes are made to improve traffic flow through the work zone. These traffic control changes are made by relaying messages to the motorist through the Driver Information subsystem consisting of full-size portable, variable message signs (VMS) and smaller work zone portable variable message signs. The information can also be made available to the public on a World Wide Web page via the Internet.

The communications subsystem relies on spread spectrum radio, cellular phone and Integrated Services Digital Network (ISDN). Each of these communication devices is used for specific links in the project.

SUMMARY OF RESULTS AND CONCLUSIONS

Overall, the operational test of the PTMS in a work zone application was successful. There were some problems encountered with the wireless communications system that indicated care must be taken in the siting of the PTMS nodes and in the configuration of the wireless communications system within the work zones. However, the overall system was relatively easy to deploy and operate, it showed beneficial effects on traffic and was well received by the motorists.

The PTMS is currently being deployed in three locations. Two PTMS nodes are deployed at I-94 in the area of former work zone to provide the TMC with video surveillance. The PTMS continue to be used for this function on this high volume freeway segment until the permanent video surveillance equipment is installed. Also, Maryland Department of Transportation is testing the PTMS for its remote surveillance capabilities.

The PTMS has recently been deployed as part of a major bridge reconstruction project. The PTMS was included in the contract specifications for traffic control on the project so this is a full deployment rather than an operational test. The PTMS was specified on the basis of unit cost per day. The system consists of two PTMS nodes, each with VMS, Autoscope and surveillance cameras. In addition, there are five trailer mounted VMS. The trailer mounted VMS used in this operational test had standard cellular phone connections for communications. This is a relatively slow process for transmitting the data needed to operate the trailer VMS. The communications has been revised for this deployment to be via Cellular Digital Packet Data (CDPD) which provides a much faster communications link for more rapid response to changing traffic conditions.

Analysis of Traffic Impacts

- There was a significant increase in the traffic volume that moved through the work zone when the PTMS was in operation (3.6 percent higher in the morning peak period and 6.6 percent higher in the afternoon peak period). The more orderly flow of traffic appears to have resulted in increased capacity.
- There was a significant decrease in the traffic volume that exited I-94 to TH 280 in the afternoon peak period (5.3 percent lower). This is likely due to increased driver confidence in traveling through the work zone because of the real-time traffic information provided by the PTMS.
- The PTMS decreased the variability in speed for traffic traveling within the work zone by over 70 percent which suggests improved safety.
- The PTMS decreased the average speed for traffic approaching the work zone by 9 miles per hour which also suggests an improvement in safety as vehicles approaching the work zone slowed down sooner.

Analysis of System Operation

- PTMS can be deployed in a wide variety of work zones with relative ease.
- The actual time to prepare, deploy and set up each node is relatively short, especially given the complexity of the PTMS equipment and its capabilities.
- The PTMS is a unit that would be set up in work zones with special traffic needs.
- The PTMS was successfully installed and operated at the TMC.
- The PTMS was developed using TCP/IP communications protocols to simplify integration into existing TMCs.
- The overall system operation was successful.
- The machine vision cameras mounted high on the towers require care that construction activities do not inadvertently cause the skids to move.
- The Autoscope setup is not complex but requires some special training.
- The PTMS video and data can be successfully transmitted over spread spectrum radios.
- Care must be taken in siting the nodes to avoid multipath interference problems.

Analysis of User Reaction

- 66 percent of the drivers surveyed remembered seeing the lighted PTMS VMS messages.
- Of those remembering the PTMS VMS messages, most remembered specific messages and felt more informed about traffic conditions.
- Of the specific messages remembered, very high percentages were considered easy to read, easy to understand, useful and to correctly reflect traffic conditions.
- System operators indicated that the PTMS could be mastered in 2 to 3 hours, was easy to operate and was reliable.
- Transit operators said the video surveillance feature would be very useful for rerouting buses from work zones with significant delays.
- Focus groups called for real-time traffic information that was easy to read and the motorist survey indicated the PTMS was successful in these respects.

Analysis of System Costs

- The cost of a operational PTMS depends on the number of PTMS nodes needed and the additional optional equipment needed.
- The cost for a basic PTMS with all necessary communications equipment is $78,850.
- Additional basic nodes would cost $59,850.
- Deployment cost will vary based on PTMS delivery distance, number of PTMS nodes and ISDN installation cost and monthly charges.
- The feature being developed to automatically change sign messages based on speeds detected will significantly reduce staff time to operate the system.

PORTABLE TRAFFIC MANAGEMENT SYSTEM
SMART WORK ZONE APPLICATION
OPERATIONAL TEST EVALUATION REPORT

1.0 INTRODUCTION

1.1 Overview Of The Operational Test

As part of its statewide Intelligent Transportation System (ITS), the Minnesota Department of Transportation (Mn/DOT) and its private sector partners, sponsored the operational test of the Portable Traffic Management System (PTMS) in a work zone application. The overall goal of the operational test was to provide useful real-time information to motorists about traffic conditions as they approach and pass through a work zone. The intended purpose of providing the real-time information in a work zone is to improve safety for motorists, improve safety for construction personnel and minimize the work zone-related delays experienced by motorists.

As a federally-approved ITS operational test, an independent evaluation was required. The evaluation plan for the PTMS Work Zone Application Operational Test was developed in accordance with Minnesota Guidestar guidelines. These guidelines were based on guidelines developed for the Federal Highway Association (FHWA) by the Mitre Corporation and for the Federal Transit Administration (FTA) by the Volpe National Transportation System Center. This final report presents the summary of the evaluation results.

1.2 Structure Of The Report

Chapter 1 introduces the project and describes the basic concept of the PTMS Work Zone Application. It also summarizes the structure of the report.

Chapter 2 of this report presents the project background, the history of the project and the basics of the PTMS system design for its application in work zones. Chapter 2 also describes the basic operational test.

The approach of the evaluation is described in Chapter 3. The overall evaluation strategy describes the general steps of the evaluation process. The deployment of the PTMS at two work zone sights is described. The changes required as part of the ongoing development of the PTMS for the work zone applications, both changes specifically required for operation at the two sights as well **as** the general development of the system are described. The goals, measures of effectiveness (MOEs), and the methods used to collect the data used in the evaluation process are then discussed. The four individual tests performed to evaluate various aspects of the system are described.

Chapter 4 describes the two work zone sights where the PTMS was deployed during the operational test. It also discusses the basic strategies of operation used in the operational test at the two sights.

Chapter 5 presents the results of Test One - Traffic Operations. This test focused on the affect of the PTMS on traffic operations in the work zone.

Chapter 6 presents the results of Test Two - System Operation. This test focused on the overall operational aspects of the PTMS within the work zones.

Chapter 7 presents the results of Test Three - User Reaction. This test focused on the reaction of the motorists, system operators, construction personnel and transit operation personnel to the real-time traffic information and perceived effects of the PTMS.

Chapter 8 presents the results of Test Four - System Costs. This test focused on the costs to deploy the PTMS in a work zone.

Chapter 9 presents a discussion of the lessons learned in the deployment and operation of the PTMS in the two work zones. It also includes a discussion of the key issues that need to be resolved for future deployment of the system.

Chapter 10 presents a summary of the results and conclusions drawn from the evaluation of the PTMS in the two work zones.

2.0 BACKGROUND

2.1 Project History

The work zone application of the PTMS is the logical extension of the PTMS concept that was originally developed to help handle traffic at major sporting events at the National Sports Center (NSC) and other major events in the Twin Cities. It was conceived as a response to periodic traffic congestion problems resulting from major events generating significantly more traffic than typically occurs at the locations. These traffic problems were not sufficient to support major upgrading of facilities for periodic events, but did warrant better traffic control during those events. This portable system was developed as a traffic management system that could be easily moved and adapted to a number of event locations. An operational test was conducted on the original PTMS and the results are summarized in “Portable Traffic Management System, Final Evaluation Report” dated July 13, 1995, by Castle Rock Consultants and is available from both Mn/DOT and FHWA. Following the successful test of the PTMS concept, it was decided that the same basic concept may be applicable to some work zone applications in conjunction with the use of additional advanced technologies.

Improving the safety of workers and motorists in work zones and maintaining adequate traffic flow in work zones has become increasingly important as the emphasis has shifted from constructing new highways toward maintenance and reconstruction of existing facilities.

The Interstate Highway System is now substantially complete. Much of the system infrastructure has reached its design life and is in need of repair and upgrading to meet current standards. Many of the facilities in need of upgrading are highly congested segments of the system, so traffic management during construction is a prime concern. The FHWA and Mn/DOT are continuing to focus on developing even better ways to improve motorist and worker safety in work zones while minimizing traffic congestion on the overall transportation system.

Management of construction traffic has steadily improved over the years with the advent of better lighting, signing, advanced warning and barriers to separate construction workers from traffic. These improvements are reflected in continual upgrading of the federal and state standards. Also, greater attention to safety by contractors and an effort to inform the public of the hazards associated with construction under traffic conditions and the benefits of safety have significantly improved traffic management during construction.

Continued improvement in safety and traffic control strategies in work zones is needed. The management of traffic in construction work zones has relied primarily on static signs and warning lights that are not changed to reflect actual conditions either as the construction stages change or as the traffic demand changes. One reason for this has been the inability to collect real-time traffic data in construction zones. Another reason has been the significant increase in work zone personnel needed to change the signs to respond to construction and traffic conditions.

Inductive loops have been used for years to collect real-time traffic flow data in permanent applications. However, inductive loops are typically impractical to use in construction work zones. The very nature of construction activities often results in the existing loops being destroyed. The cost of installation, the number of loops necessary to provide adequate real-time traffic data, the permanence of their location and the fact that multiple lane shifts are often required during construction make the use of inductive loops infeasible in typical construction work zones.

New technologies are now available that can provide the same real-time data collection functions as inductive loops but do not require permanent installation. These devices include Machine Vision (video image processing), infrared, magnetic, microwave, sonic and ultrasonic detection devices. Wireless communication systems provide even more flexibility in obtaining and relaying real-time traffic data. Clearly, the tools are available to develop a system that uses these detection devices and wireless communication to provide Traffic Management Centers with all of the traffic information needed to monitor and control traffic in a construction work zone. The same real-time traffic could be used to provide immediate traffic information to the motoring public.

The goals for the PTMS Work Zone Application Operational Test project were formulated within the framework of the applicable National ITS Program goals and Mn/DOT goals. The test goals and objectives are as follows:

- Develop a PTMS for application in work zones that will improve the flow of traffic through the work zone.
- Develop a system that will provide real-time traffic flow information to motorists approaching the work zone.
- Develop a system that will increase safety both for motorists and construction personnel in the work zone.
- Develop a system that is truly portable and adaptable to various construction projects.
- Develop a system that can be integrated with local traffic management systems.
- Develop a system that promotes public acceptance by providing pertinent and accurate real-time traffic information.
- Develop a cost-effective system.
- Develop the partnerships, both public and private, necessary to enable the successful development and implementation of a PTMS in a work zone application.

2.2 Project Participants And Roles

The PTMS Work Zone Application was developed through a public/private partnership agreement. Contributions to the project were made by FHWA, Mn/DOT and ADDCO, Inc. Contributions, including both direct and indirect funds, were made to the project by the three main project partners (see Table 1).

TABLE 1
CONTRIBUTIONS BY PROJECT PARTNERS

Project Partner	Contribution
Federal Highway Administration	$750,000
Minnesota Department of Transportation	$500,000
ADDCO, Inc.	$240,000
Total Project Funding	$1,490,000

Mn/DOT was the lead partner and provided the overall project management and funding. Contributions included:

- Staff time for participation in developing equipment alternatives, message design, equipment placement and project management,
- Staff time for coordination of operational test activities,
- Staff time for coordination of the system evaluation, and
- Direct funding.

The FHWA provided assistance, monitoring of the project's progress and technology transfer from other ITS projects. Contributions included:

- Direct funding,
- Staff time for technical review throughout the project, and
- Information and technology transfer to and from other ITS projects.

ADDCO provided the technical expertise on equipment, software development, and systems integration. Contributions included:

- Staff time and materials for developing basic node and related fixtures,
- Staff time and materials for designing, developing and manufacturing the components for communicating information to motorists,

- Staff time for integrating the communication, vehicle surveillance, and driver information portions of the system into a central control/operations center,
- Staff time and materials for designing and manufacturing specific equipment required to mount and operate standard off-the-shelf equipment (e.g., pan and tilt mechanism with adequate precision to allow movement and resetting to tolerances required by Machine Vision),
- Staff time for system deployment, and
- Funding for capitol equipment costs.

Image Sensing Systems supplied three Autoscope Machine Vision devices that provided traffic detection for the PTMS. Vano Associates assisted ADDCO on the design and development of the communication system. Computer Room Concepts developed the World Wide Web sight that included the traffic data and video images from the work zone that were provided by the PTMS and general information about the project. Warning Lites of Minnesota assisted in the delivery of the PTMS skids to the sights.

BRW, Inc., and Alliant Engineering, Inc., provided the transportation engineering and day-to-day project management. This included the following activities:

- The final system design plans,
- Development traffic operations plans,
- Assistance in equipment alternatives analysis,
- Facilitation or communication between the partners and public agencies,
- Operational test documentation,
- Final Design Report, and
- Team meeting materials, meeting documentation and overall project documents to Mn/DOT.

SRF Consulting Group, Inc., was the independent evaluation consultant for the project. The evaluation focused on the following main issues:

- System benefits on traffic operations,
- System costs,
- System functional characteristics, and
- Perceived benefits of the system.

2.3 System Design

2.3.1 Overview of the System Design

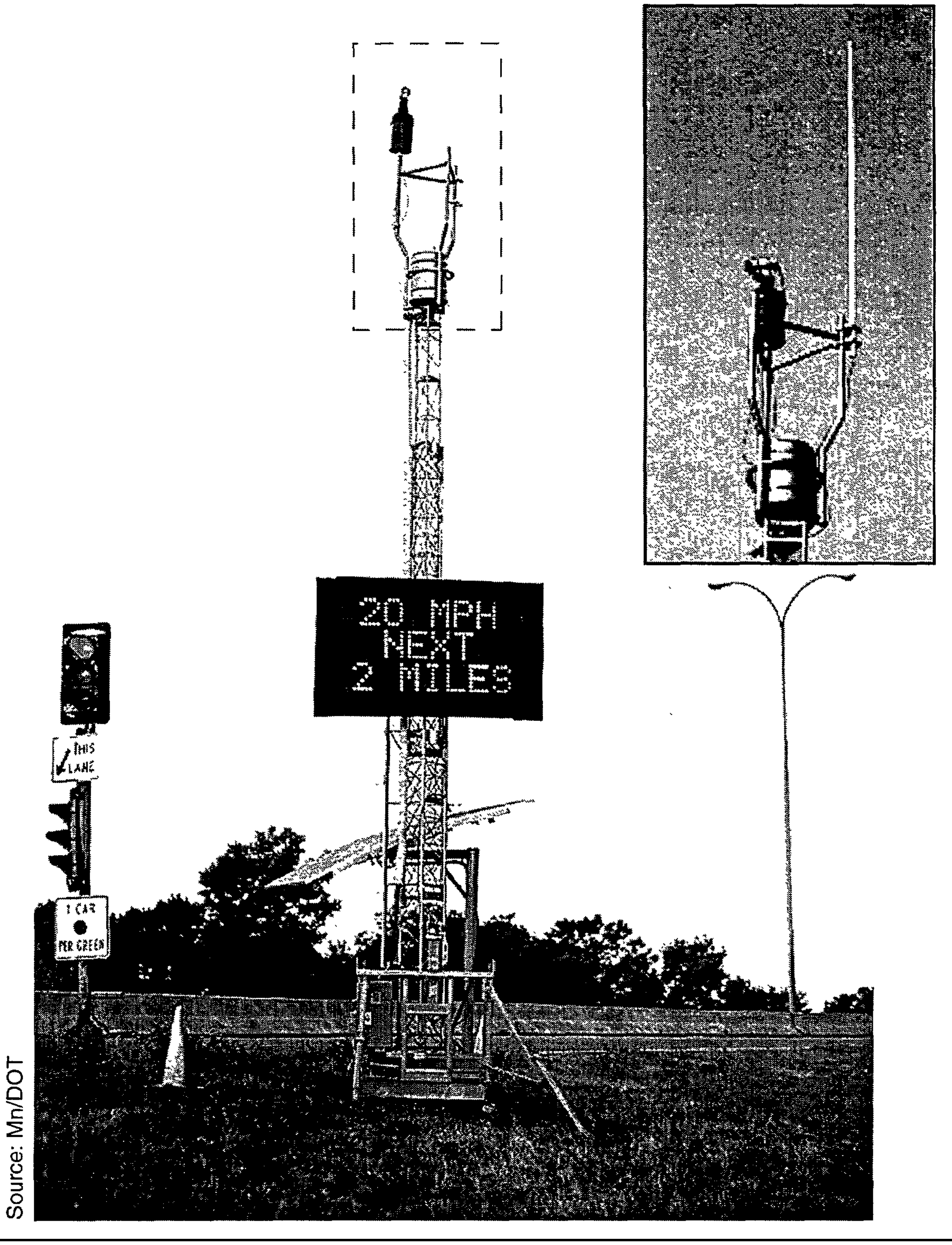
The PTMS Work Zone Application is based on the concepts tested in the Portable Traffic Management System operational test. It is an integration of existing, off-the-shelf, and emerging traffic management technologies into a complete portable traffic control system. The system is portable, wireless and able to withstand the elements within the work zone. It provides traffic engineers with data such as speeds, volumes and incident detection so that decisions can be made and communicated to the traveling public. The system consists of four basic subsystems:

- Vehicle Detection/Surveillance
- Traffic Control Center
- Driver Information
- Communications

The PTMS Work Zone Application consists of portable skids that can house several different pieces of hardware, in addition to an on-board central processing unit (CPU) and the spread spectrum radio communication device. The skids are placed in strategic locations in the work zone and, when linked to one another by the spread spectrum radio, form the nodes in the PTMS network. The nodes can include both vehicle detection devices and driver information devices. Figure 1 shows the PTMS skid deployed in the work zone with both types of devices installed. The inset in Figure 1 shows a close up view of the top of the PTMS tower. The on-board CPU and related components are housed in the cylindrical enclosure.

The vehicle detection/surveillance subsystem consists of several different components. Video cameras placed at strategic locations in the work zone provide real-time information on traffic flow to system operators. Portable Machine Vision provides data such as traffic volume, speed, incident detection and vehicle intrusion into the work zone. The Machine Vision camera is mounted at the top of the tower and is shown on the left side of the inset in Figure I.

The data from the vehicle detection/surveillance subsystem is transmitted to the Traffic Control Center at the Mn/DOT Traffic Management Center. The data is reviewed by system operators and decisions are made regarding traffic control changes necessary to improve traffic flow through the work zone.



System Skid Deployed

Portable Traffic Management System
Smart Work Zone Application

Figure 1

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The traffic control changes are made by relaying messages to the motorist through the Driver Information subsystem. The Driver Information subsystem consists of full-size portable, variable message signs (VMS) and smaller work zone portable variable message signs. The information can also be made available to the public on a World Wide Web page via the Internet.

The communications subsystem relies on spread spectrum radio, cellular phone and Integrated Services Digital Network (ISDN). The spread spectrum radio antenna is mounted at the top of the tower and is shown on the right side of the inset in Figure 1. Each of these communication devices is used for specific links in the project. This system will also include a master controller and a radio link to the traffic control center.

A schematic of the PTMS Work Zone Application is shown in Figure 2. This schematic illustrates how the various system components are connected to form the entire system.

2.3.2 Equipment Specifications

- Vehicle Detection/Surveillance

The vehicle detection/surveillance subsystem consists of several different technologies.

- Closed Circuit Television Cameras (CCTV)

Sony EVI-330 closed circuit video cameras are placed in strategic locations in the work zone. These cameras can be used for black/white, color, or remote surveillance with compressed video. Equipped with computer controlled zoom, focus and iris, the video output is National Transportation Safety Council (NTSC) compatible. The cameras include an environmentally secure housing that can withstand the elements of the construction work zone. The cameras can be utilized in temperatures within the range of O-50 degrees Celsius. The cameras are mounted on precision pan/tilt/zoom units which are in turn mounted on the top of the work zone tower. This is off-the-shelf equipment.

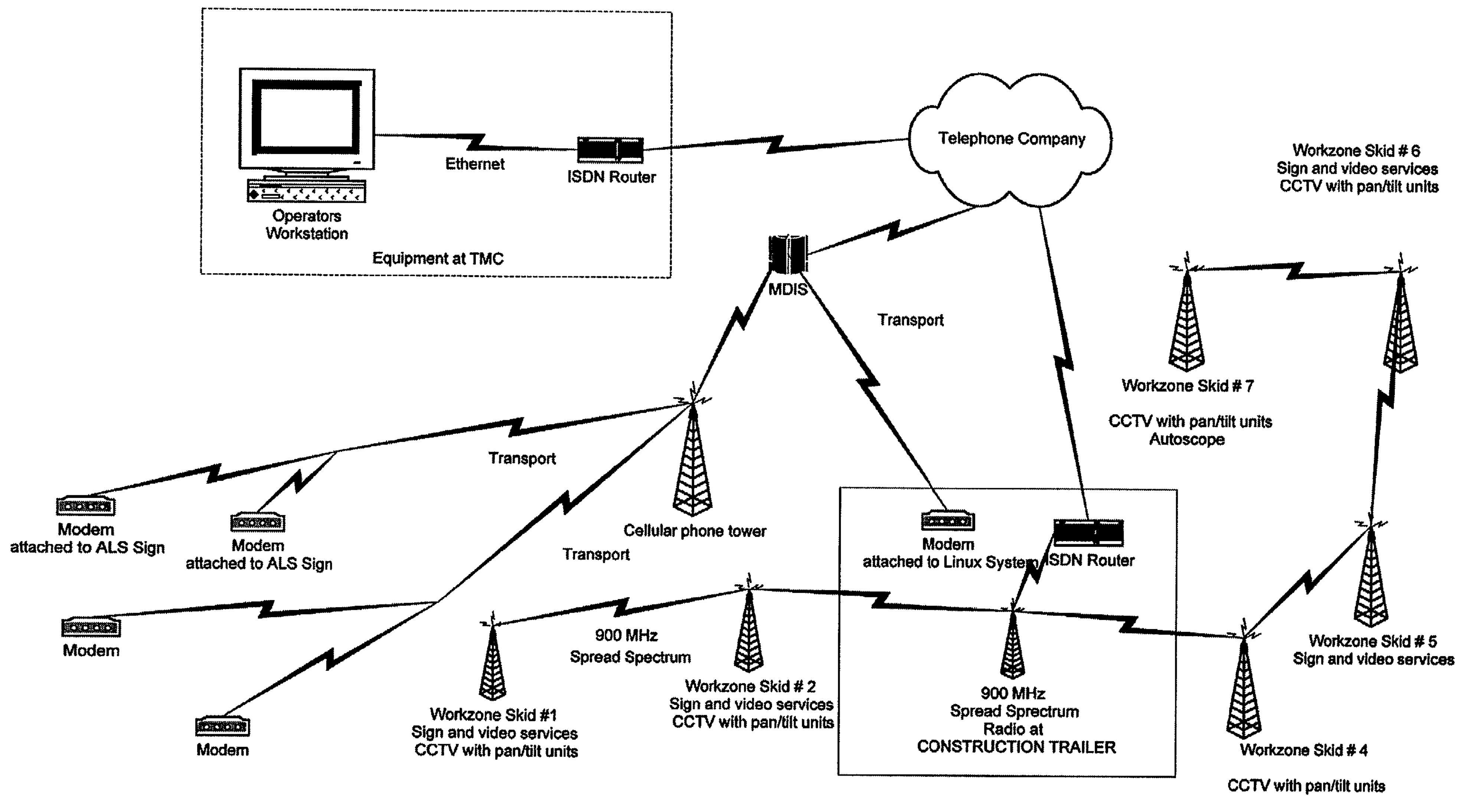
- Pan/Zoom/Tilt Units

Developed by ADDCO for this project, the precision pan/tilt/zoom units provide computer control for accuracy and repeatability. The exacting specifications result in 370 degrees of rotation, 90 degrees of tilt and one-quarter degree accuracy. This accuracy is very important when utilizing Machine Vision for data collection.

- Machine Vision

Machine Vision is another component of the Vehicle Detection/Surveillance subsystem. Machine Vision technology uses video cameras and computers to emulate the function of the human eye. The Autoscope 2004 Wide Area Vehicle Detection System by image Sensing Systems (ISS) was utilized during the PTMS Work Zone Application project.

Smart Work Zone Communication Diagram



PTMS Schematic

Portable Traffic Management System
Smart Work Zone Application

Figure 2

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The Autoscope 2004 is an image processor that accepts video signals from multiple roadside cameras. Detection zones placed on the video image emulate an inductive loop and are able to gather data such as speed, volume, occupancy, queue lengths and vehicle classification. This information is analyzed by traffic management professionals and decisions on traffic control are made. The cameras gathering video images for the Machine Vision must be mounted on the precision pan/zoom/tilt units. This allows camera repositioning for remote surveillance and incident detection. When the operator is finished viewing other roadway sections, the pan/tilt/zoom unit can be utilized to return the camera to its pre-set Machine Vision location. This is off-the-shelf equipment.

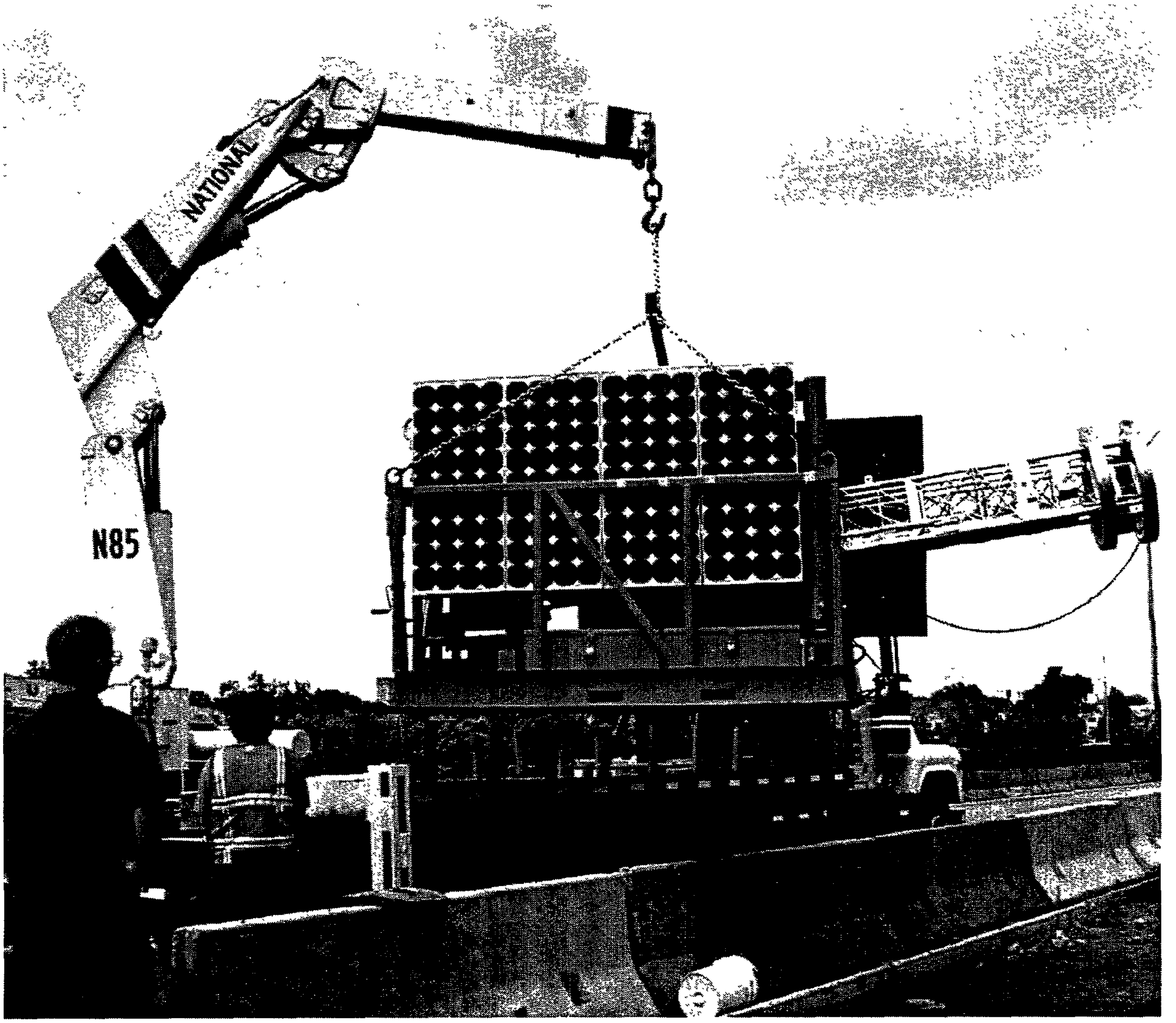
- Speed Radar

The Vehicle Detection/Surveillance subsystem also includes a speed radar that can be placed on work zone skids for speed data collection. This speed data is then transmitted back to the traffic control center for analysis. Decatur Electronics Radar Detector units can be placed on some of the PTMS skids that are not equipped with Machine Vision to provide additional speed data to supplement the Machine Vision speed data. This is off-the-shelf equipment.

- Remote Terminal Units

The cameras and detection devices are mounted on a protective housing containing the Autoscope 2004 image processing unit and a Remote Terminal Unit (RTU). The RTUs are DOS-based 486 platforms that process the video images and traffic data for communication back to the traffic control center. There are two types of RTUs. An RTU1 is a 40 mhz 486 serial compression processor that can compress traffic data into a format that can be relayed to the traffic control center; an RTU2 is a 100 MHz 486 video compression processor that is utilized to compress video images into a format that can be transmitted. Both the RTU1 and the RTU2 connect directly via 10BT cable to the base station system. The radio, camera and housing units are mounted on a tripod that can telescope up to 40 feet into the air (see Figure 1). The RTUs utilize standard computer components but were custom assembled for this project.

The tripod is mounted on a skid, the portable structure that serves as the base of the unit and houses the batteries required to power the system. The skid also includes a solar collector, which provides an alternative energy source to power the equipment. These skids can be loaded on a flat bed truck and moved around the work zone as necessary. Figure 3 shows a skid being unloaded from a flatbed truck and placed in its work zone location. While the vehicle detection/surveillance units are basically existing technology, the software interface enabling the data to be transmitted from one location to another is newly developed. The skid has also been developed specifically for this project and will have applications in areas outside of the work zone.



Source: ADDCO Manufacturing, Inc.

Locating System Skid

Portable Traffic Management System
Smart Work Zone Application

Figure 3

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- Communications

The Communications subsystem for this project included the use of spread spectrum radio, cellular telephone and ISDN phone links. Each of these devices was used for specific types of communication. The spread spectrum radio provided the link between the work zone nodes and the operations center computer. The signal is transferred from node to node, and acts as both a relay and as a means of communication between nodes. This is important in future applications of the technology as algorithms are developed to automatically make the traffic management decisions. The Work Zone VMS were also mounted on the nodes and communicated via the spread spectrum radio. The project utilized 10 Spread Spectrum radios operating at 900 MGz and 2.4 GHz. The cellular telephone provided the link to the full-size trailer-mounted VMS. The ISDN link provided a means of data transmission from the work zone sight to the Traffic Operations Center.

The complete system performs as part of an Ethernet network. Each of the Remote Terminal Units is equipped with an Ethernet EHUB, which allows multiple devices to share the Ethernet. From the RTUs, the signal is transmitted to a Pentium P-60 computer in the project construction trailer. This computer, which is running on a UNIX platform, is equipped with an Ascend P25 Router, which connects the Ethernet to the ISDN phone lines at 128 kbps data rates. The data is then transmitted to other users via the ISDN lines. These are all off-the-shelf devices.

- Driver Information Systems

Three systems can be described as driver information systems. These are:

- Full size Variable Message Signs (VMS) that can be either permanently installed in locations where there is frequent need to provide timely and pertinent information to drivers or they can be trailer-mounted and placed along the roadway at any location to provide information on traffic or roadway conditions. These VMS units have proven to be very effective as advanced warning signs at locations outside of the work zone. This is off-the-shelf equipment.

- Work Zone Variable Message Signs (WZVMS), signs that can be mounted on skids in the work zone, are a new technology. Developed by ADDCO, the WZVMS is a system of l-foot by l-foot LED units that can be attached together to form a sign. This sign can vary in size depending on the conditions of the work zone, and the sign lettering can be varied in height to be suitable for the work zone speeds. These units are utilized at certain locations in the work zone to inform drivers of approach speeds, incidents and even workers in the traveled area.

- **An** additional option available for providing traffic information to the public is the development of a World Wide Web sight that can be accessed via the Internet to allow motorists to view traffic data prior to making routing decisions. A Web sight was developed as part of this operational test. The work zone traffic data collected by the PTMS and images from the cameras were used to provide the basic information needed for the Web sight (see Appendix A). This Web sight showed real-time video images, speeds and volumes within the work zone. This capability also provides the possibility of placing kiosks in several strategic locations (large office buildings, large shopping malls, etc.) to allow people who otherwise do not have access to the Internet access to the same Web sight.

The VMS units are equipped for communication via cellular phone while the WZVMS units are equipped with spread spectrum radio devices for wireless communication. Both systems are capable of being turned on and off remotely. The VMS units have the most potential for redirecting traffic from areas of congestion or other problems. The trailer-mounted units are portable and can be deployed rapidly or relocated should the need arise. They are capable of displaying a wide variety of messages, although the sequence of different displays on a given sign should be limited to two or three because of the limited time a driver has to absorb the information. The WZVMS units have been developed using full LED technology, which opens the possibility of the use of graphics as a system of relaying messages. These units are useful in the event of lane closures, lane movements, speed control and incident communications.

- Traffic Control Center

A key to the successful use of PTMS for work zone applications is the ability to integrate the various pieces of equipment into a system that improves traffic operations in and around the construction zone. Demonstrating the ability to successfully provide the data acquired by the PTMS in the work zone to the TMC was one of the main goals of the operational test. This was accomplished by bringing the communications, surveillance, and driver information systems together in a PTMS traffic control center located in the TMC. This made it possible for the regular TMC traffic operations professionals to operate the system along side the TMC traffic control system.

For this operational test, the PTMS was installed and operated at the TMC but the system was not fully integrated into the basic TMC traffic control system. However, the PTMS computer and communications systems were developed to use standard communications protocols to streamline the process of integrating the PTMS into existing traffic management centers. The issue of integration of the PTMS with the TMC is discussed further in Section 6.3.

The traffic control center for this project was located at the Mn/DOT Traffic Management Center (TMC). The TMC houses the equipment and personnel that manage the freeway system in the Twin Cities metropolitan area. The incoming data was transmitted across the ISDN link from the work zone to the PTMS traffic control center located at the TMC. This data was analyzed by a traffic management professional who made decisions about the traffic control and relayed messages back to the traveling public.

The traffic control work station in the PTMS traffic control center consists of a Pentium P60 Computer running Windows95 operating system. Using this CPU, the operator can view the video images and the traffic data from the work zone. The video image can also be displayed on the TMC monitors, if necessary. The Pentium-based CPU can also communicate preset WZVMS messages to the construction zone and, through a modem connection, access the trailer-mounted VMS that are equipped with cellular telephones. The software controlling the system is a Graphical User Interface application on the Windows95 platform. The Traffic Control Center equipment is a function of the need to have a system that is cost effective and portable and also commercially viable once the operational test is complete.

3.0 EVALUATION APPROACH

3.1 Overview

The evaluation process for this project consisted of four basic steps:

- Preparation of an evaluation frame of reference document,
- Preparation of the evaluation test plans,
- Implementation of the evaluation plans, and
- Preparation of the evaluation report.

The evaluation frame of reference identifies the basic guidelines from which the evaluation plans were developed. It describes the history that led to the development of the PTMS for the work zone, the sights for the tests, the goals of the system and of the evaluation, the project participants and the key external influences that could affect conducting the evaluation.

The evaluation plans expand on the evaluation frame of reference by identifying the specific individual test plans. The test plans provide a detailed discussion of the proposed evaluation goals, objectives, measures of effectiveness and data to be collected for each of the individual test plans. The evaluation plans describe the process required to conduct the individual evaluation test plans and provide the basis for the final evaluation report.

During the implementation of the evaluation test plans, data was collected, as feasible, and analyzed according to the process laid out in the evaluation plans. In addition, the external influences affecting either the availability, quality and quantity of data were noted.

This evaluation report details the results of the operational test. It assesses the success of the PTMS application to work zones, identifies the key issues yet to be resolved and discusses the lessons learned from the project.

3.2 Overall Evaluation Strategy

The concept of the work zone application of the PTMS is that the portable nodes will provide the means to collect real-time data on traffic flow through the work zone which can be provided to drivers approaching and traveling through the work zone, thus improving traffic operations and improving the safety of the motoring public and construction workers. The success of PTMS in work zones depends on drivers' ability to understand the traffic information being provided and their willingness and ability to react to traffic conditions. This can be done by adjusting their speed as they approach the work zone or by diverting to alternative routes, if they are available. An added potential is that the data collected by the PTMS units can be communicated to a traffic management center that can gain additional information about the traffic operations in the work zone and can incorporate this information into the permanent traffic control system.

The general approach to the evaluation was to assess the overall functionality, benefits and costs of the PTMS Work Zone Application. This was accomplished by collecting data before the system information was made available to motorists and comparing these data to data collected after the system information was made available. The system was tested at two sights (described in Section 4). The same basic data and information were collected at both sights. However, the second sight had much different physical characteristics.

The evaluation effort heavily relied on the data collected by the various systems deployed as part of this project and information from in-place Traffic Management Center (TMC) data collection systems on the freeway. Traffic data were collected using the Machine Vision capabilities of the system. In addition, a survey of motorists was conducted to determine their reaction to the PTMS Work Zone Application.

The PTMS Work Zone Application provided information on speed and traffic volume through selected parts of the work zone. Incident and accident information was to be gathered from existing sources of data, TMC logs, State Patrol logs and Mn/DOT accident data, as well as from the PTMS logs. However, it was determined that the operation of the PTMS was for too short a duration to provide a meaningful comparison of accident data, so these data were not analyzed.

Equipment and system reliability was tracked for use in the evaluation. This included partial and full system disruptions, repairs, upgrades and other factors.

Cost data associated with the installation and operation of the PTMS Work Zone Application were collected. The cost of the PTMS will typically be an additional cost to the current type of work zone traffic controls, so its benefits needed to be compared to the additional cost.

The primary external influences that were initially identified as having a significant affect on system performance were: weather, changes in the transportation system due to construction activity (lane closures, repairs, etc.), incidents causing traffic delays (accidents, stalled vehicles, etc.) and major events. Each of these was monitored to account for their effect.

It was recognized that it would be essential to have a flexible evaluation plan to allow modification as the operational test was conducted. This was in part because the evaluation process relied heavily on the data collected by the PTMS devices, Changes that affect the data available from the PTMs, in some cases, required changes in the evaluation plan.

3.3 Goals And Individual Tests

Four main evaluation goals were identified to determine whether the anticipated benefits of the PTMS application to a work zone were realized. These goals guided the approach to the evaluation. Each of these four main evaluation goals is the basis of an individual test. The first individual test deals with the evaluation of the benefits of the system on traffic operations. The second individual test deals with an evaluation system of the functional characteristics of the system. The third individual test deals with an evaluation of the benefits of the system as perceived by construction personnel and motorists, The fourth individual test deals with an evaluation of the overall costs associated with installation and operation of the PTMS Work Zone Application.

3.4 Objectives And Measures Of Effectiveness

Specific objectives and measures of effectiveness were developed for each of the evaluation goals and individual tests. The objectives reflect measurable aspects of the goals. The identified measures of effectiveness (MOEs) are the specific means of measuring the objectives. The MOEs are described in Table 2.

3.5 Data Collection

3.5.1 Overview

The following basic data collection activities were identified in the evaluation plans for measuring the effectiveness of the PTMS in the work zone application. The analysis of the results of this data provided the means to determine how well the work zone application of the PTMS met the intended goals identified at the project inception. The amount and type of data collected were adjusted based on the test conditions as the operational test proceeded. Also, additional data pertinent to the project that were not included in the original test plans were included. The results of the analysis of the data collected are presented later in Sections 5 through 8, which discuss the individual test results.

3.5.2 Machine Vision Traffic Volume Counts and Steeds

The Autoscope Machine Vision devices were used by the system to provide speed information and video surveillance to the operators. The volume data provided a means of assessing how well the devices were detecting the traffic in the work zone. The speed information from the Autoscope devices was used to evaluate the effect of the PTMS on the work zone traffic. This involved assessing changes in the variability of the speeds and change in average speeds in the work zones.

TABLE 2
OBJECTIVES AND MEASURES OF EFFECTIVENESS

Goal 1: Evaluate System Impacts On Traffic Operations

Objective	Measure of Effectiveness
A. Evaluate the impacts on overall travel time through the work zone	• Average vehicle speeds through the work zone • Average travel times in the work zone • Approximate user cost benefits
B. Evaluate system impacts on traffic diversion	• Traffic volumes in the work zone • Traffic on diversion routes
C. Evaluate system impacts on safety in and approaching the work zone	• Number, type and severity of accidents in and approaching the work zone • Number of incidents in and approaching the work zone • Consistency of speed in and approaching the work zone

Goal 2: Evaluate System Functional Characteristics

Objective	Measure of Effectiveness
A. Evaluate the practicality of installing and operating a PTMS in work zones	• Evaluate the number and severity of problems that are not unique to this installation • Evaluate the potential for problems in other types of work zones • Identify work zone characteristics affecting feasibility of the PTMS Work Zone Application
B. Evaluate the reliability of the PTMS Work Zone Application (hardware and software)	• Evaluate the number and severity of problems that arise and are not unique to this installation • Evaluate the potential for problems in other types of work zones
C. Evaluate the features and functions of the PTMS Work Zone Application to identify their usefulness in applications	• Identify features and functions intended to improve the traffic operations that did not have a significant impact • Identify features and functions intended to improve safety that did not have a significant impact • Identify other future applications of the system or portions of the system
D. Identify any additional features and functions that may be useful in future PTMS work zone applications	• Identify features and functions that may provide additional benefits for the motorists in the work zone • Identify features and functions that may provide additional benefits for the construction personnel in the work zone
E. Evaluate the networking, communications and deployment aspects of the PTMS in work zone applications	• Identify the problems that occur with networking and communications (ISDN and spread spectrum radio) • Identify limitations in the network and communications that would limit the potential for deployment at some work zones • identify the physical requirements needed to deploy the system

TABLE 2 (CONTINUED)
OBJECTIVES AND MEASURES OF EFFECTIVENESS

Goal 3: Evaluate Perceived Benefits of the System

Objective	Measure of Effectiveness
A. Evaluate the driver perception of the PTMS in work zone applications	• Identify features and functions noticed by motorists • Identify features and functions found confusing or not useful by motorists • Identify any practical suggestions provided by the motorists for enhancing the system
B. Evaluate the construction personnel perception of the PTMS in work zone applications	• Identify features and functions noticed by workers • Identify features and functions thought to be confusing or not useful by workers • Identify any practical suggestions provided by the construction personnel for enhancing the system

Goal 4: Evaluate System Costs

Objective	Measure of Effectiveness
A. Compare staff time and costs to operate the system (estimated to be typical of fully developed system) with conventional work zone traffic controls	• Staff time required to operate and maintain the systems - Cost of staff time
B. Compare deployment costs of the PTMS in a work zone application (estimated to be typical of fully developed system) with costs of conventional work zone traffic controls	• Total cost of fully developed hardware and software • Total cost of conventional work zone traffic controls

35.3 Traffic Management Center Loop Detection Traffic Volume Counts

The traffic volumes from TMC loop detectors were collected for I-94 and I-35 in the vicinities of the two work zones, These data were compared to the Autoscope volume counts as a check. Also, there was the possibility for some traffic to divert from westbound I-94 to northbound TH 280 if drivers felt the traffic conditions identified on the PTMS variable message signs (VMS) in the work zone warranted the diversion. The TMC loop detector volumes at I-94 and TH 280 were used to evaluate whether the PTMS had any affect on this diversion. It should be pointed out that it was not a goal of the PTMS to affect this diversion, and the WZVMS were not placed to induce diversion and the messages on the VMS did not suggest diversion. However, the diversion analysis was done to determine whether the PTMS had this additional affect on traffic operations in the work zone.

3.5.4 Motorist Survey

A telephone survey of motorists was conducted to assess how the users reacted to the PTMS signs. The survey target was drivers who passed through the I-94 work zone during the peak periods when the signs were being operated.

3.55 Communications Evaluation

National Engineering Technology Corporation (NET) evaluated the PTMS communications system. NET reviewed the system specifications and design and monitored the overall performance of the system in the work zones.

3.5.6 PTMS Operator Interview

The two persons who operated the PTMS at the Mn/DOT TMC when it was deployed in the two work zones were interviewed. The interviews provided information on the length of time needed for training, ease of use, usefulness of the system, problems encountered and suggestions for improvements.

3.5.7 Construction Personnel Interview

Construction personnel were interviewed to determine the effect the PTMS had on the construction operations in these two work zones.

3.5.8 Metropolitan Council Transit Operations Interview

Personnel from the Metropolitan Transit Operations office were interviewed to determine the extent to which the PTMS affected the transit routes passing through the work zone on I-94.

3.5.9 Work Zone Focus Groups

The Human Factors Laboratory of the University of Minnesota and Mn/DOT Market Research personnel conducted three focus group sessions to identify the key concerns and problems motorists have with metropolitan area work zones.

3.510 World Wide Web Site Use

An World Wide Web sight was developed to test the ability to present information from the PTMS units in the work zone to users of the Internet.

4.0 WORK ZONE SITES

4.1 Sites Included In Operational Test

The operational test of the PTMS Work Zone Application took place on Interstate 94 between downtown Minneapolis and downtown St. Paul, Minnesota and on Interstate 35 in the southern portion of the Twin Cities metropolitan area.

The I-94 construction project (S.P. 2781-289) included widening the Mississippi River bridge (Dartmouth Bridge), reconstruction of an interchange, reconstruction of a mile of mainline interstate highway and construction of four bridges. The location of the operational test on I-94 is shown in Figure 4.

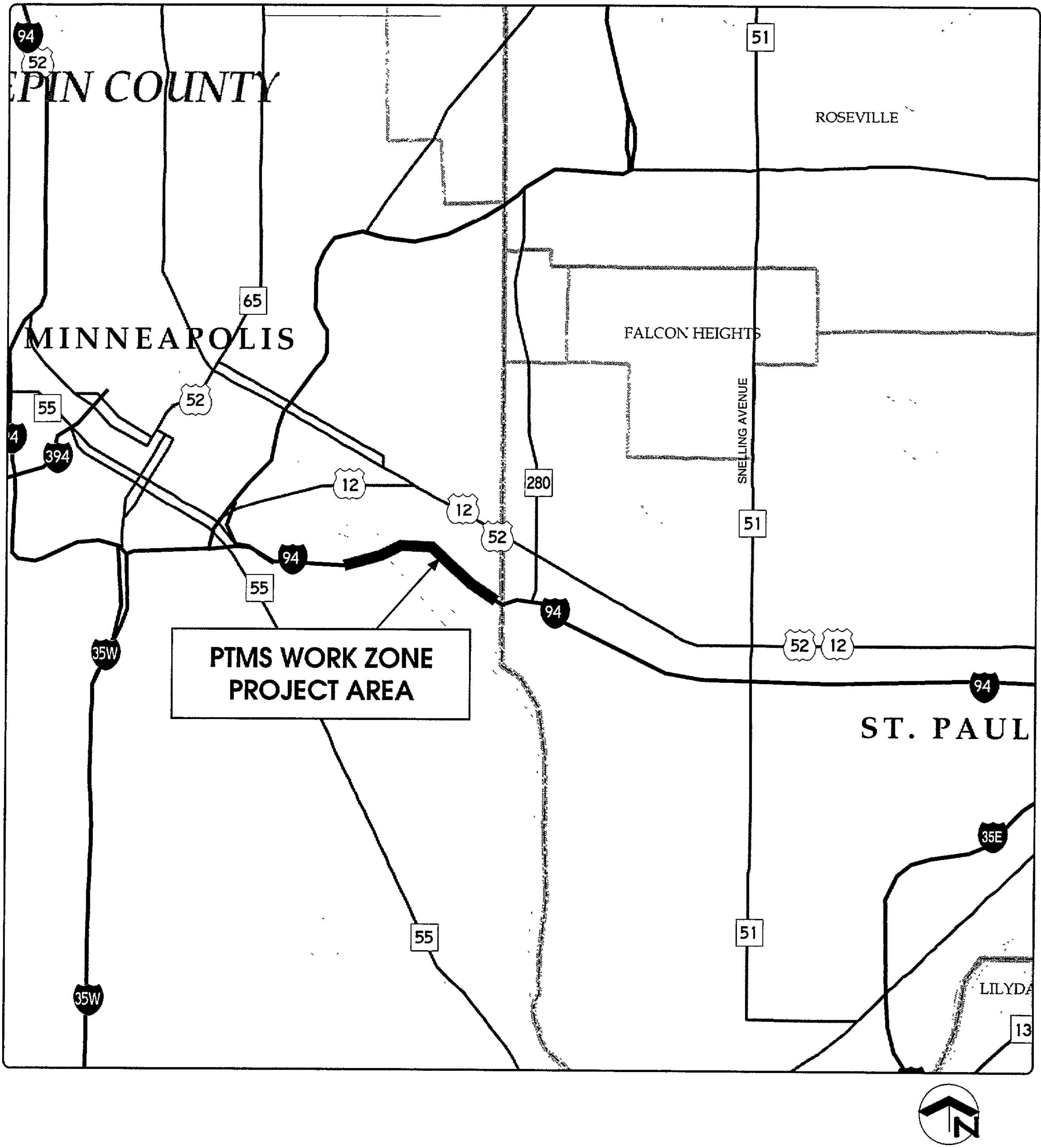
Portions of the PTMS were relocated to a second project work zone in September 1996. The second sight was on Interstate 35 at the County State Aid Highway 50 interchange in Lakeville, Minnesota. The construction project, (S.P. 1980-57) included the reconstruction of 2.5 miles of rural mainline concrete interstate and a new folded, half diamond interchange. The location of the second operational test sight is shown in Figure 5.

4.2 Interstate 94 Work Zone, Riverside Avenue To TH 280

The I-94 project was chosen as a sight for the operational test for the following reasons:

- The high volume of traffic that must be maintained through the corridor
- I-94 roadway geometric complexities
- The complexity of the construction staging on the project
- The schedule of the construction project
- The TMC's lack of complete freeway surveillance by CCTV and permanent data collection loops in the vicinity of the work zone
- Proximity to the Mn/DOT Traffic Management Center

Interstate 94 between the downtowns of Minneapolis and St. Paul, Minnesota is one of the highest volume roadways in the Twin City metropolitan area with an average daily traffic volume in 1994 of 141,000 vehicles. A minimum of two through lanes in each direction was required throughout the construction project to minimize the traffic delays. In addition, the interchange reconstruction involved the I-94 link to the University of Minnesota's main campus. Several ramps were only allowed to be shut down for a 3-month period during the summer of 1995. These issues added to the complexity of **the construction staging.**



I-94 Work Zone Project Area

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Figure 4

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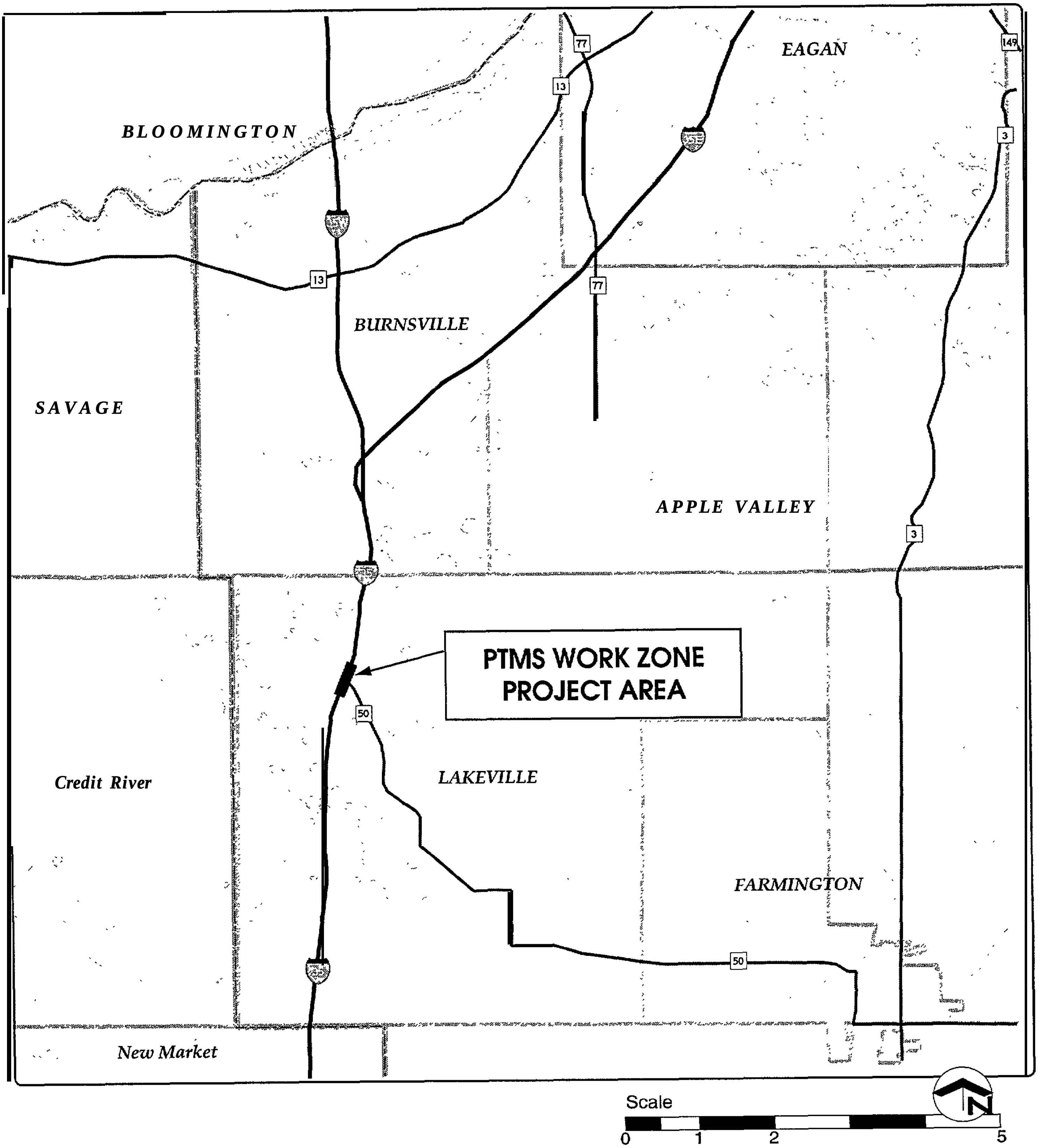


I-35 Work Zone Project Area	Figure 5
Portable Traffic Management System Smart Work Zone Application	SRFf10942089.7

The project began in October 1994 with the construction of bridge 27856 connecting 27th Avenue from south of I-94 to north of I-94. During the 1995 construction season, work took place on three bridges, three ramps, a portion of the mainline and the outside lanes and shoulders on the river bridge. Construction in 1996 included finishing the three bridges, one ramp, extensive mainline work and the inside lanes and shoulders on the river bridge. The operational test began July 1, 1996 in the later stages of the project. It lasted through the end of the project on August 29, 1996.

The deployment location of the skids to form the PTMS nodes in the I-94 work zone are shown in Figure 6. The figure also shows how each of the nodes was configured.

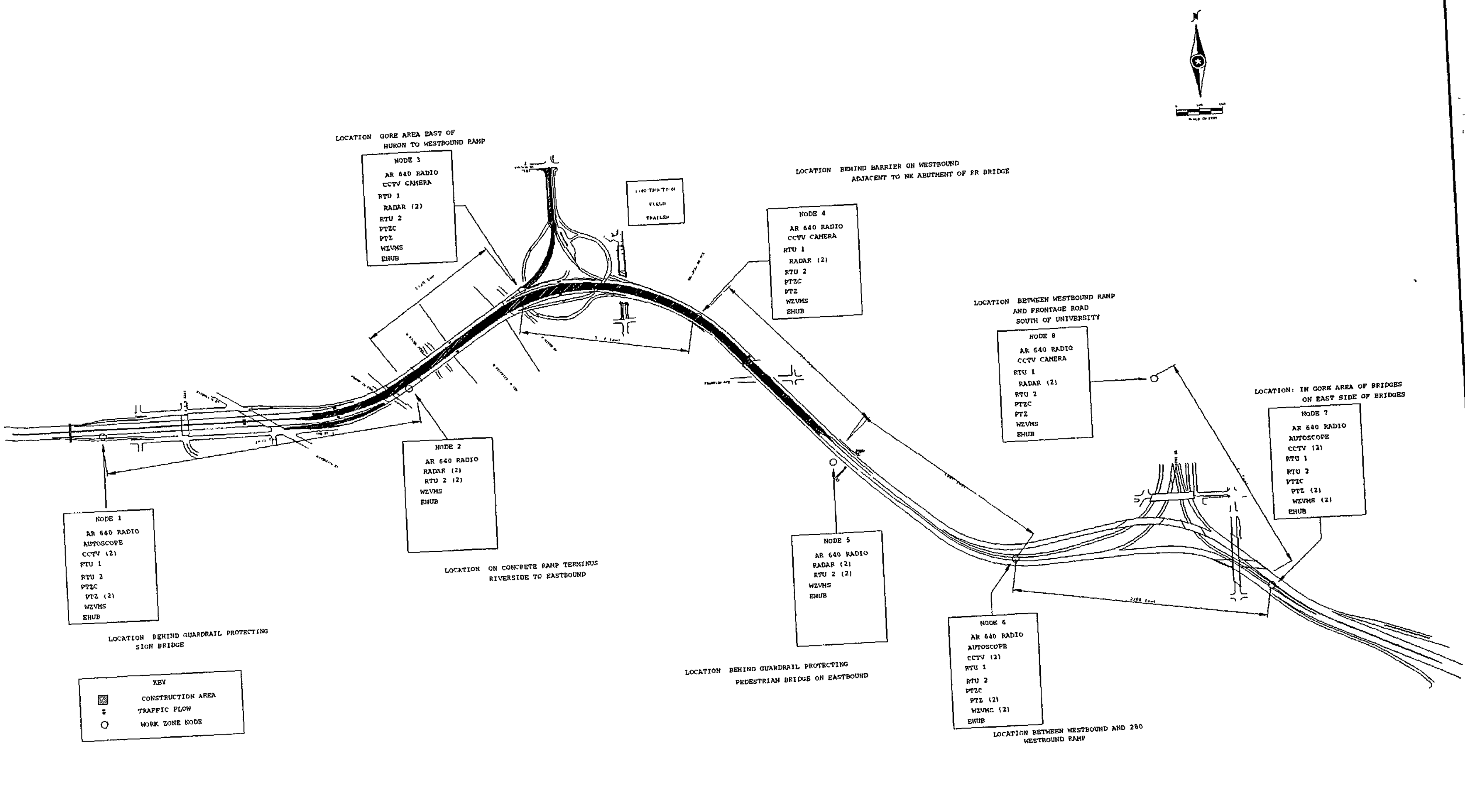
4.3 Interstate 35 Work Zone, CSAH 50 Interchange In Lakeville, Minnesota

The I-35 project was chosen for the operational test for the following reasons:

- The rural nature of the project,
- The high volume of traffic that must be maintained through the corridor,
- The closure of one of the northbound lanes during a portion of the project, and
- The schedule of the construction project.

Interstate 35 is the principal commuter route from the south into the Twin Cities metropolitan area with an average daily traffic volume in 1994 of 58,000 vehicles. The construction project began in the spring of 1995 on the interchange and mainline, with two lanes remaining open at all times in both directions. During stages 4 and 5 in 1996, traffic was reduced to one lane northbound at the south end of the project . During these stages, the PTMS system was utilized in the work zone from September 7, 1996, to October 14, 1996.

The deployment location of the skids to form the PTMS nodes in the I-35 work zone are shown in Figure 7. The figure also shows how each of the nodes was configured.



PTMS Node Locations at I-94 Work Zone

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Smart Work Zone Application

Figure 6

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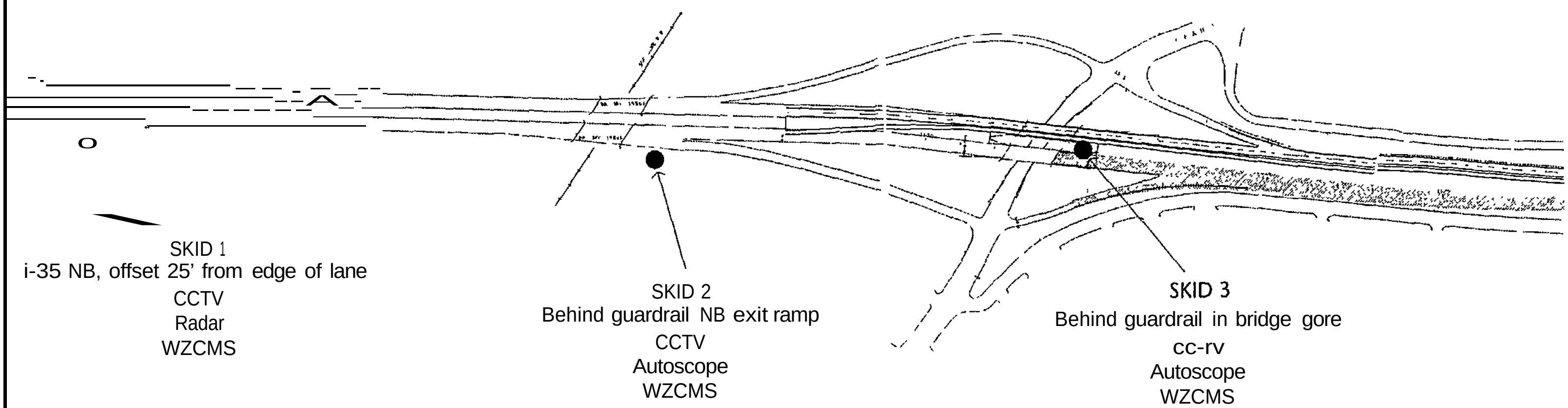


PTMS Node Locations at I-35 Work Zone

Portable Traffic Management System
Smart Work Zone Application

5.0 TEST ONE -- TRAFFIC OPERATIONS

5.1 Overview

Individual Test One focused on the affect of PTMS on traffic operations within a work zone. The basic design of this evaluation was to compare several aspects of the traffic operations in the work zone before and after the traveler information function of the PTMS was provided to motorists in the work zone. The test plan called for the traffic operations in the work zone to be analyzed by assessing the change in the relative uniformity of the speeds, change in travel time, change in number and severity of accidents, and change in traffic volumes to assess the effect of the PTMS on traffic volume passing through the work zone and to quantify whether any traffic diversion occurred.

The hypotheses to be tested were as follows:

- The system will improve safety by causing the traffic speed profile through the work zone to be more uniform and speed changes to be more gradual.
- The system will reduce overall travel times through the work zone by improving average speeds and causing diversions during periods of heavy congestion in the work zone.
- The system will improve traffic operations in the work zone and will allow additional traffic to pass through the work zone during the peak periods.

The objectives and related measures of effectiveness that were used to analyze the effects of the PTMS on traffic operations in the work zones are presented in Table 3.

TABLE 3
TEST ONE -- TRAFFIC OPERATIONS
OBJECTIVES AND MEASURES OF EFFECTIVENESS

Goal 1: Evaluate System impacts On Traffic Operations

Objective	**Measure of Effectiveness**
A. Evaluate the impacts on overall travel time through the work zone	• Average *vehicle speeds through the work zone* • *Average travel times in the work zone* • *Approximate user cost benefits*
B. Evaluate system impacts on traffic diversion	• Traffic volumes in the work zone • Traffic on diversion routes
C. Evaluate system impacts on safety in and approaching the work zone	• *Number, type and severity of accidents in and approaching the work zone* • *Number of incidents in and approaching the work zone* • Consistency of speed in and approaching the work zone

NOTE: Measures of effectiveness that were not available are shown in italics.

The key conditions/assumptions in this analysis were that the external factors affecting the work zone will be similar during the baseline and operational periods of the system. These external factors were accounted for to the greatest extent possible by monitoring the weather and outside traffic conditions (accidents, other construction, etc.) to isolate the effects of the PTMS. Weather conditions were relatively benign during the tests at the two sights and there was very little precipitation. Also, there were no significant major incidents or accidents on the overall system that would have significantly affected the data analyzed.

The Autoscope units were set up by ISS and ADDCO staff with input from SRF. The data was checked against TMC loop volume counts and manual volume counts to ensure that the system was providing acceptable volume data. The data collected were reviewed as they became available to ensure that the system was operating as it had been set up. The MOEs and related plans for data collection are shown in Table 4.

TABLE 4
TEST ONE -- TRAFFIC OPERATIONS
DATA TO SUPPORT MEASURES OF EFFECTIVENESS

	Traffic **Data**		**Other Data**		
Measures of Effectiveness	Autoscope Volume and Speed Data	TMC Volume Data	TMC and State Patrol Logs	Motorist Surveys and Focus Groups	System Logs
1. Average vehicle speeds through the work zone	XXX				
2. Average travel times in the work zone	NC				
3. Approximate user cost benefits	NC				
4. Accident reduction	XXX		NC		NC
5. Incident reduction	NC		NC		NC
6. Consistency of speed in and approaching the work zone	XXX				
7. Change in traffic volumes on I-94 in the work zone	XXX	XXX			
8. Traffic on diversion routes	XXX	XXX		XXX	

NC - Data not collected.

5.2 Analysis Of Traffic Data Collected At I-94

A significant amount of traffic data were collected at the I-94 work zone sight. This included traffic volumes and speed data from the Autoscope units from July 26, 1996 to August 29, 1996. It also included the collection of traffic volume data from the TMC permanent loop locations over the entire period for comparison with Autoscope volumes and for analysis of the affect of the PTMS on traffic volumes in the work zone. In addition, manual counts were done in the peak hour to check both of the electronic counts.

The data downloaded from the Autoscope units in the PTMS were checked against TMC loop volume counts and manual volume counts to ensure that the system was operating correctly. The speed data were reviewed and compared against observed speeds to ensure that the system was operating properly. The data downloaded from the Autoscope units were reviewed when they became available to ensure that the system continued to operate properly and to determine if any construction activities affected the system.

The WZVMS were generally operated in both directions from August 10 to August 28, 1996, during the peak traffic periods. During this time, the signs were operated by a staff person assigned to this project as her primary responsibility for this period. There were problems with the wireless communications system, which are discussed further in Section 6, that resulted in Node 7 being operational during only part of this test period (see Figure 6). However, there was a trailer mounted VMS located to the east of Node 7 that provided traffic information as drivers approached the work zone.

The TMC volume data were used to analyze the affect of the PTMS on the volume of traffic passing through the work zone as well as the volume of traffic that diverted from westbound I-94 to TH 280. It must be noted that this PTMS deployment was designed to improve traffic operations within the work zone and was not designed to directly affect traffic diversion from westbound I-94 to northbound TH 280. The messages displayed on the various VMS provided traffic information about the work zone but did not contain messages directly suggesting that drivers should take the alternate route. Also, if diversion was intended to be a part of the message set, a VMS would have been located further upstream to give the drivers more time to evaluate the alternate route suggested. However, the data were available to assess diversion and this analysis provides additional insight into the effects of the PTMS on the work zone traffic.

The impact of the PTMS on traffic volumes passing through the work zone was assessed by using a T-test on the total westbound traffic volumes from the TMC loop detectors. This test assesses whether the two sets of sample data are statistically different from each other and the confidence level. It was hypothesized that improved traffic operations resulting from the PTMS would effectively increase the capacity of I-94 through the work zone. During the peak periods this increased capacity would result in an increase in the traffic volumes passing through the work zone.

The analysis showed that the PTMS did result in a significant increase in the traffic volume during the peak periods. The total traffic volumes entering the work zone were compared for a period before the VMS were operated and then for the period when the VMS were operated. There were no changes in construction activity during these periods that would have affected the traffic volume other than the operation of the VMS. The increase in total westbound traffic entering the work zone in the morning peak period averaged 3.6 percent and the increase was significant at the 90 percent confidence level (see Table 5). In the afternoon peak period the increase in total westbound traffic entering the work zone averaged 6.6 percent and the increase was significant at the 99 percent confidence level.

The reason for this increase in volume appears to be the added capacity from more orderly traffic operations in the work zone due to the PTMS messages. The increase may also be because drivers had more information available to them when entering the work zone. The westbound entrance to this work zone has limited sight distance because of the combination of roadway grades, curves and visual barriers presented by multiple bridges and high retaining walls. It is likely that the increased information available to the drivers helped to offset the effect of the limited sight distance.

Similarly, TMC loop volume data were evaluated to assess whether the PTMS driver information resulted in a diversion of traffic from westbound I-94 to northbound TH 280. The volume change on both westbound I-94 and northbound TH 280 was tested to quantify the changes in volume and to determine the statistical significance of any changes.

The increase in total westbound traffic prior to the TH 280 exit in the morning peak period averaged 3.6 percent and the increase was significant at the 80 percent confidence level. The corresponding change in traffic on the TH 280 exit was a decrease but this was found to not be statistically significant at the 80 percent confidence level.

The increase in total westbound traffic prior to the TH 280 exit in the afternoon peak period averaged 3.1 percent and the increase was significant at the 95 percent confidence level. The corresponding change in traffic on the TH 280 exit was a decrease of 5.3 percent and the increase was significant at the 98 percent confidence level.

One reason for the increased volume on westbound I-94 through the work zone and the decrease in volume on TH 280 appears to be the effect of the added capacity discussed earlier. However, it is theorized that the apparent tendency for drivers to use I-94 instead of diverting to TH 280 may be due to the added driver confidence resulting from having more real-time information about the traffic conditions in the work zone.

Drivers are less likely to divert to an alternate route as they approach a congested work zone if they know that the congestion is for only a short segment and that the delay will be relatively minor. Again, this benefit of the PTMS was greater in this location because of the limited sight distance.

TABLE 5
STATISTICAL ANALYSIS OF PTMS IMPACT ON TRAFFIC VOLUMES

	Morning Peak Period		Afternoon Peak Period	
Location	Change	Confidence Level	Change	Confidence Level
Westbound I-94 After Exit to TH 280	+ 3.6 %	90%	+6.6%	99%
Westbound I-94 After Exit to TH 280	+ 3.6 %	80 %	+3.1 %	95 %
Exit to Northbound TH 280	Not Significant	NA	-5.3%	98%

The effect on traffic accidents was not directly analyzed because of the relatively short duration of the operation of the system at the two sights. It was determined that the time of analysis was too short to provide a reliable indication of the accident reduction potential of the PTMS system in the work zone. The impact of the system on safety was analyzed by assessing its effect on the consistency of the speeds within the work zone.

5.3 Analysis Of Traffic Data Collected At I-35

The WZVMS were fully operational at the I-35 work zone for 8 days until the construction ended. During this time the signs were actively operated for the morning peak period from 6 a.m. to 9 a.m. There is a significant directional split at this location with the northbound direction being the highest volume for this heavy commuter route entering the Twin Cities from the south. The operators of the PTMS watched the video output and changed the VMS as needed to reflect the conditions and speeds in the work zone.

Traffic data were collected at the I-35 work zone sight. This included traffic volumes and speed data from the Autoscope units over the baseline period from September 6, 1996, to October 6, 1996, when no PTMS messages were displayed, and over the period from October 7, 1996, to October 14, 1996, when PTMS messages were displayed. Traffic volume data were also collected from the TMC permanent loops for use in validating the Autoscope volume data. In addition, manual counts were done in the peak hour to check both of the electronic counts.

The main purpose for collecting speed and volume data from the Autoscope units is to provide the information needed to select the proper messages to be displayed by the PTMS units. It is important to note that to perform these functions for the PTMS, the recorded volumes and speeds only need to be relatively close to the actual volumes and speeds. This places a lower demand for accuracy on the results than would be required for vehicle detection for signal actuation or speed detection for enforcement. Based on this level of accuracy, the Autoscope traffic volumes from the two units were compared to each other, to the traffic data from the Mn/DOT ATR (automatic traffic recorder) station volume counts and to manual volume counts. The speed data were reviewed and compared against observed speeds to ensure that the system was operating properly. Also, throughout the test period the data downloaded from the Autoscope units were reviewed when they became available to ensure that the system continued to operate properly.

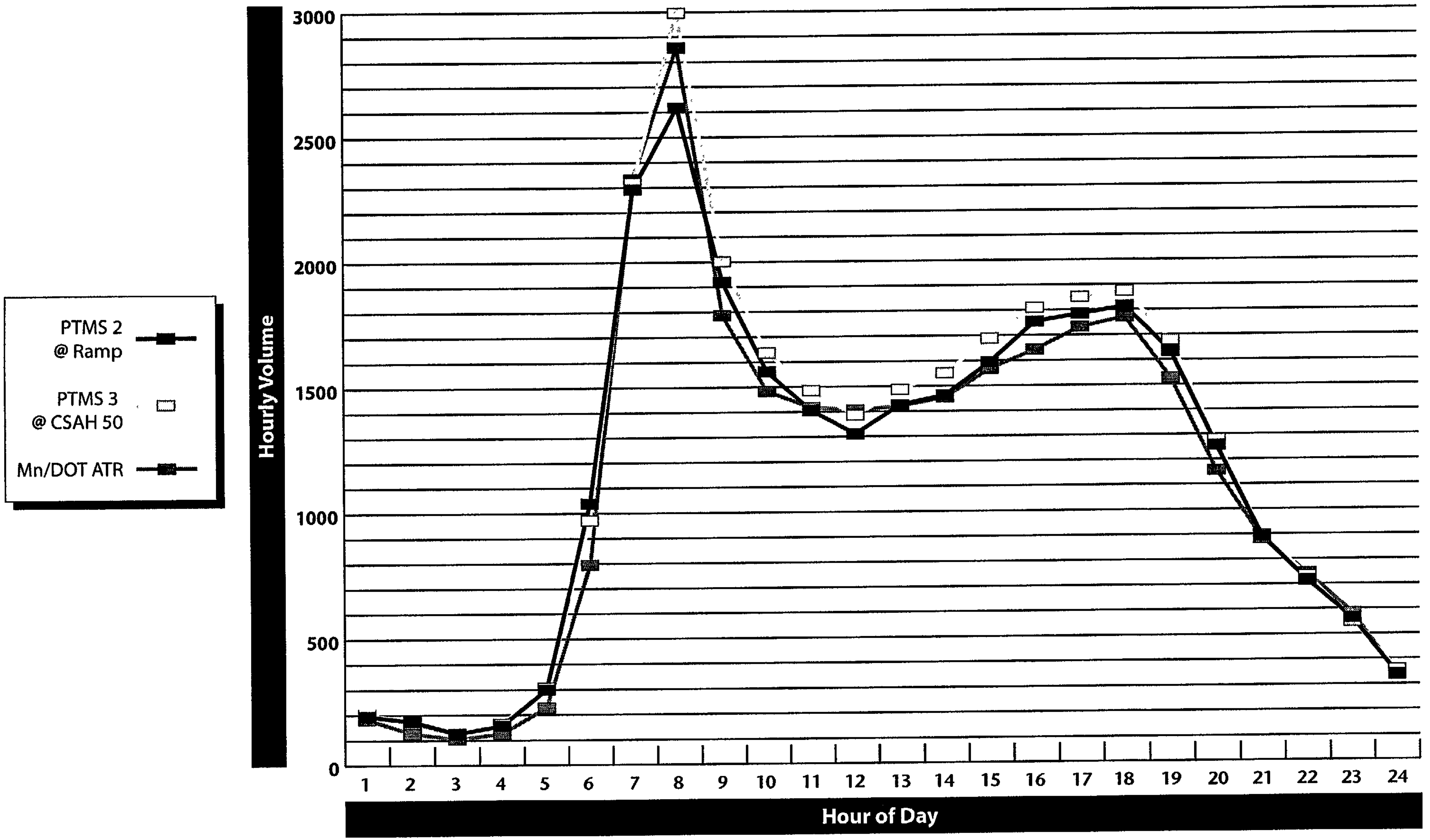
The comparison of traffic volume counts between the two PTMS units (Nodes 2 and 3) over a period of approximately 4 days showed a total daily volume difference of approximately 1.3 percent. Comparison of the Autoscope hourly volume counts with the corresponding ATR hourly volume counts showed a very similar magnitude and hourly distribution pattern (see Figure 8). The daily totals of the PTMS units at the ramp and north of CSAH 50 were within approximately 2.5 and 6.5 percent of the ATR daily total. These comparisons indicated that the traffic volumes being recorded by the PTMS units were adequate for the PTMS use and for the analysis.

The manual counts were taken in the same location as the PTMS Node 2. Comparison of the Autoscope and manual counts showed that the Autoscope was recording volumes that were approximately 7.5 percent higher than the corresponding manual count (see Figure 9). This was considered adequate for the operation of the system and for this analysis.

The speed data were validated by observing the Autoscope output of speeds and by observing the traffic being detected. The results showed that the Autoscope units were providing a good representation of the actual traffic speeds under both light traffic conditions where speeds were high as well as under congested conditions.

The Autoscope speed data were analyzed to determine the affect the PTMS had on the uniformity of flow at each of the two PTMS units. The uniformity of the speed was used to provide an indication of the relative traffic safety in the work zone. Reduced variability in the traffic speed would likely result in a smoother flow of traffic and reduced need for sudden braking. This analysis is important because the short test period did not support analysis of accident data.

The uniformity of flow was determined by comparing the individual l-minute speed readings with the 15-minute moving average at each of the PTMS units. The difference between the individual and 15-minute moving average speed was squared to provide



Traffic Volume Comparison for I-35 Work Zone

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Smart Work Zone Application

Figure 8

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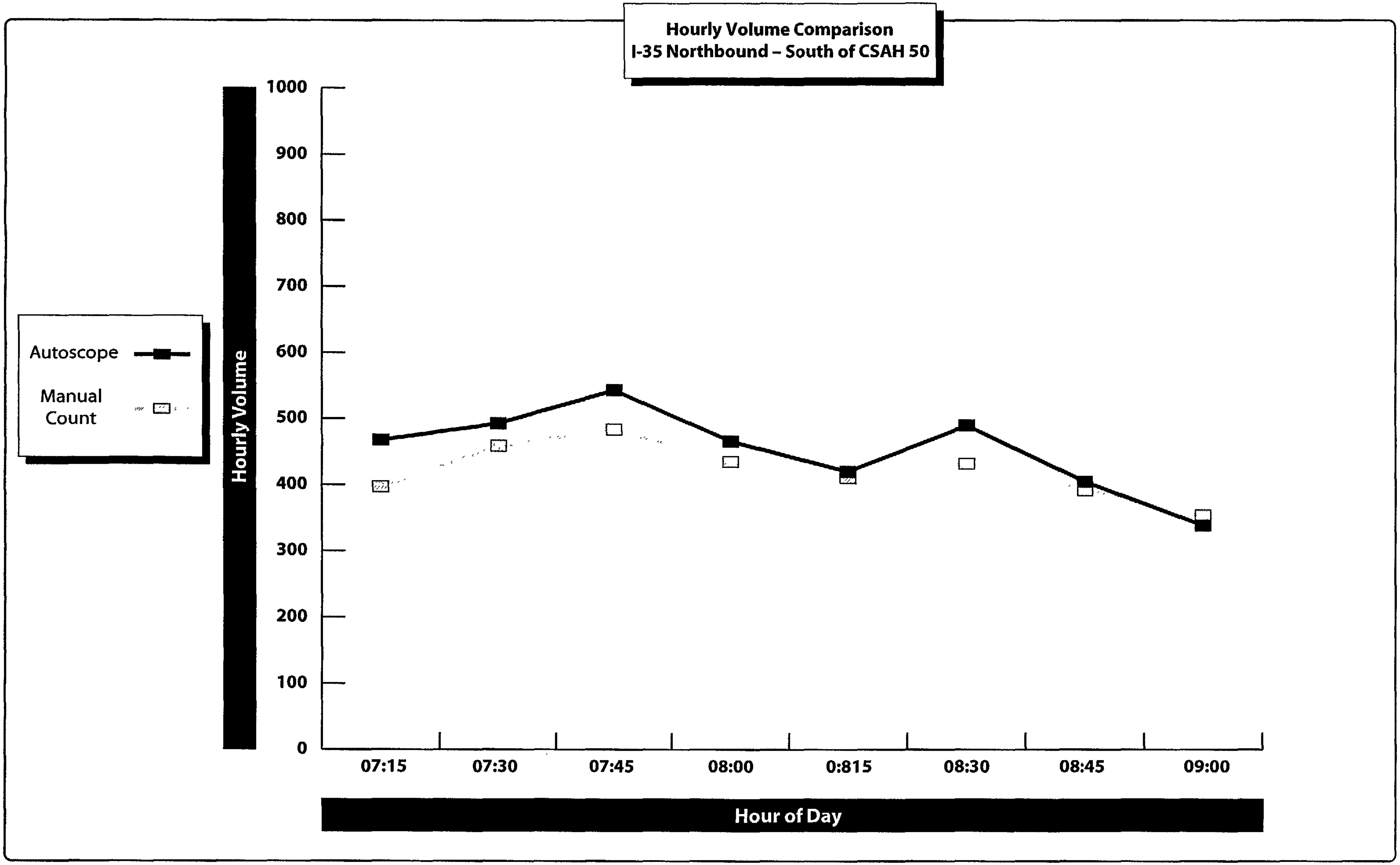

Manual Count Versus Autoscope at I-35 / CSAH 50

Portable Traffic Management System
Smart Work Zone Application

Figure 9

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values with positive signs. These values were divided by the number of observations for each data collection period to account for differences in the time and number of vehicles observed. These data were analyzed to determine if there was a significant difference between the two sample populations. The T-test was again used as described in Section 5.2.

The results indicate that there was not a statistically significant change in the variability of the l-minute speeds compared to the 15-minute moving average for the PTMS Node 2 (refer to Figure 7). This means that the uniformity in speed of the vehicles approaching the work zone was no different with or without the PTMS messages. In contrast, there was a statistically significant difference in the variability of speeds at PTMS Node 3 (at an 80 percent confidence level) and the variability of the speeds with the PTMS messages was lower. This means uniformity of speeds of vehicles traveling through the work zone better, suggesting that the PTMS would improve safety in the work zone.

The Autoscope speed data were also analyzed to determine the effect the PTMS had on the average speed at PTMS Nodes 2 and 3 (see Table 6). The average speeds were tested for significance using a T-test. The results indicated that the difference in average speed at the PTMS Node 2, when the PTMS messages were present, was significantly lower than without the messages (at a 99 percent confidence level). The difference in average speed was 9 mph since the speed without the signs was 32 mph and with the signs was 23 mph. This indicates that the PTMS messages caused the average traffic approaching the work zone to slow down more than the standard static work zone signs. However, the average speed of the vehicles through the work zone remained basically the same. The conclusion is that the provision of the real-time traffic information caused the drivers to slow sooner as they approached the work zone and provided for a more uniform speed through the work zone. Each of these conditions would likely lead to safer traffic conditions in the work zone.

TABLE 6
STATISTICAL ANALYSIS OF PTMS IMPACT ON SPEED UNIFORMITY

	Variability in Speed		Difference in Average Speed	
Location	Change	Confidence Level	Change	
PTMS Node 2 Approaching Work Zone	Not Significant	NA	- 9 mph	99 %
PTMS Node 3 In Work Zone	- 71 %	80 %	Not Significant	NA

5.4 Summary of Analysis of Traffic Impacts

The results of the analysis of the impacts of the PTMS units on work zone traffic are summarized as follows:

- There was a significant increase in the traffic volume that moved through the work zone when the PTMS was in operation. The increase was 3.6 percent (at a 90 percent confidence level) in the morning peak period and 6.6 percent (at a 99 percent confidence level) in the afternoon peak period. One possible reason for this is the more orderly flow of traffic resulting in increased capacity.

- There was a significant decrease in the traffic volume existing I-94 to TH 280 in the afternoon peak period. This decrease in traffic exiting to TH 280 was 5.3 percent (at a 98 percent confidence level). The corresponding decrease on TH 280 in the morning peak period was not statistically significant. A likely reason for the decrease on TH 280 and, the corresponding increase on I-94 is because of increased driver confidence in traveling through the work zone because of the real-time traffic information provided by the PTMS.

- The PTMS decreased the variability in speed for traffic traveling within the work zone by over 70 percent (at an 80 percent confidence level). This suggests an improvement in safety because the speeds are more uniform within the work zone.

- The PTMS decreased the average speed for traffic approaching the work zone by 9 miles per hour (at a 99 percent confidence level). This also suggests an improvement in safety as the vehicles approaching the work zone slowed down sooner for the work zone.

6.0 TEST TWO -- SYSTEM OPERATION

6.1 Overview

Individual Test Two focused on the overall operational aspects of the PTMS within the work zones. Test Two evaluated how well the system operated. It evaluated the effort necessary to deploy and operate the system. It also evaluated the ability to remotely control the PTMS and to bring the data and video to the TMC.

The basic design of this evaluation was first to identify the portability of the system by identifying the level of effort and the personnel category required to deploy the system and make it operational. The second issue was to identify the level of effort needed to install and operate the PTMS traffic control center in the Mn/DOT Traffic Management Center and to evaluate the potential to link the PTMS data with the TMC. The third issue is to evaluate the system reliability and how well it operated after the initial development and debugging.

The hypotheses to be tested are as follows:

- The system has the capability to be deployed quickly in a wide variety of work zones.

- The system can be installed and operated from a remote location such as a local Traffic Management Center with relative ease and with the possibility linking the PTMS data into the TMC system.

- The overall system and its components are reliable after initial system debugging.

The objectives and related measures of effectiveness that were used to analyze the system operation of the PTMS in the work zones are presented in Table 7.

The key conditions/assumptions were that the external factors that affected the work zone were typical of those found in work zones of similar activities, size and scope. The factors affecting the wireless communications subsystem were identified in an effort to quantify the extent to which the specific conditions at these two work zone sights affected the quality of communications. However, the two sights provided a very limited sample of sight conditions so it was difficult to fully quantify the effect on communications.

TABLE 7
TEST TWO -- SYSTEM OPERATION
OBJECTIVES AND MEASURES OF EFFECTIVENESS

Goal 2: Evaluate System Functional Characteristics

Objective	Measure of Effectiveness
A. Evaluate the practicality of installing and operating a PTMS in work zones	• Evaluate the number and severity of problems that are not unique to this installation • Evaluate the potential for problems in other types of work zones • Identify work zone characteristics affecting feasibility of the PTMS Work Zone Application
B. Evaluate the reliability of the PTMS Work Zone Application (hardware and software)	• Evaluate the number and severity of problems that arise and are not unique to this installation • Evaluate the potential for problems in other types of work zones
C. Evaluate the features and functions of the PTMS Work Zone Application to identify their usefulness in applications	• Identify features and functions intended to improve the traffic operations that did not have a significant impact • Identify features and functions intended to improve safety that did not have a significant impact • Identify other future applications of the system or portions of the system
D. Identify any additional features and functions that may be useful in future PTMS work zone applications	• Identify features and functions that may provide additional benefits for the motorists in the work zone • Identify features and functions that may provide additional benefits for the construction personnel in the work zone
E. Evaluate the networking, communications and deployment aspects of the PTMS in work zone applications	• Identify the problems that occur with networking and communications (ISDN and spread spectrum radio) • Identify limitations in the network and communications that would limit the potential for deployment at some work zones • Identify the physical requirements needed to deploy the system

The initial deployment of the PTMS at the I-94 sight was expected to involve significant development and debugging of the system hardware and software as well as refinement of the PTMS structure. This was because of the incorporation of a variety of relatively complex subsystems into an overall system. The initial testing of subsystems in the laboratory or simulated field deployment was not expected to reveal all of the problems that could occur with full scale deployment of the system with all of the nodes operating. It was anticipated that much of the development activities could be concluded at the first sight to provide a more typical operational test at the second sight. It was intended that the second sight would provide both the opportunity to collect more traffic data as well as to serve as an excellent test of the ease of deployment of the system. This proved to be the case.

The equipment was initially set up by ADDCO. ISS provided personnel to set up the Autoscope units. The setup and operation of the PTMS was observed by SRF and NET to evaluate the operational and portability aspects of the system. The debugging and operation of the PTMS and the communications subsystem was initially operated by ADDCO. However, the PTMS was ultimately operated for both sights TMC staff trained in its use. System and staff logs were evaluated to assess the level of effort needed to set up and operate the PTMS.

SRF and NET collected the data and made the observations used in the evaluation. The data collected were reviewed as they became available to ensure that the system was operating as intended. The MOEs and related plans for data collection are shown in Table 8.

6.2 Evaluation Of Portability And Ease Of Deployment

One of the basic goals of this system was to have it be relatively easy to move to various locations and to deploy. Deployment of the system requires some initial review of the sight and planning. This is needed to ensure that the PTMS elements can gather the data needed and that the message signs are located where they are needed.

The following are the basic steps needed in the sight planning to locate the PTMS elements:

- Identify space requirements of the equipment,
- Identify alternate sights for equipment set-up because of the changeable conditions encountered in work zones,
- Recommend location sights for the equipment, and
- Develop the system operation scenarios for the particular work zone.

TABLE 8
TEST TWO -- SYSTEM OPERATION
DATA NEEDS TO SUPPORT MEASURES OF EFFECTIVENESS

	Data				
Measures of Effectiveness	TMC Personnel Surveys	System logs	Review of equipment specs	Surveys of partners	Measure
1. Identify the problems that occur with networking and communications (ISDN, spread spectrum radio and fiber optics)		XXX	XXX		
2. Identify limitations in the network and communications that would limit the potential for deployment at some work zones		XXX	XXX		
3. Identify the physical requirements needed to deploy the system	XXX	XXX	XXX		
4. Evaluate the number and severity of problems that are not unique to this installation		XXX	XXX		
5. Identify work zone characteristics affecting feasibility of the advanced portable traffic management system	XXX	XXX	XXX		
6. Evaluate sight preparation time unique to system				XXX	XXX
7. Evaluate the time needed to prepare the system for deployment				XXX	XXX
8. Evaluate the time to deploy the system in a new location				XXX	XXX
9. Evaluate the potential for problems in other types of work zones				XXX	XXX

The PTMS Work Zone Application involves the deployment of two main types of field equipment. The PTMS skids and the trailer mounted Variable Message Signs (VMS). These two pieces of equipment have different siting requirements so they are addressed separately.

The trailer mounted variable message signs and associated electrical generation equipment used in the PTMS are mounted on a trailer that is 8 feet wide and 8 feet long. In Minnesota the VMS trailer must be located at least 4 feet from the edge of the traveled lane. So, in Minnesota, the space required by the trailer mounted VMS is 8 feet along the length of the roadway and 12 feet perpendicular to it. Signs also needs to be located where there is adequate sight distance, based on vehicle speeds, for the drivers to read the messages.

The PTMS skids used in the operational test are 4 feet by 8 feet when fully collapsed for transporting. When deployed at the sight, there is an overhang from the modular VMS and the solar panel. The skid is considered a fixed object because it weighs approximately 4,000 pounds. As such, it either must be placed outside of a barrier (temporary or permanent) or outside of the clear zone to protect it from collisions with vehicles. The skids with Machine Vision, in many cases, need to be placed within the clear zone to provide the design parameters required by the Machine Vision devices, yet also need to be located outside of barriers. Skids equipped with VMS will also need to be located where there is adequate sight distance, based on vehicle speeds, for the drivers to read the messages.

The following are the basic guidelines for the placement of the PTMS skids within the work zone:

- To have the potential to remotely operate and view the video output of the PTMS provision must be made for an ISDN line or equivalent (such as a Switch56 configuration where ISDN is not available). The availability and installation time for the ISDN line will be dependent on the local telephone company so adequate planing should be done to avoid deployment delay due to the ISDN installation.

- Locate to avoid or minimize need to move skids during various construction phases, especially those equipped with Machine Vision which would need to be reconfigured and recalibrated,

- Locate to minimize interference with construction activities,

- Consider all construction activities, staging areas and material stockpiling areas when selecting locations,

- Locate the skid to ensure proper wireless communications by providing line of sight between towers that is unobstructed by horizontal or vertical curvature or by objects such as structures and trees,

- Locate the skid on pavement or soil not prone to settling as differential settling may significantly affect the aiming of detection devices mounted high on the 40-foot tower, and

- Avoid locating the skid near construction activities that result in vibrations that might affect the settling of the skid, such as pile driving, breaking pavement, etc.

The evaluation of the deployment of the PTMS skids was based on the activities at both I-94 and I-35 work zones. These sights represent significantly different physical sights. The I-94 sight was very complex with horizontal and vertical curves, large retaining walls and multiple bridges crossing I-94. In comparison the I-35 sight was a relatively straight and level section of roadway with no bridges crossing the portion of the work zone that was included in this operational test. Therefore, the two sights represented significantly different challenges to the wireless communications system.

The first step was to contact the local telephone companies for each sight to determine the availability of ISDN and the time to make the necessary installation into the construction trailer and the TMC. The computer in the construction trailer was linked to the PTMS nodes via wireless ethernet and linked to the computer located at the TMC via ISDN line. In the I-94 work zone an ISDN line was installed. In the I-35 work zone a Switch56 configuration was needed to emulate an ISDN line because actual ISDN service was not yet available in this location. Details of the Switch56 configuration can be obtained from ADDCO if ISDN is not available.

The initial planning for locating the skids and trailer mounted VMS was done using the construction staging plans and candidate sights were identified. The construction sight was then visited to observe any conditions not reflected in the staging plans that may affect selection of locations for the equipment.

The wireless communications potential for each candidate sight was then evaluated. Two wireless radio units were used to assess the radio signal integrity between the location selected for the base node and the other locations identified. This step could an additional radio unit to avoid problems obtaining line of sight between towers for solid communications. This process required two persons and took about 1 to 1.5 hours at the sight plus travel time to and from the sight.

The wireless communications system requires a knowledge of both spread spectrum radio equipment and the configuring of computer communications protocols and system addresses. As such, the system requires personnel with significant level of expertise in the work zone design phase where the initial sights are selected and to configure the system. This is discussed further in the section on communications and Appendix B.

The next step was to prepare the PTMS skids and trailer mounted VMS. In this case, the skids were essentially used in the same configuration as they were used at the I-94 sight. Therefore, the only preparation required was a basic system test to ensure that all components were operational, which takes approximately 1 to 2 hours. The batteries were fully charged overnight.

The two PTMS skids were loaded onto a 22-foot flatbed truck equipped with a boom. It took about 15 minutes to load the two skids, and about 15 minutes to set each skid in its selected location. It should be noted that this is the time needed to set the skids in place after any necessary lane closures are accomplished. In all but one case the skids were placed without the need for additional traffic control in the form of lane closures. Where necessary, the additional effort needed for a lane closure to place a skid would be typical of the traffic control necessary to set up any temporary lane closure for the particular location and jurisdiction.

The next steps required two people from ADDCO to get the system fully deployed. This involves mounting some equipment such as the radio antenna on the tower. Then the VMS was assembled and deployed. Next, the tower was raised to a vertical position and extended to its full height. The solar panels were then unfolded and rotated to the proper position. This entire process took about 40 minutes.

The Autoscope system was then configured for the PTMS nodes using the Machine Vision system. The actual time needed to set the system varies from skid to skid because of the number of lanes, the number of detection zones specified and the complexity of the particular sight. However, the time to set up each node typically took about 20 to 30 minutes to set up each sight and check for proper operation. The Autoscope units can be remotely accessed and all setup operations done without needing to be at the particular node. Therefore, any future adjustments to the setup that are necessitated by changes in the work zone, such as lane shifts, can be also made by simply moving the camera, if necessary, and defining the new detection zones. The time to accomplish this is typically about 15 minutes.

The conclusion is that the PTMS can be deployed in a wide variety of work zones with relative ease. The time necessary to set up the PTMS varies depending on the complexity of the sight and the number of PTMS nodes to be deployed. The actual time to prepare, deploy and set up each node is relatively short, especially given the complexity of the PTMS equipment and its capabilities. However, the PTMS is a unit that would be set up in work zones with special traffic needs, such as high traffic volumes, poor sight distances, special traffic control needs, surveillance needs, etc.

6.3 Installation At Traffic Management Center

Installation of the PTMS into the TMC required communications via ISDN line (or equivalent) and a location for the equipment at the TMC (refer to Figure 2). The communications required ordering an ISDN phone line connection to be installed at both the PTMS base station at the construction trailer and at the TMC. The PTMS control unit housed at the TMC is essentially a standard sized desktop or tower computer system with an ISDN router (the same size as an external modem). It requires a relatively small space and can be accommodated on a standard office desk, table or a special computer stand. The installation of the system at the TMC was done with relative ease. The control unit was set up at the TMC, connected to the work zone PTMS via the ISDN line and was then fully operational.

The communications protocol of the PTMS units was developed using TCP/IP to allow the communications to be compatible with current standards. The installation of the PTMS control unit within the TMC demonstrated the ability to provide the data (speed, volume, etc.) and video output from the PTMS to the TMC. This demonstrated that the PTMS could be successfully installed and operated from a TMC remote from the work zone. Though it was not the intention of this operational test to fully integrate the PTMS within the overall TMC operational system, the standard communications protocol would make it relatively straightforward to actually integrate the PTMS into a typical TMC.

6.4 Overall System Operation

This section discusses the overall operation of the PTMS Work Zone Application. It focuses on the integrity and limitations of the hardware and software developed for the system. The user and operator evaluations of the system are addressed in the third individual test focusing on user reaction to the system.

It is important to point out that the PTMS Work Zone Application is a relatively complex combination of various subsystems. While it is a logical step from the previously developed PTMS that was the subject of an earlier operational test, it contains many new subsystems and elements not in the previous system. Therefore, it was understood at the outset that this operational test would likely include a significant amount of system development work prior to deployment. Also, it was likely that some additional development would be needed after deployment. The importance of this is to distinguish between the development nature of the initial units and the performance that is indicative of a finished product.

An example of this is the development and fabrication of a special pan and tilt mechanism for the Autoscope cameras to allow them to be moved for surveillance and then to be automatically returned to the original position within strict tolerances. These tolerances were required so that the Autoscope vehicle detection zones would be properly located on the video image. No standard pan and tilt mechanisms were found, however, so this one needed to be developed.

6.4.1 Sensitivity of the Skid to Construction Activity

The PTMS Work Zone Application was operated at the two work zone locations on I-94 and I-35. The basic results of the operation of the system proved to be quite acceptable. They provided the basic functions for which they were designed and did so, for the most part, with relatively few equipment problems. The notable exception to this was the wireless communications system which exhibited significant problems at the I-94 sight but operated well at the later I-35 sight. The communications subsystem, which is especially complex, was evaluated separately and is discussed in the following section.

There were some hardware and software problems with the system. As stated above, many of these problems were of a development nature and are not indicative of the basic operational characteristics of such a system nor of its operation in its final production version. Therefore, the focus of this discussion is on problems or limitations that are mainly related to the final production system and are not related to the developmental nature of the system tested.

Two additional problems related to the aiming of the camera occurred during the operational tests at I-94 and I-35. The first occurred at I-94 where the PTMS skid was apparently moved slightly by construction personnel. This would have involved either deliberate or accidental movement using heavy equipment because of the weight of the skid. The movement resulted in the camera being aimed significantly off from the original location. Any movement is amplified by the fact that the camera is located near the top of the 40-foot tower. Therefore, light movements of the base cannot be allowed. This condition may be unique to this operational test since the construction personnel were aware of the test but the system was not incorporated into the responsibility of the construction contractor. It does point out the importance of the skid placement away from construction activity, of making construction personnel aware of the importance of not moving the skid and of the need to monitor the video images.

The second problem with aiming occurred at I-35. This was the result of the pavement removal operation on a bridge that involved breaking the pavement with a power hammer. The hammer blows were significant enough to cause a visible shake in the video image. The result of this vibration was that the skid settled into the soil in this location. One of the corners was on softer soil and settled more that the others. The result was that the camera, located near the top of the tower was aimed well off of the roadway. This again points out the importance of skid location, the importance of adequate soils at the base and the need to monitor the video images.

6.4.2 Skills Needed For System Setup

The system includes some relatively complex subsystems. Primary among these are the communications system setup and Autoscope setup. Each of these will require trained personnel to ensure that it is done properly.

Setup of the Autoscope units is not a complex task but still requires some training of personnel. The setup of Autoscope involves proper aiming and zooming to obtain a proper video image. Detection zones are then identified on the video image and their lengths determined. It is essential that these zones are set up carefully so that the vehicle detection performance is adequate. For example, locating a detection zone where part of the zone contains an object that will move in the wind or where movement of the tower will make that object move into and out of the zone may cause false detections. Examples of such objects are tree branches, telephone lines and power lines. Also, the proper calibration is important to correctly detect the speeds and includes dimensions for lanes, height of the camera relative to the roadway, dimensions of the detection zones, etc. This proper calibration is very important in the PTMS operation as the speed data is central to the control of the real-time messages to drivers.

6.4.3 Active Svstem Operation

The value of this system is in the ability to present motorists with real-time information about traffic conditions in the work zone. This required that the system be actively operated by personnel for that this is a prime responsibility. This was essential for this operational test because the system required the operator to monitor the speeds of the vehicles and traffic conditions to select the proper messages to display. During the operational test at I-94 the real-time traffic information was provided during the final three weeks of the test when a student worker was assigned to operate the system during the peak periods.

During the I-35 operational test personnel were assigned to actively operate the system during the morning peak period of the final eight days. The result was the provision of real-time information that was updated on a continuous basis.

It should be noted that development of an automatic message selection system is underway. The intent is to allow the system to select messages based on the speeds detected by the Autoscope systems in the skids. It will also sound an alarm to notify the operator that the speeds have fallen below a specified threshold as an indication of a potential incident. When the camera is moved for use in surveillance, the system will turn off the speed detection alarm until the camera is reset to the detection position. The system will still require monitoring personnel to respond to the alarms and to monitor that it is operating properly. Particular attention should be paid to proper camera aim and assessing how well the speed detection seems to be operating given a visual check of traffic flow.

6.5 Communication Subsystem

National Engineering Technology Corporation (NET) evaluated the PTMS communications system. NET reviewed the system specifications and design and monitored the overall performance of the system in the work zones. The following are the basic conclusions of this analysis. The detailed report is reproduced in Appendix A.

The analysis of the communications system identified the problem with the spread spectrum radio system performance at the I-94 work zone as the key issue. The tests demonstrated that the wireless networks would provide adequate communications to support the general deployment. However, the focus of the test was on the use of the field equipment and the communications environment was not adequately tested to establish the operational limitations of the deployed system. Therefore, additional testing would be needed to identify the exact condition limits for the wireless communications system in the work zones. This reinforces the need to include a field check of the sights to verify that the radio system signal integrity would be adequate.

The main problem with the operation of the radio system at the I-94 sight can be traced to the problem with multipath interference. Multipath is the interference of the primary signal that has traveled over two different paths. Depending on the difference in path lengths relative to the wavelength of the radio wave, the interference can be either constructive or destructive. Where it is destructive the direct signal is effectively canceled by the signal traveling on the indirect path. The result is a loss of communications between the two nodes experiencing the multipath interference problem and any other radios communicating through these nodes. There is a more detailed discussion of this issue in Appendix B.

The I-94 sight, where the problems with the radio were encountered, was a very complex sight with significant horizontal and vertical curves, bridges crossing I-94, large metal structures and high retaining walls. The node experiencing the most significant radio problem was Node 7 which was located furthest from the root radio and behind three bridges. In contrast, the I-35 sight was less complex and there were no problems with the radio system.

A summary of the conclusions in the NET report are presented as follows:

- PTMS video and data can be successfully transmitted over the spread spectrum communications

- The deployment of the Arlan spread spectrum radios may require additional analysis. The test demonstrated that the wireless communication system will work where the radios required the signal to be transferred through an intermediate radio when communicating with the radio at the main hub. This was the case at the I-35 sight where no communications problems were encountered. However, the tests were inconclusive where communication with the main hub required two or three intermediate radios. This was the case with one node at the I-94 sight where communications problems were experienced. The problems under these conditions could not be analyzed beyond the multipath interference.

- Even with the counter measures to eliminate the multipath interference, the links were dropped at times when the radios appeared to attach themselves to a higher level node, thereby eliminating repeaters in the configuration. This remains an issue because without the ability to use repeaters, there could be a limit on the length of a work zone that could be covered. Based upon the flexibility of these radios, it should be possible to change the architecture of the network and use point-to-point links to further disperse the radios. This concept would need to be tested.

- Because this was an operational test there was no attempt to integrate the data into the existing systems at the TMC. The ability to place data (video) from the equipment to the Wide World Web suggests that the equipment should be able to directly interface any system using TCP/IP as its basic protocol but this was beyond the scope of this operational test.

- There is an issue with positioning the radios. For a construction zone, such as the one along I-35, the location of the radios can be determined with a minimum of technical expertise. The envisioned procedure would place the root node transceiver in its location and a portable transceiver would be used to verify the communications links before the skids were deployed. In many installations, the contractors may not have the technical expertise to position the radios. The requirement would be for the author of the plans, specifications, and estimate (PS&E) to locate the radios on the plans. Having the contractor verify field locations based upon field measurements works well on paper, but often results in problems when it comes to actual project execution.

- There is also a potential issue in setting up the network. For both of the field tests, the ADDCO staff had experts who could make the necessary assignments of TCP addresses. While it should be possible to establish procedures that would reduce the amount of expertise required, it is not obvious that personnel without networking knowledge would be able to set up the equipment. ADDCO has addressed this issue with the concept of providing technical support out of their distribution network. This concept should be tested to determine its practicality.

Overall, the communications equipment and network adequately supported the requirements of the PTMS Work Zone Application project. However, there remain issues that need to be addressed in future tests to verify that the problems on the I-94 deployment were unique to that installation.

6.6 Summary Of Analysis Of System Operation

The results of the analysis of the system operation are summarized as follows:

- PTMS can be deployed in a wide variety of work zones with relative ease.

- The actual time to prepare, deploy and set up each node is relatively short, especially given the complexity of the PTMS equipment and its capabilities.

- The PTMS is a unit that would be set up in work zones with special traffic needs.

- The PTMS was successfully installed and operated at the TMC.

- The PTMS was developed using TCP/IP communications protocols to simplify integration into existing TMCs.

- The overall system operation was successful.

- The Machine Vision cameras mounted high on the towers require care that construction activities do not inadvertently cause the skids to move.

- The Autoscope setup is not complex but requires some special training.

- The PTMS video and data can be successfully transmitted over spread spectrum radios.

- Care must be taken in siting the nodes to avoid multipath interference problems.

7.0 TEST THREE -- USER REACTION

7.1 Overview

Individual test three evaluated the user reaction to the PTMS Work Zone Application. This consisted of the reaction of the motorists, system operators, construction personnel, transit operations personnel and a focus group of persons who have traveled through urban area work zones. The findings of the surveys and interviews are presented in the following sections.

The hypotheses to be tested were as follows:

- The system will provide useful real-time information to the motorists.
- The system will provide a useful tool for managing traffic in work zones.

The objectives and related measures of effectiveness that were used to analyze the user reaction to the PTMS in the work zones are presented in Table 9.

TABLE 9
TEST THREE -- USER REACTION
OBJECTIVES AND MEASURES OF EFFECTIVENESS

Goal 3: Evaluate Perceived Benefits of the System

Objective	Measure of Effectiveness
A. Evaluate the driver perception of the PTMS in work zone applications	• Identify features and functions noticed by motorists • identify features and functions found confusing or not useful by motorists • Identify any practical suggestions provided by the motorists for enhancing the system
B. Evaluate the construction personnel perception of the PTMS in work zone applications	• Identify features and functions noticed by workers • Identify features and functions thought to be confusing or not useful by workers • Identify any practical suggestions provided by the construction personnel for enhancing the system

NOTE: Measures of effectiveness that were not available are shown in italics.

SRF and Norma K. Friedrichs & Associates (NKF) conducted the interviews and surveys used in the evaluation. The MOEs and related plans for data collection are shown in Table 10.

TABLE 10
TEST THREE -- USER REACTION
DATA NEEDS TO SUPPORT MEASURES OF EFFECTIVENESS

	Data							
Measures of Effectiveness	Autoscope Volume and Speed Data	TMC and State Patrol Logs	Motorist Surveys and Focus Groups	Construction Personnel Surveys	TMC Personnel Surveys	System Logs	Surveys of Partners	Measure
1. Identify features and functions noticed by motorists			XXX					
2. Determine if motorists find the information accurate, timely and useful			xxx					
3. Identify features and functions found confusing or not useful by motorists			XXX					
4. Identify any practical and useful suggestions provided by the motorists, construction personnel and TMC personnel for enhancing the system			XXX	XXX	XXX			
5. Identify features and functions intended to improve the traffic operations that did not have a significant impact	XXX	XXX	XXX	XXX	XXX	XXX		
6. Identify features and functions intended to improve safety that did not have a significant impact	XXX	XXX	XXX	XXX	XXX	XXX		
7. Identify other future applications of the system or portions of the system			XXX	XXX	XXX		XXX	XXX

7.2 Motorist Survey

A survey of motorists was conducted to assess the impressions the motorists had of the PTMS VMS and how the users reacted to the messages. The target motorists were those who drove through the I-94 work zone during the peak periods when the PTMS VMS messages were being operated. The drivers who qualified were identified and a survey was conducted by telephone.

The telephone numbers of the motorists using the work zone in the peak periods were obtained by the following process:

- License plates of non-commercial vehicles were observed and entered into laptop computers,

- Files containing the license numbers was delivered to the Minnesota Department of Public Safety (DPS) for processing,

- The DPS matched the license plates with owner registrations and provided a file that was stripped of confidential information and contained only the name and address of the registered owner,

- The file was delivered to Telematch, Inc., where the names and addresses were matched with the latest electronic files for listed telephone numbers and a file and printout of the resultant phone numbers was returned, and

- Norma K. Friedrichs and Associates, Inc., (NKF) used the resulting printed telephone numbers to conduct the telephone survey.

The survey form was developed by the Project Evaluation Team with additional assistance from Mn/DOT staff. A copy of the survey form used in the telephone interviews is presented in Appendix C. The PTMS VMS messages for each traffic scenario for the I-94 and I-35 work zones are presented in Appendix D. Note that the survey was conducted for motorists on I-94 and was done prior to the operation of the PTMS in the I-35 work zone.

The following are the key findings of the survey.

- Of the drivers surveyed, 66 percent remembered seeing the lighted PTMS VMS messages.

- Of that group, those who remembered seeing the lighted PTMS VMS messages,

  - 79 percent remembered one or more specific messages.

  - 51 percent said they took some action in response to the messages.

  - 61 percent said that they were “much more” or “somewhat more” informed about traffic conditions than in other similar urban work zones.

  - 90 percent said they received the traffic information they needed.

- Of the specific messages remembered,
  - 79 percent were considered “very easy to read” and 17 percent were considered “somewhat easy to read.”
  - Over 99 percent of the specific messages remembered were considered “easy to understand.”
  - 83 percent of the messages remembered were displayed far enough in advance.
  - The information contained in 76 percent of the messages was considered to be a correct indication of the current traffic situation.
  - 60 percent of the messages remembered were considered to be useful by the drivers.

The overall conclusion from the survey of the motorists who drove through the I-94 work zone when the PTMS was operational is that the work zone application of the PTMS was well received. It should be noted that these very positive reactions to the PTMS messages are from the survey of the I-94 portion of the operational test, where communication problems resulted in somewhat less real-time information being provided to the motorists than was planned.

7.3 System Operator Interview

The two persons who operated the PTMS as it was deployed in the work zones were interviewed. The interviews provided information on the length of time needed for training, ease of use, usefulness of the system, problems encountered and suggestions for improvements. The following are the key responses of the operators:

- Operation was mastered with approximately 2 to 3 hours of training.
- All aspects of the system were easy to use and all functions were useful.
- No technical system problems were encountered in the operating system.
- The suggested addition of an audible alarm to warn the operator that speeds had fallen indicating an incident has been incorporated.

7.4 Construction Personnel Interview

The construction supervisory personnel for the two work zones were interviewed to determine their reaction to the PTMS Work Zone Application as it affected construction personnel. In both cases they indicated that the PTMS did not impact the construction personnel because of the fact that the construction activities in the two work zones were exclusively behind temporary or permanent barriers. It should be noted that this is the condition where construction activities are protected by barriers. The benefits of any improvement in traffic control would likely result in improved worker safety for those construction zones where protective barriers are not present throughout the sight.

7.5 Transit Operations Personnel Interview

Metropolitan Council Transit Operations drivers on bus routes using I-94 had the same access to PTMS messages as the average motorist. There were no comments on the system passed on to operations personnel. Transit dispatchers had access to the video from the World Wide Web sight. The dispatchers found that the anticipated significant delays (up to 20 minutes expected) never occurred and so they did not re-route buses from I-94. However, dispatchers indicated that they felt that the video information from the PTMS via the Internet was potentially very useful for construction projects that would have a greater impact on traffic delays than did the I-94 construction project.

7.6 Focus Group Results

Three focus groups were conducted with drivers familiar with urban work zones for the purpose of obtaining the opinions related to the improvement of the work zones from the perspective of the motorists. Two groups were drivers who regularly drive during peak traffic periods and the third was a group of older drivers who typically traveled in the off-peak periods. The sessions Included general discussions about urban work zones and let the participants give their opinions about what they felt works well, what needs improvement and what types of improvements they suggest. The focus groups were also shown typical signs used in urban work zones and asked to comment on their opinions about the effectiveness of the signs. As was expected, the participants discussed a broad range of topics related to work zones. However, the portion of their discussion that related to work zone traffic control and signs is discussed here as it relates directly to this operational test.

The following are basic conclusions of the focus group that are relevant to this operational test:

- In general, the participants were complimentary about the traffic control and signing in work zones in the metropolitan area,

- The discussion called for more real-time traffic information in the work zones but also stressed that real-time traffic information must be accurate so that drivers do not learn to ignore it,

- They indicated that it is important that signs identify whether construction activity is and is not present, and

- They indicated that visibility and readability of the signs is very important.

7.7 Summary Of Analysis Of User Reaction

The results of the analysis of the user reactions are summarized as follows:

- 66 percent of the drivers surveyed remembered seeing the lighted PTMS VMS messages.

- Of those remembering the PTMS VMS messages, most remembered specific messages and felt more informed about traffic conditions.

- Of the specific messages remembered, very high percentages were considered easy to read, easy to understand, useful and correctly reflected traffic conditions.

- System operators indicated that the PTMS could be mastered in 2 to 3 hours, was easy to operate and reliable.

- Transit operators said the video surveillance feature would be very useful for rerouting buses from work zones causing significant delays.

- Focus groups called for real-time traffic information that was easy to read and the motorist survey indicated the PTMS was successful in these respects.

8.0 TEST FOUR -- SYSTEM COSTS

8.1 Overview

Individual test four evaluated the cost of deploying the PTMS in work zones. This consists of the costs of the system and the cost to locate the system in the field and set it up.

The typical work zone application of the PTMS is intended to supplement the conventional traffic control devices in a work zone. As such, much of the cost of the system would be additional to a construction project. Therefore, its cost must be assessed in comparison to the additional benefits it provides.

The hypothesis to be tested was as follows:

- The cost to deploy and operate the PTMS will be comparable to the overall benefits of the system.

The objectives and related measures of effectiveness that were used to analyze the system cost of the PTMS in the work zones are presented in Table 11.

TABLE 11
TEST FOUR -- SYSTEM COSTS
OBJECTIVES AND MEASURES OF EFFECTIVENESS

Goal 4: Evaluate System Costs

Objective	Measure of Effectiveness
A. Compare staff time and costs to operate the system (estimated to be typical of fully developed system) with conventional work zone traffic controls	• Staff time required to operate and maintain the systems • Cost of staff time
B. Compare deployment costs of the PTMS in a work zone application (estimated to be typical of fully developed system) with costs of conventional work zone traffic controls	• Total cost of fully developed hardware and software • *Total cost of conventional work zone traffic controls*

NOTE: Measures of effectiveness that were not available are shown in italics.

SRF collected the information used in the evaluation. The MOEs and related plans for data collection are shown in Table 12.

TABLE 12
TEST FOUR -- SYSTEM COSTS
DATA NEEDS TO SUPPORT MEASURES OF EFFECTIVENESS

	Data	
Measures of Effectiveness	Surveys of partners	Measure
1. identify costs to operate the system	XXX	XXX
2. Identify costs to deploy the system	XXX	XXX

8.2 System Cost

The cost of the system as deployed in a work zone depends upon the particular needs for the work zone. This is because the PTMS consists of a basic system to which a number of optional pieces can be installed to tailor it to the specific conditions and needs of the work zone. A single PTMS deployment cost is not necessarily relevant to another work zone deployment. Therefore, the costs presented are based on the cost of each basic PTMS unit with the cost of the various components and options listed. The price list of the basic PTMS and its various components was provided by ADDCO on April 9, 1997. The prices are presented in Table 13.

8.3 Deployment Cost

The cost to deploy the system in a construction zone would be based on the level of effort to accomplish the following tasks:

- Plan for the siting of the PTMS nodes,
- Install ISDN lines,
- Prepare and configure system,
- Deliver system,
- Set up the system,
- Monitor the system (daily cost),
- Remove the system

The planning for the siting of the PTMS nodes in the work zone should be done at the early stages of the project when developing the construction staging plans and general traffic control. The additional effort necessary to include the PTMS in the work zone will

TABLE 13
ADDCO PRICE LIST FOR PTMS COMPONENTS FOR WORK ZONES

Component	Cost
The Basic System consists of the following components:	
1. Skid Mount platform providing a 40-foot tower	
2. CCTV Camera with Precision Pan/Tilt/Zoom unit	
3. Video compression / control processor	
4. 900 MHz. Spread Spectrum Wireless Ethernet Communication	
5. 600 watt Tilt and Rotate Solar Panel with 3,520 amp/hour battery pack	
Price for the above Basic Package is (note 1)	$59,850
The following options are available:	
6. 3X6 foot 24 by 48 pixel LED Message Sign (note 2)	$9,800
7. Optional Autoscope Machine Vision System (note 3)	$20,200
8. Speed Radar option (note 4)	$2,000
9. Basic Skid Trailer Option (note 5)	$4,000
Required Base Station / Land Line Communications and Control	
10. Solar Powered pole mount Relay/Termination	$6,800
11. ISDN Router for above (1 required)	$1,200
12. ISDN Router for Control Computer (1 required)	$1,200
13. ADDCO Base Station Software (Win 95/NT) (note 6)	$6,800

Configuration Notes:

Note 1: Minimum Surveillance System configuration using wireless communications from skid to ISDN land line and single control point would require items 1, 2, 3, 4, 5, 10, 11, 12 for a cost of $78,850. Each additional node would cost $59,850.

Note 2: Message sign must be ordered on skid from factory. Sign can not be field installed unless skids are ordered with mounting components installed.

Note 3: Autoscope can be added to any node (for field installation, add $1,500 for field upgrade kit).

Note 4: Speed Radar option can be field installed.

Note 5: Trailer option allows skid to be removed and used as skid.

Note 6: Software requires Pentium Processor running WIN 95 or NT, with 10BT Ethernet installed. ADDCO can provide computer system with software installed, contact factory for current price.

TERMS

All prices are FOB St. Paul, Minnesota. Delivery is 10 weeks ARO.
Prices include 2 days on-sight installation and training support.

include identification of sights that will both provide the space for the PTMS nodes as well as providing the proper location for the VMS and traffic monitoring devices. In complex work zones where there are significant grades and obstacles a visit to the work zone would be advised. However, as the designer becomes more familiar with the placement of the PTMS nodes the level of effort will be reduced significantly. After the designer is experienced with locating PTMS nodes it will likely become an insignificant part of the construction staging and traffic control design process.

The wireless communications potential for each candidate sight must be evaluated. This requires two wireless radio units to assess the radio signal integrity between the location selected for the base node and the other locations identified. For the operational test at I-35, this process required two persons and took about 1 to 1.5 hours at the sight plus travel time to and from the sight.

At the present time, the availability, installation cost and monthly cost of ISDN lines varies greatly across the country. Anyone interested in using this system should make a check on the availability and costs of ISDN lines one of the first steps in the process.

The cost to prepare the system for deployment in a work zone will depend somewhat upon whether the system is currently configured to meet the needs of the work zone or it will need to have additional devices added to it. For this analysis it was assumed that the PTMS would have all of the available optional kits installed so that any additional devices could be added by simple installation. It is difficult to quantify the cost of adding all of the various combinations of devices but the cost would be relatively minor given the basic design of the system and the relatively simple installation that would be required. Therefore, the preparation of the system for deployment can be assumed to be very similar to the effort to redeploy the system. The re-deployment of the system at I-35 provided a good indication of the level of effort to prepare the system. The preparation required a basic system test to ensure that all components were operational which took approximately 1 to 2 hours and then the batteries were fully charged overnight.

Loaded the PTMS skids onto a flatbed truck equipped with a boom takes only a few minutes (about 15 minutes to load two skids in this operational test). It takes about 15 minutes to set each skid in its selected location (after lane closures are accomplished, if necessary). The cost of the delivery and drop-off will be dependent on the distance of the work zone from the source of the PTMS equipment.

The system setup requires two trained personnel. This assembling and deploying the VMS, raising the tower to a vertical position and extending it to its full height and unfolding and rotating the solar panels into position. This entire process takes about 40 minutes for each PTMS.

Configuring the Autoscope system for PTMS equipped for Machine Vision requires a person who has been adequately trained in its operation. The actual time needed to set the system varies from skid to skid because of the number of lanes, the number of detection zones specified and the complexity of the particular sight. However, the time to set up each node would typically take about 20 to 30 minutes. The Autoscope units can be remotely accessed and all setup operations done remotely. So trained staff, such as TMC personnel can perform this task.

Monitoring of the system will depend on a number of variables. First, a feature is currently being developed where VMS message selection by the PTMS is automated based on Autoscope speed data. This will essentially reduce monitoring time to having an operator available to check the system when the PTMS sounds the audible warning when speeds have dropped to a threshold specified by the operator. Prior to this, the cost of monitoring will be dependent on the number of peak periods monitored, the length of the periods and the number of days the work zone will require the PTMS.

All of these variables make it very difficult to perform a specific benefit/cost analysis. The actual costs will depend on such things as the type of work zone, number and configuration of PTMS nodes, availability and cost of ISDN service, availability of staff with the proper training, number and length of the congested periods to be monitored and availability the automated sign selection feature. When these variables are coupled with the length of time the system will be deployed in a work zone it makes it very difficult to provide a typical benefit/cost analysis. Therefore, the cost analysis is best assessed by the reader of this report based on the requirements of a particular work zone and the benefits outlined in Section 5 discussing traffic impacts and Section 7 discussing user reactions to the PTMS.

8.4 Summary Of Analysis Of System Costs

The results of the analysis of the user reactions are summarized as follows:

- The cost of a operational PTMS depends on the number of PTMS nodes needed and the additional optional equipment needed.
- The cost for a basic PTMS with all necessary communications equipment is $78,850.
- Additional basic nodes would cost $59,850.
- Deployment cost will vary based on distance from PTMS equipment source, number of PTMS nodes and ISDN installation cost and monthly charges.
- The feature being developed to automatically change sign messages based on speeds detected will significantly reduce staff time to operate the system.

9.0 LESSONS LEARNED AND KEY ISSUES TO BE RESOLVED

9.1 Overview

During the PTMS Work Zone Application operational test some valuable lessons were learned and some key issues arose that will need to be resolved. This section summarizes the lessons learned and presents the key issues that need to be resolved for future deployments. It also identifies changes that have been made or are being made in response to the experience gained in the operational test.

9.2 Lessons Learned

9.2.1 Effect of PTMS Node Location on Wireless Communications System

The PTMS was found to operate as intended at the I-35 work zone whereas this was not the case at the first deployment at the I-94 work zone. One reason for the difference in performance was the difference in the work zone physical layout. Another reason was the additional development work done by ADDCO during the I-94 deployment and prior to the deployment at I-35.

The main problem at the I-94 sight was the spread spectrum radio performance. A significant level of effort was required to isolate the basic cause of the problem which turned out to be multipath interference and a software bug that caused the radio to turn off its ethernet port when it could not make contact with another radio within a period of time. This resulted in a lack of consistent communications which caused some of the skids to go off-line until they could be restarted. This required going out to the skid to restart the system. Therefore, the overall system did not operate consistently at the I-94 sight.

The lesson provided by this experience is the importance of the physical sight and the placement of the skids. The multipath interference in this test caused significant problems that prevented the system from operating as intended. Also, the software bug made this multipath problem even more severe by requiring that technicians had to visit the skids to reactivate them. It is important to locate the root radio to minimize the number of radios through which signals must be transferred. Also, care is needed when locating nodes near bridges, large metal structures and high retaining walls because the resulting multipath interference can cause problems. ADDCO is addressing the siting issues.

9.2.2 Effects of Construction Activity on PTMS Skids with Machine Vision

The PTMS skids with the Machine Vision cameras are very sensitive to any construction activities that could cause the skid to be moved or to settle into the soil. The Machine Vision camera is mounted high on the 40-foot tower, any movement of the skid can result in significant changes in the aim of the camera. The results of this are that the Machine Vision will not work properly and will need to be setup and validated again. Perhaps the best solution for this is to have the construction contractor responsible for the operation of the PTMS in the work zone. In this way the contractor can be made aware of the importance of not affecting these skids and can take the appropriate action necessary to ensure that this is accomplished.

9.2.3 Automatic Camera Return Position

There was initially a problem with the aiming of the cameras for the Machine Vision system. The cameras would be aimed, the Autoscope zones defined and the system operation validated. Subsequent checks of the data showed that the camera aim had been changed and not returned to the proper position. This problem occurred whenever there was any interruption of power. During the course of the test the software was revised so the camera returns to the last position on power-up and an automatic log of all camera positions has been incorporated. This effectively solved the problems encountered because it was only a problem when the system was running without an operator watching the video outputs..

9.2.4 Staffing of the System

The system is based on providing real-time traffic information to the motorists. To accomplish this in its configuration as tested a staff person must be actively operating the system during any periods of congestion. This requires a staff person to be assigned to the system as their primary task. In response to this ADDCO is developing the software necessary to have the Autoscope speed data gathered at the various skids to control a set of messages. The intent is that the staff person would still need to be available to monitor the system but not have to have full time control of the system.

9.3 Key Issues To Be Resolved

9.3.1 Multipath Radio Interference

The problem with the multipath radio interference poses a potential problem for use of the PTMS in any work zone that has significant horizontal and vertical curves and significant structures in the form of bridges, retaining walls, large metal structures, etc. The limiting factors that affect the spread spectrum radio system need to be determined. Until this occurs, care should be taken when using radios to help locate the sights for the PTMS skids. Also, ADDCO is developing procedures and services with the intent to minimize these siting problems.

9.3.2 Radio Ethernet Port Closure

The problem with the radio software closing the ethernet port on the radio is being investigated by ADDCO and the radio supplier. This is believed to be a software bug that did not occur in previous applications of the radio. Resolution of this will make this vital communications link more reliable and will greatly benefit the overall performance of the PTMS in work zones.

9.3.3 Automatic Operation of the System

The extent to which the system will be able to operate automatically based on the speed output of Autoscope will need to be determined. The sensitivity of the data collected to the aiming of the cameras will continue to require human observation. ADDCO is currently in the process developing the software to provide the capability for the PTMS to automatically change the VMS messages based on the speeds sensed by the Autoscope units. This provide for automatic operation of the messages along with operator notification of the low speed condition. The PTMS will indicate and alarm, audible and visual, when the observed speeds fall to a level preset by the operator.

9.3.4 Expertise Required in Deployment

The expertise that is required to deploy the system will need to be determined. Currently it appears that the complexity of the system will either require special personnel to be used or extensive training will be needed. The extent to which the system can be made simple to deploy will depend on additional setup features to be added and well written detailed instruction manuals. Again, ADDCO is currently developing procedures and services to simplify the deployment effort. The expertise needed can be developed through training programs. Also, it is possible that the expertise will be developed by the companies around the country that provide traffic control services.

9.3.5 Integration into Traffic Management Center

The installation and remote operation of the PTMS in a work zone application was successfully demonstrated. Also, the exporting of the video signal and data from the Autoscope units to a World Wide Web sight was demonstrated. Based on these successful demonstrations and the fact that the PTMS was designed to use TCP/IP communications protocol, it is assumed that the full integration of the PTMS into a typical Traffic Management Center could be accomplished without a significant level of effort and without substantial development time.

10.0 SUMMARY, RESULTS AND CONCLUSIONS

10.1 Summary

Overall, the operational test of the PTMS in a work zone application was successful. There were some problems encountered with the wireless communications system that indicated care must be taken in the siting of the PTMS nodes and in the configuration of the wireless communications system within the work zones. However, the overall system was relatively easy to deploy and operate, it showed beneficial effects on traffic and was well received by the motorists.

The PTMS is currently being deployed in three locations. Two PTMS nodes are deployed at I-94 in the area of former work zone to provide the TMC with video surveillance. The PTMS will be continue to be used for this function on this high volume freeway segment until the permanent video surveillance equipment is installed. Also, Maryland Department of Transportation is testing the PTMS for its remote surveillance capabilities.

The PTMS has recently been deployed as part of a major bridge reconstruction- The PTMS was included in the contract specifications for traffic control on the project so this is a full deployment rather than an operational test. The PTMS was specified on the basis of unit cost per day. The system consists of two PTMS nodes, each with VMS, Autoscope and surveillance cameras. In addition, there are five trailer mounted VMS. The trailer mounted VMS used in this operational test had standard cellular phone connections for communications. This is a relatively slow process for transmitting the data needed to operate the trailer VMS. The communications has been revised for this deployment to be via Cellular Digital Packet Data (CDPD) which provides a much faster communications link for more rapid response to changing traffic conditions.

10.2 Results and Conclusions

Analysis of Traffic Impacts

- There was a significant increase in the traffic volume that moved through the work zone when the PTMS was in operation (3.6 percent in the morning peak period and 6.6 percent in the afternoon peak period). The more orderly flow of traffic appears to have resulted in increased capacity.
- There was a significant decrease in the traffic volume that exited I-94 to TH 280 in the afternoon peak period (5.3 percent). This is likely due to increased driver confidence in traveling through the work zone because of the real-time traffic information provided by the PTMS.

- The PTMS decreased the variability in speed for traffic traveling within the work zone by over 70 percent which suggests improved safety.

- The PTMS decreased the average speed for traffic approaching the work zone by 9 miles per hour which also suggests an improvement in safety as vehicles approaching the work zone slowed down sooner.

Analysis of System Operation

- PTMS can be deployed in a wide variety of work zones with relative ease.

- The actual time to prepare, deploy and set up each node is relatively short, especially given the complexity of the PTMS equipment and its capabilities.

- The PTMS is a unit that would be set up in work zones with special traffic needs.

- The PTMS was successfully installed and operated at the TMC.

- The PTMS was developed using TCP/IP communications protocols to simplify integration into existing TMCs.

- The overall system operation was successful.

- The machine vision cameras mounted high on the towers require care that construction activities do not inadvertently cause the skids to move.

- The Autoscope setup is not complex but requires some special training.

- The PTMS video and data can be successfully transmitted over spread spectrum radios.

- Care must be taken in siting the nodes to avoid multipath interference problems.

Analysis of User Reaction

- 66 percent of the drivers surveyed remembered seeing the lighted PTMS VMS messages.

- Of those remembering the PTMS VMS messages, most remembered specific messages and felt more informed about traffic conditions.

- Of the specific messages remembered, very high percentages were considered easy to read, easy to understand, useful and to correctly reflect traffic conditions.

- System operators indicated that the PTMS could be mastered in 2 to 3 hours, was easy to operate and was reliable.

- Transit operators said the video surveillance feature would be very useful for rerouting buses from work zones with significant delays.

- Focus groups called for real-time traffic information that was easy to read and the motorist survey indicated the PTMS was successful in these respects.

Analysis of System Costs

- The cost of a operational PTMS depends on the number of PTMS nodes needed and the additional optional equipment needed.

- The cost for a basic PTMS with all necessary communications equipment is **$78,850.**

- Additional basic nodes would cost $59,850.

- Deployment cost will vary based on PTMS delivery distance, number of PTMS nodes and ISDN installation cost and monthly charges.

- The feature being developed to automatically change sign messages based on speeds detected will significantly reduce staff time to operate the system.

APPENDICES

APPENDIX A

World Wide Web Site

Minnesota Department of Transportation Real Time Work Zone Traffic Data

I-94 & University of Minn.

HOME [traffic data] [images] [schedule] [info]

This web site is *not* under construction but I-94 is!

Traffic sensor data and camera images are collected from the work zone and are uploaded to this web site. The traffic sensors measure average vehicle speed in the construction area. This data is presented by sensor and location. Sensors are located in the northbound traffic lane. The sensor data is uploaded to this web page every 2 minutes. We have several cameras sending image data here about every 5 minutes. The cameras are located in various locations in the workzone.

The camera images are about 30k in size. If you have a 14.4k baud modem, each image will take about 30 seconds to display on your computer.

A current construction schedule is also included to help you make travel plans.

This site also contains information about this Smart Work Zone project.

Link to current Minneapolis/St. Paul weather.

If you would like to comment on or get additional information on the Smart Work Zone project, you can e-mail Mark Cady at *mcady@nic.dot state. mn. us.* or send regular mail to :

District Traffic Engineer
MnDOT Metro Division
3485 Hadley Ave.
Oakdale, MN 55 **128**

This page was last updated on Sept. 6, I996.

Minnesota Department of Transportation
Real Time Work Zone Traffic Data

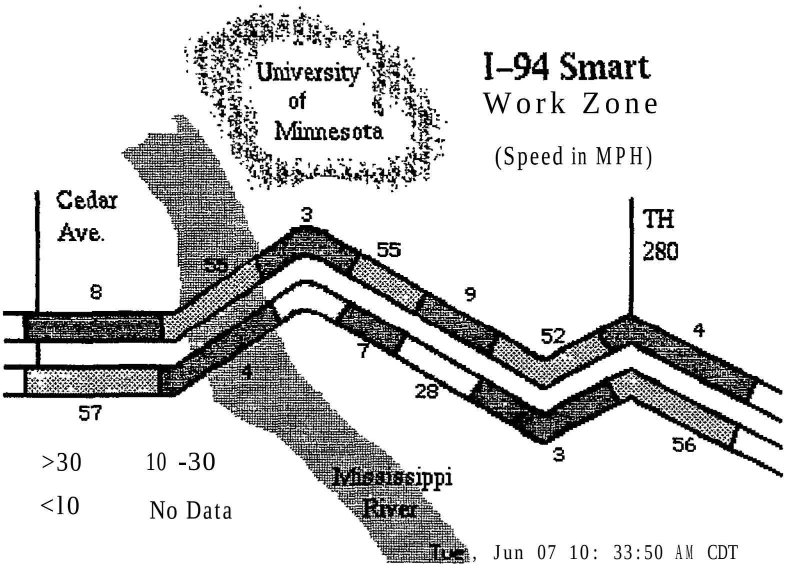
Mn/DOT I-94 Traffic Data for
Wed May 09 02:39:50 PM CDT

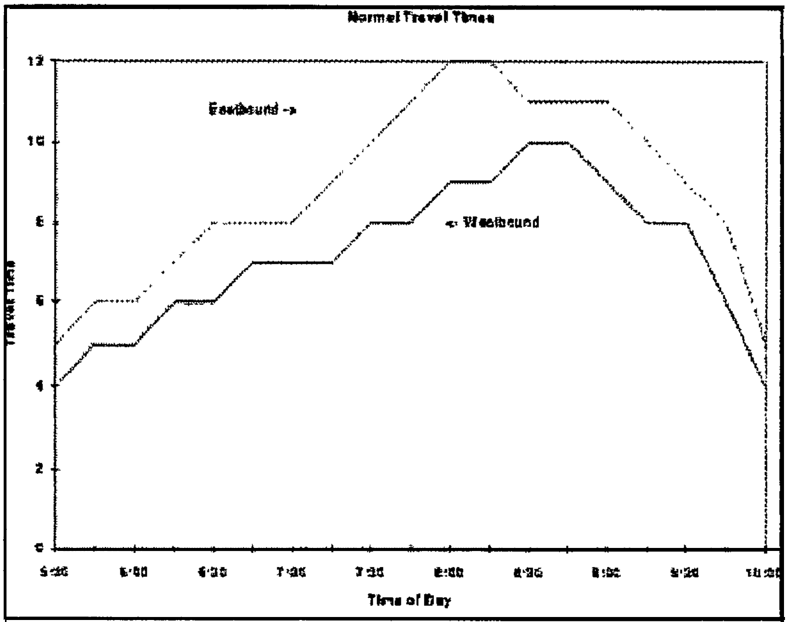
[home] TRAFFIC DATA [images] [schedule] [info]

Current travel time (minutes)
Eastbound = nd
Westbound = nd

I-94 Average Speed (MPH)	Cedar Ave	Riverside Ave.	U of M Exit	Minn 280
Westbound <---	nd	nd	nd	nd
Eastbound --->	nd	nd	nd	nd

nd = no data available





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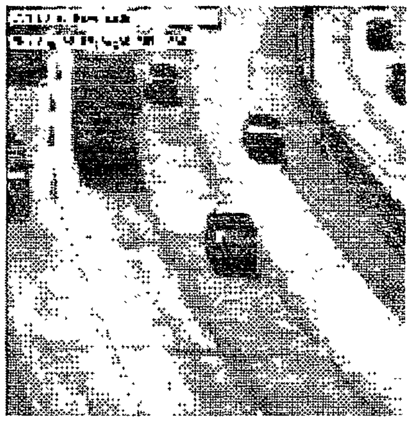
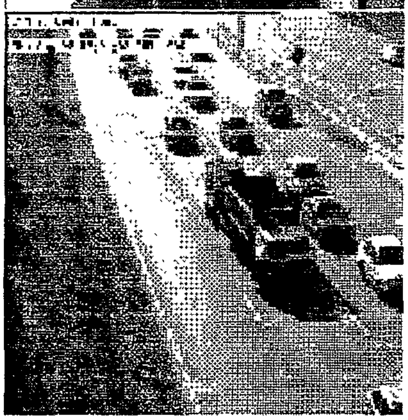
Minnesota Department of Transportation
Real Time Work Zone Traffic Data

I-94 Image Data

[home] [traffic data] IMAGES [schedule][info]

These pictures are updated every 5 minutes.
To see the full sized image just click on it.





No Camera image is available!

The views and opinions expressed in this page are strictly those of the page author. The contents of this page have not been reviewed or approved by the University of Minnesota.

APPENDIX B

NET Report

Review of Communications for the Smart Work Zone Project

1 Overview

During the Summer of 1996, two tests were conducted to evaluate the concept of a Smart Work Zone. The primary focus of the tests was on the operational use of vehicle detectors, surveillance video cameras, and changeable message signs to improve the safety and traffic flow of the work zones. As part of this focus, the communications networking was also evaluated.

The primary goal of the Smart Work Zone demonstrations was to evaluate the effectiveness of the equipment for managing travel and incidents in the work zone and the acceptance by the traveling public of this equipment. This report supplements that evaluation. As such, it focuses on the communications system, and its ability to support the operational requirements of the traffic management systems.

1.1 Operational Requirements

The primary function of the communications system is to transfer sensor detection and control information between the traffic operations center and the traffic control elements in the field. The operational requirements of the Smart Work Zone that affect communications include:

- detecting the speed of traffic in the work zone.
- providing video imaging to monitor traffic conditions and to provide incident verification.
- providing control of the video surveillance cameras.
- providing control of the changeable message signs.

Two methods were proposed to detect speed in the work zone. The first technique uses video image processing, ie, Autoscope. This technique establishes detection zones in the video image from a fixed position CCTV camera. By processing the video image, the volume and speed can be detected. A second technique, using radar detectors, was also proposed. These sensors would directly measure the speed of the vehicles using Doppler techniques. The radar detection was not successfully deployed due to apparent interfacing problems between the computers and the radar detectors.

The cameras used for the Autoscope were also used for surveillance. Special step-motors were used to pan and tilt the cameras. By using these special motors, the operators were able to return the cameras to their original orientation for vehicle detection.

The video from the cameras was "captured," digitized, and processed using a standard protocol. This technique captures and processes single images. These images are stored as data files and transmitted to the operations center on a regular basis. The operator has the ability to set the refresh rate and the quality of the picture being processed. Together these parameters establish the bandwidth requirements for the communications media.

The final requirement was to control the messages on the changeable message signs. The system allowed the operators to store fixed messages that could be used appropriately for recurring conditions. The system also allowed the operators to create and display new messages as required.

1.2 Communications Requirements

The operational requirements dictated that information be transmitted between the field equipment in the work zones and the operations centers. These data transfers consisted of real-time control signals to the cameras for their panning, tilting, and zooming (PTZ) functions, control signals to operate the changeable message signs, and video file transfers from the surveillance cameras to the operators.

To transfer data within the work zone, a communications included spread spectrum radios that were networked in a server/client architecture. As depicted in Figure 1, this architecture resembles and inverted tree with its root at the top. The server or “root” of this network was connected through leased circuits to the traffic management center.

The purpose of the communications analysis in this project was to determine how well these configurations and choices of transmission media satisfied the operational objectives of the project.

2 Communications Architecture

The architecture of the communications network consists of two different systems, each with its own architecture. The first network supports the field infrastructure and consists of a wireless local area network using carrier-sense, multiple access with collision detection (CSMA-CD). The server in this network resides at the primary or root node. All other nodes are “clients” and align themselves with the server node. A secondary function of the root node is to act as a gateway for the information collected from the field nodes. This gateway function interfaces the second network which is configured as a point-to-point communications link to transmit the data between root node in the field and the traffic management center,[1]

2.1 Field Elements

From the communications perspective, the field infrastructure can be broken down into

1 The term traffic management center is being used in a generic sense. In this case, the term indicates “any” system using traffic information to affect a safer or more efficient flow of vehicles in the work zones by disseminating information about conditions in the work zone to motorists and other travelers.

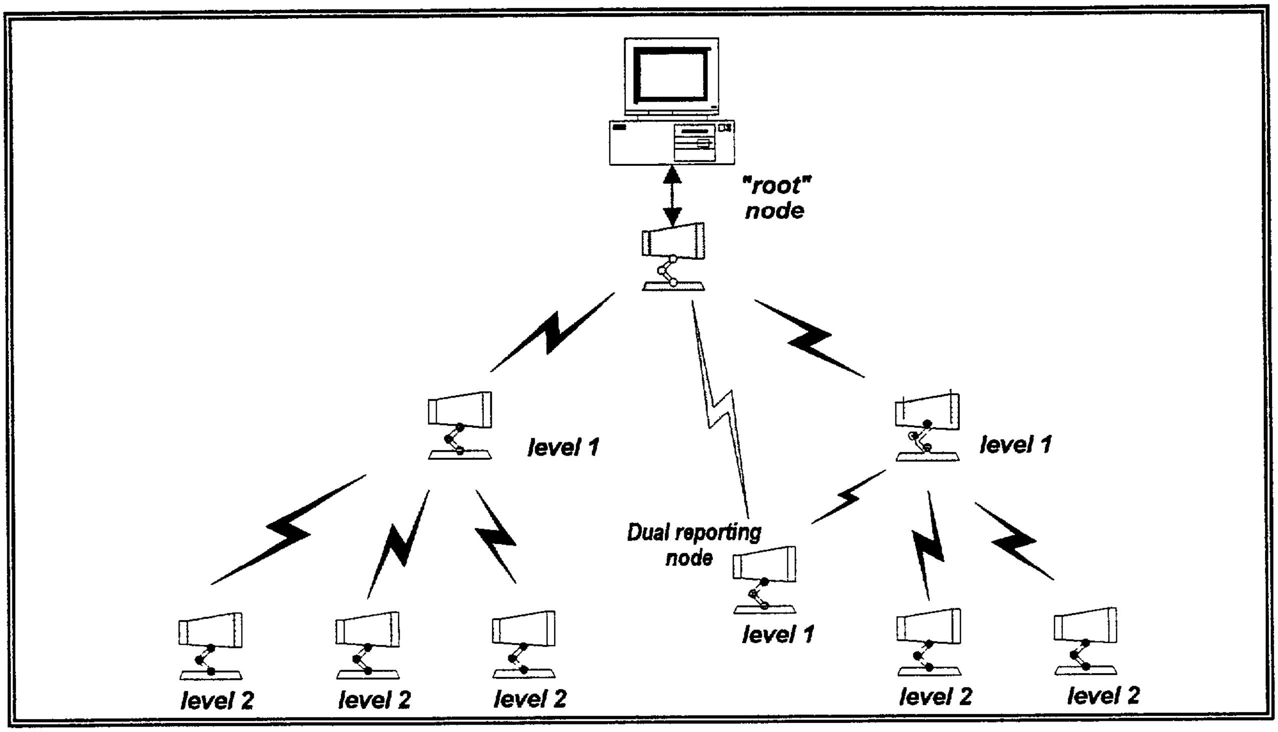


Figure 1 Architecture of Communications Field Elements

the central server or "root," the field elements with their bridging wireless radio transceivers, and the transmission path between the transceivers including antennas and transmission lines.

In the current system, the field elements are interconnected using Arlan Model 640 multipoint wireless bridges. These radios utilize spread spectrum transmission and the tcp/ip protocol. These radios have built-in intelligence to "learn" configuration of the network. When power is initially applied to the radios, they immediately begin monitoring the messages on the network to identify the addresses on the network and begin seeking the "root" or serving node.

If the node cannot talk directly to the root node, it will seek other nodes that are communicating with the root and attach itself to that node. These nodes will then act as repeaters for the information transfer between the initiating node and the root node.

The level 2 and higher radios are constantly seeking lower level repeaters or the root node. If propagation changes and a node closer to the root (including the root) becomes available, the existing tree will change to allow the transceiver to attach to the node closest to the root. In Figure 1, this is depicted as the dual reporting node. In this case, the closest node (physically or by signal strength) is at level 1. If, however, there is a direct path to a node operation at a lower level, the node will align itself with the node closest to the root. In the figure, the lower level node is the root.

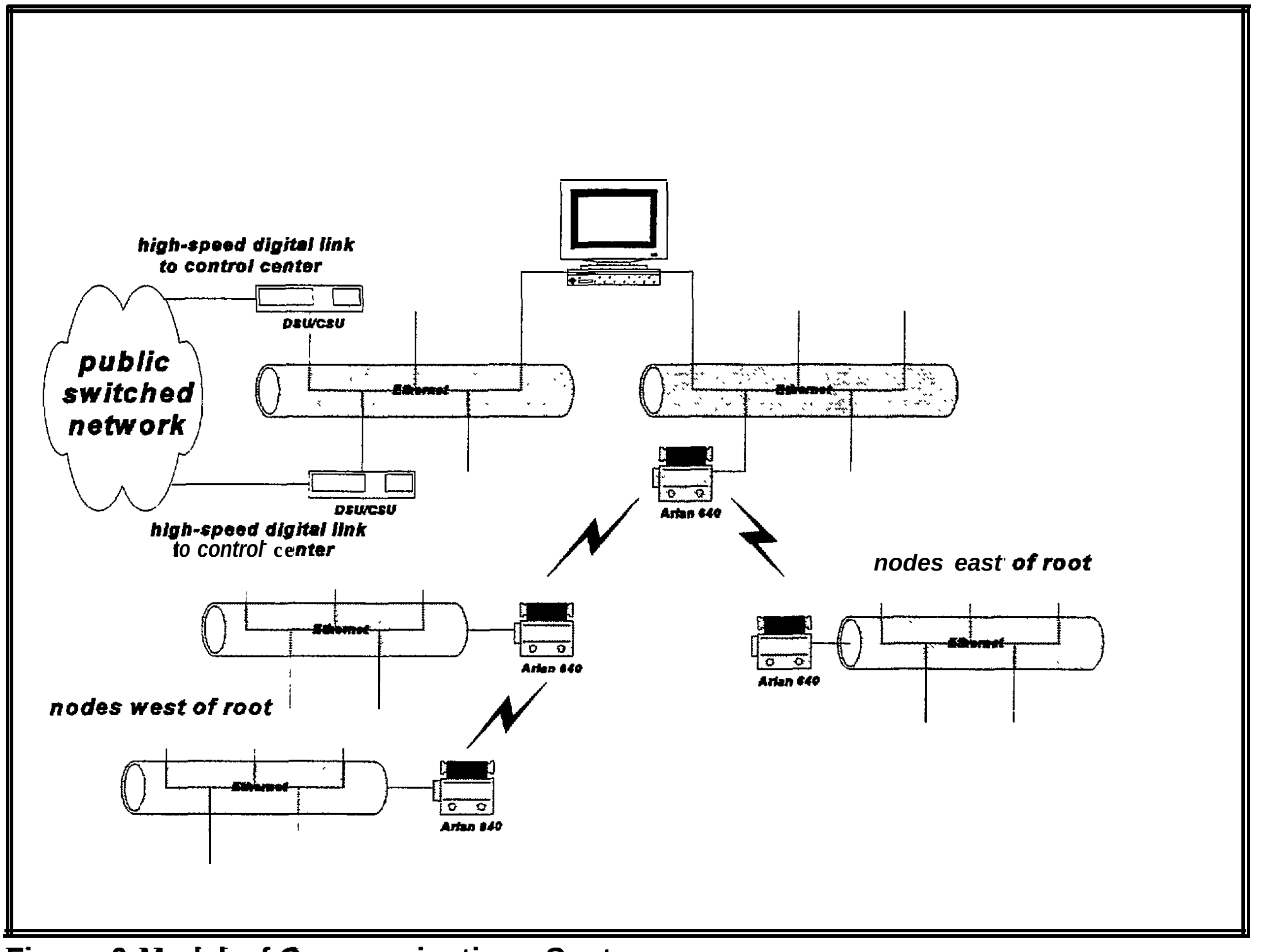


Figure 2 Model of Communications Systems

2.1.1 Model

Schematically, the communications network can be depicted as shown in Figure 2. Within the work zone, a site is selected as the root node. This site acts as the server for the nodes in the work zone and a gateway to the traffic management center. The equipment is physically connected within a node using a collapsed Ethernet. This provides flexibility, expandability, and simple interfacing. Likewise, using TCP/IP provides a simple, but effective means of adding elements to the network without changing the initial configuration of the equipment.

This communications model provides the greatest flexibility for designing and provisioning the transportable platforms or "skids." Each skid can be equipped with two single-board computers which connect to the Ethernet. These computers can each be assigned a TCP/IP address. The sensors can be connected directly to the I/O ports of the computers. This allows flexibility for supporting new and different sensors and equipment configurations.

The typical application includes vehicle detection, surveillance video, and a variable message sign. The information that is transmitted between the traffic management center and the skids in the field includes:

- JPEG[2]-encoded frames of video from the field to the tmc
- Camera control from the tmc to the cameras
- Volume, occupancy, and speed data from the field to the tmc
- Text and control signals from the TMC to the variable message sign

The transmission requirements are asymmetric. That is, the quantity of data flowing from the field to the tmc is an order of magnitude greater than the data following from the TMC to the field.

2.1.2 I-94 Deployment

The initial deployment of the Smart Work Zone equipment was along I-94 from just east

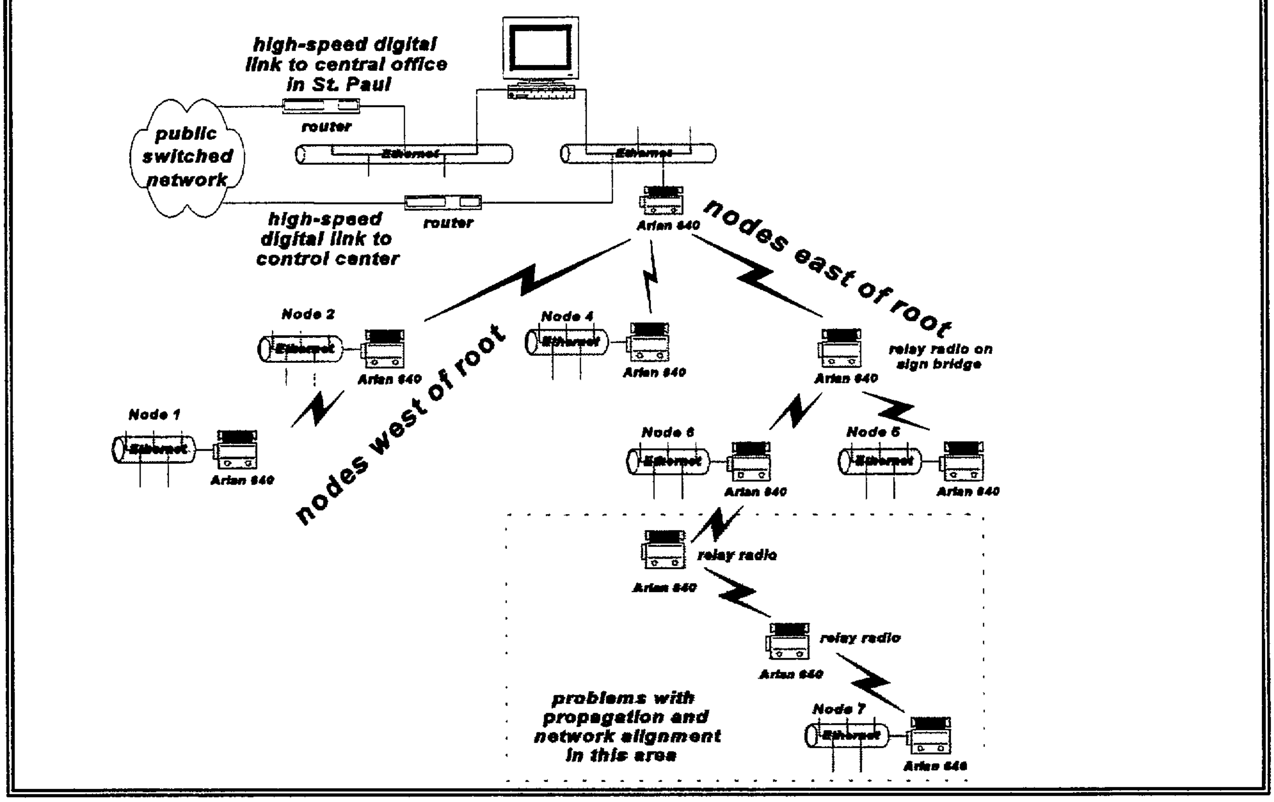


Figure 3 I-94 Communications Deployment

[2]JPEG is the standard protocol for encoding and compressing video images as identified by the Joint Photographic Experts Group.

of University Avenue to just west of 36th Street. Figure 3 is a schematic of this deployment. The root was located at the construction field office, just east of Huron Avenue. Two sites were located west of the root, one located south, southeast of the root, and six sites located east of the root. There were a total of five cameras and six changeable message signs. Two radios were used to relay information on the eastern end of the work zone and extend the limits of coverage to University Avenue.

Initially, there was only one radio to relay information. Due to problems with multipath propagation, an additional relay radio was added. This additional radio used an antenna mounted on a stub pole at a nominal height of 12 feet. Lowering the height of the antenna significantly reduced the affects of the multipath. The equipment that was affected by this multipath is shown on the drawing in the shaded area.

There was an additional communications problem with the units in the shaded area. The radios have internal algorithms that seek higher nodes closer to the root. At times, propagation would allow the nodes in the shaded area to "hear" a higher node on a short-term basis. When the propagation returned to normal, the radios did not find the original configuration and communications with the equipment was lost.

21.3 I-35W Deployment

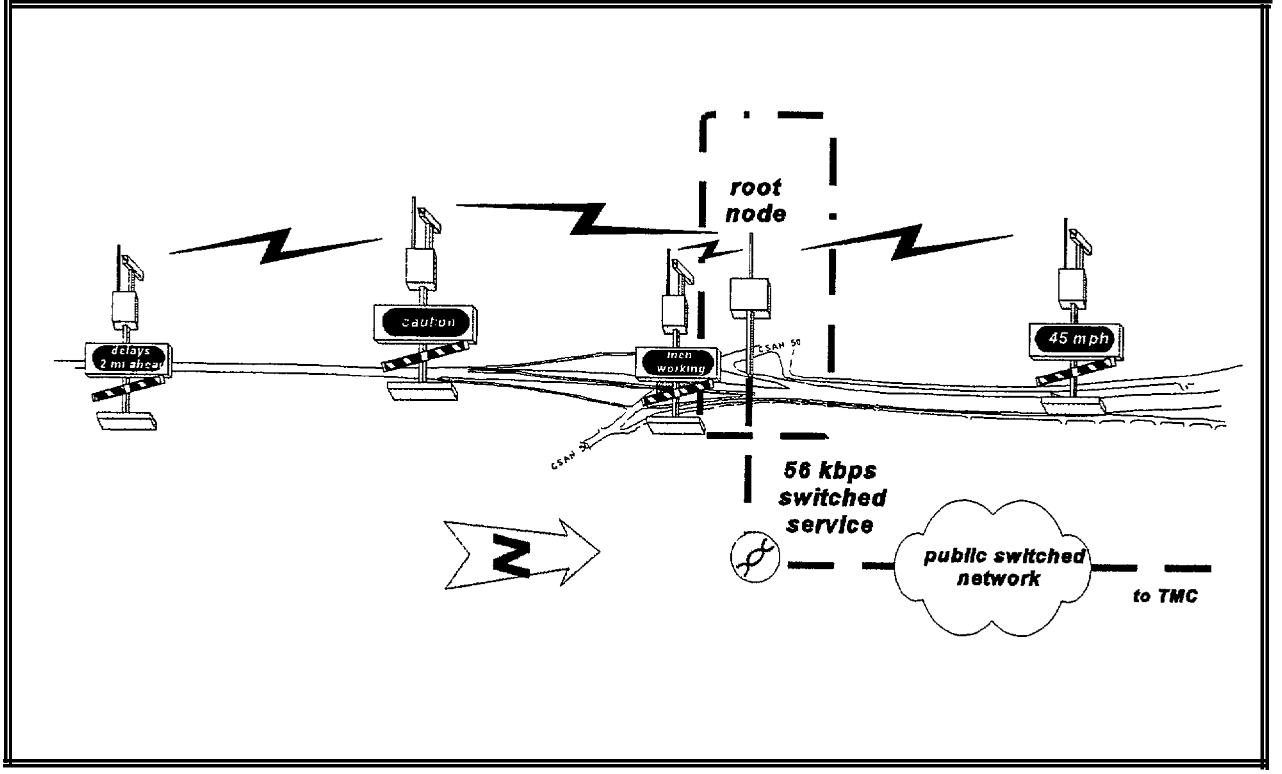


Figure 4 Deployment of System Along I-35

An additional test was conducted in a work zone on I-35. Based upon the results of the installation on I-94, additional time was spent locating the communications equipment.

The root node was deployed in a NEMA enclosure on a stub pole. The pole was placed next to **a** parking lot near an interchange. By placing the equipment adjacent to a commercial facility, access for power and telephone companies is easier.

The basic configuration of the equipment is shown in Figure 4. One skid was located north of the root and three skids were located south of the root. With the exception of the skid farthest south, all skids communicated directly with the root. Thus, the only radio that was attached to a node other than the root, was the one at the southern end of the work zone.

2.2 Field to Management Center

The root node in the field acts as a gateway between the field elements and the operations centers. A high speed transmission link is required to connect this node to the centers. The speed of this link determines the time that required to transfer the video files. This speed determines the rate at which the video images can be refreshed.

2.2.1 Requirements

The high speed links between the root node and the operations centers are required for three functions, the transmission of traffic data from the sensors in the field to the operations center, the transmission of video files from the cameras and their associated hardware to the operations center, and the transmission of control signals from the centers to the field equipment. These control signals include the control of the cameras and messages on the changeable message signs.

2.2.2 Deployment

For the I-94 deployment, the root computer was connected to two centers using Integrated Digital Services Network (ISDN) links. These links operate at a nominal data rate of 128 kbps, The first link was established between the traffic management center in Minneapolis and the root node. This link was used for the management of the field equipment. A second node was established between the central office in St. Paul and the root node. This link was used to transfer the video files from the field to the Internet server in St. Paul. This allowed MnDOT to provide video from the cameras on the Internet.

For the I-35 deployment, ISDN links were not available from the servicing telephone company. For this test, two 56 kbps “switched digital service” links were leased and used to connect the root node to the TMC in Minneapolis.

3 Deployment Criteria

In addition to the technical performance of the communications system, was the ability of deploying the equipment. There were initial considerations given to the technical communications parameters and their affect on the location and interconnection of the equipment. Additionally, there was the operational considerations of how construction personnel would actually place, interconnect, and network the communications elements.

3.1 Initial Considerations

Prior to the field deployments, several issues were identified concerning the communications deployment. These issues focused on the analysis of the communications subsystems and the installation of t'he field equipment.

3.1.1 Networking Criteria

In deploying repeaters and nodes, there are two primary elements which determine the maximum distance between nodes. The first of these is the receive signal amplitude, This level is a function of the transmitter power and the propagation losses and establishes the bit-error-rate of the link. The second element is the maximum round-trip delay of the signal. This parameter is based upon the collision detection window of the network itself. Each of these will be examined in greater detail.

Propagation Losses

The signal level at the receiver of any communications link determines the quality of the signal that is detected by the receiver. In an analog system, this is expressed as the signal-to-noise ratio and in a digital system this is expressed as the bit-error-rate. In a typical system, this is usually expressed as the system gain, where the system gain is defined as the output power of the transmitter minus the minimum power required at the receiver for a given bit-error-rate(signal-to-noise ratio).

The normal method of designing communications links is to estimate the path loss and ensure that the total path loss does not exceed the system gain. For a line-of-sight communications system, the nominal free space path loss is given by the formula

$$L_{fs} = 20\log(F_{MHz}) + 20\log(d_{miles}) + 36.6dB$$

The specifications for the Arlan 640 transceivers do not identify a value for the receiver's sensitivity. Thus, one cannot calculate the system gain directly. However, using their statement that the transceivers will operate six miles using yagi antennas with a nominal gain of 9 dB, one can substitute the values for the antenna gain and distance into the equation, along with the operating frequency of 915 MHZ, and obtain a nominal free space path loss of 93.39 dB. Since the transceivers will operate with this path loss, the one can substitute the 3 dB gain antennas and identify a nominal distance of 1.5 miles for line-of-sight operation using 3 dB omni antennas. As configured for the work zones, there are additional losses in the coax connecting the transceivers to the antennas that will decrease the range to approximately one mile.

The previous calculations all assume free space propagation. There can be increased path loss due to obstructions such as buildings, freeway structures, and trees. In addition, there are the affects of multipath propagation. Multipath propagation is the reception of signals traveling over different paths to the receive antenna. Depending on the difference in path lengths, these signals can either add constructively (to increase the signal level), or destructively (to decrease the received signal level). This will be discussed further in Section 4.2.

There are two additional losses associated with the propagation of radio waves, obstruction losses and absorption losses. The later of these losses is closely aligned with vegetation and moisture. Depending on the frequency of the radio signal, water molecules will absorb the radio frequency energy and produce heat. This is the phenomena used by the microwave ovens to heat their contents. Due to the moisture content of foliage and vegetation, there can be a significant loss of signal due to absorption at some microwave frequencies. In the frequency band used for this demonstration, however, there is minimal absorption of the radio waves and the loss associated with such is minimal.

Obstruction losses associated with the trees and other foliage can also be a dominant factor in the attenuation of signals.. A half-wavelength at 915 MHZ is approximately 6-9 inches. Conductive objects that have a nominal surface dimension of six-plus inches will reflect a significant amount of energy. Thus, trees along the freeway can significantly attenuate the signal if a clear line-of-sight cannot be established around them.

Collision Detection

The second issue associated with the distance between repeaters is associated with the collision detection algorithms. The local area network operates by sending information from the nodes in bursts or packets of data. Since any node can randomly access the media and transmit a packet, a specific protocol or procedure has been adopted to ensure that if two packets are transmitted at the same time, that they will be caught and re-transmitted. The procedure normally begins by detecting if any other node is currently transmitting (carrier sense). If there is, the transmitter will wait until the channel is apparently free and try again.

Even if the channel appears to be free, with no other node transmitting at a given time, there is the possibility that two nodes will attempt to both transmit their packets within a small fraction of time between each other and collide. The equipment is designed to sense these collisions take place. Under such circumstances, there is a set procedure to randomly wait until only one node transmits and the other recognizes the carrier.

The transceivers also have a finite amount of time that they monitor the link for a collision. To have the collision detected, it must be recognized by both transceivers within a specific time frame after the transmission is initiated. The mechanics of detecting collisions require that the information packet be echoed from the receiver back to the transmitter. This requires that the round-trip delay be less than the window established for the collision detection. For the IEEE 802.3 networks, this time delay has a maximum and based upon the speed of propagation for the transmission medium, can establish the maximum distance between nodes on the network.

With spread spectrum communications, it is possible to detect and possibly recover

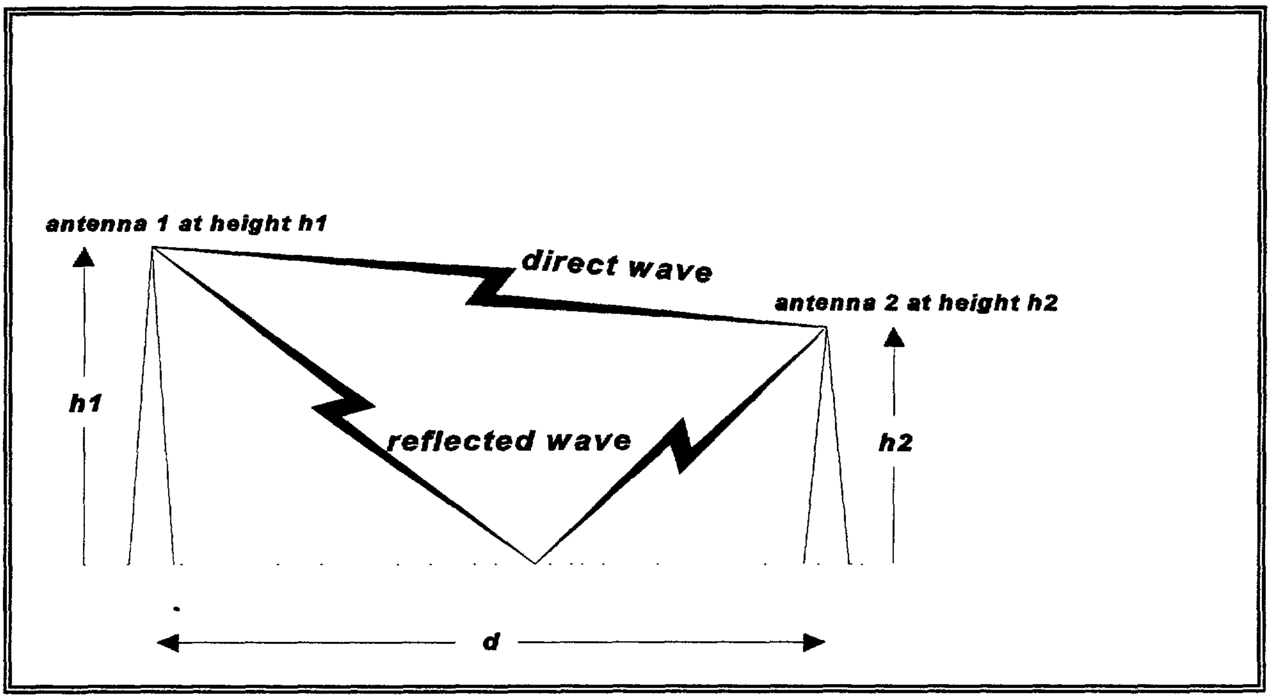


Figure 5 Model of Multipath Propagation

"colliding" signals if the signals are not synchronized. This could be another benefit of using direct sequence, spread spectrum communications. This advantage was not observed during there deployments. The instrumentation and configuration control was not available to arbitrarily increase the data density and measure the associated increase of collisions on the network.

<u>Interference</u>

There are two types of interference that are of concern in most communications systems. The first of these is interference from systems using the same frequency. This is of concern with these systems because they are unlicenced and there is no mediator. Should interference occur, it will be eliminated only through the good will of both parties. For the given radios and the conditions of their deployment, this concern has an extremely low probability of occurrence and mitigation, should the problem occur, would only require that the *System Identifier* on the radio be changed to another of the eight million options.

The second concern is front-end overload. This problem occurs when another transmitter keys-up in close proximity to the transceiver and has sufficient power to overload the receiver. Although spread-spectrum techniques were originally used by the military to avoid single-frequency jamming, some receivers are susceptible to this type of interference. The interfering signals are typically adjacent 800-MHZ public service systems or second order harmonics from the 450-MHZ systems.

3.2 Deployment Criteria

One of the non-technical issues that was considered in reviewing the communications on this project was the ability of non-technical personnel to deploy the system components. To do this, it would be necessary for simple criteria to be established to

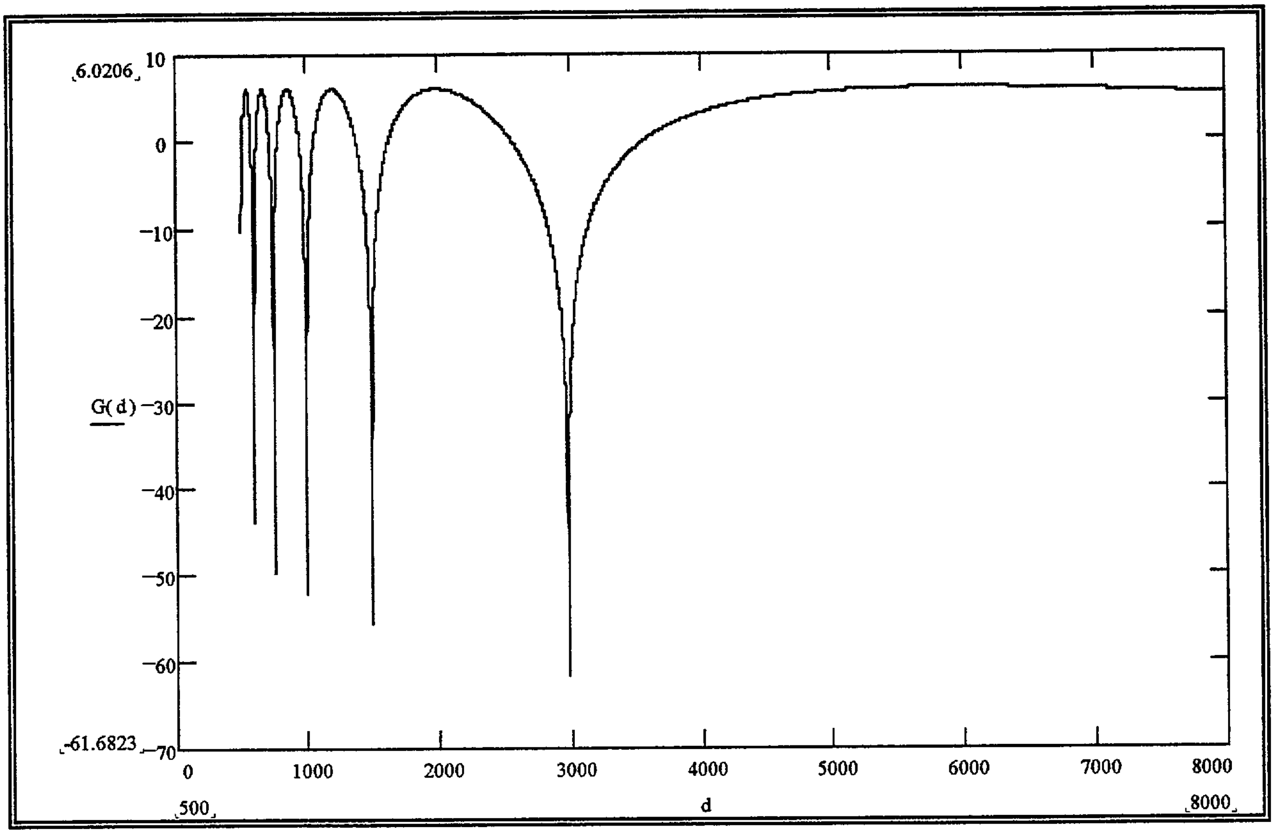


Figure 6 Antennas at a nominal height of 40 feet

allow the locations to be identified without the need to "engineer" each of the communications links. Typical criteria might include the following:

- Maximum distance between transceivers
- line-of-sight between antennas
- optical clearance between propagation paths and structures, obstructions, and trees
- establishing the identities of the network elements and nodes

4 Results

4.1 Feasibility Analysis

Both the I-94 and the I-35 deployments demonstrated that it is feasible to use spread spectrum communications to tie field elements to a central location. The design of the radios did not provide access to quantitative data that could have been used to "measure" the actual performance of the individual links.

4.2 Mulltipath Issues

Multipath is the interference of the primary signal that has traveled over two different paths. As depicted in Figure 5, the simple model usually considers the primary wave and one that has a single reflection. The equivalent heights of the antennas over a "flat earth" are h1 and h2 respectively. Depending on the difference in path lengths relative to the wavelength of the radio wave, the interference can be either constructive or destructive. Assuming the antennas are more than several wavelengths apart, the associated "gain" is a function of the distance and the relative antenna heights. It can be can be written as

$$G_{dB}(d) = 20\log[2\sin(\frac{\pi\delta(d)}{\lambda})]$$

where

$$\delta(d) \approx \frac{2 \cdot h1 \cdot h2}{d}$$

In Figure 6 the gain is plotted as function of distance for nominal antenna heights of 40 feet. There are several nulls in the range of 500 feet to 3000 feet. Figure 7 plots the gain for nominal antenna heights of 20 feet. By lowering the antennas, the number of nulls is reduced to one over the same distance.

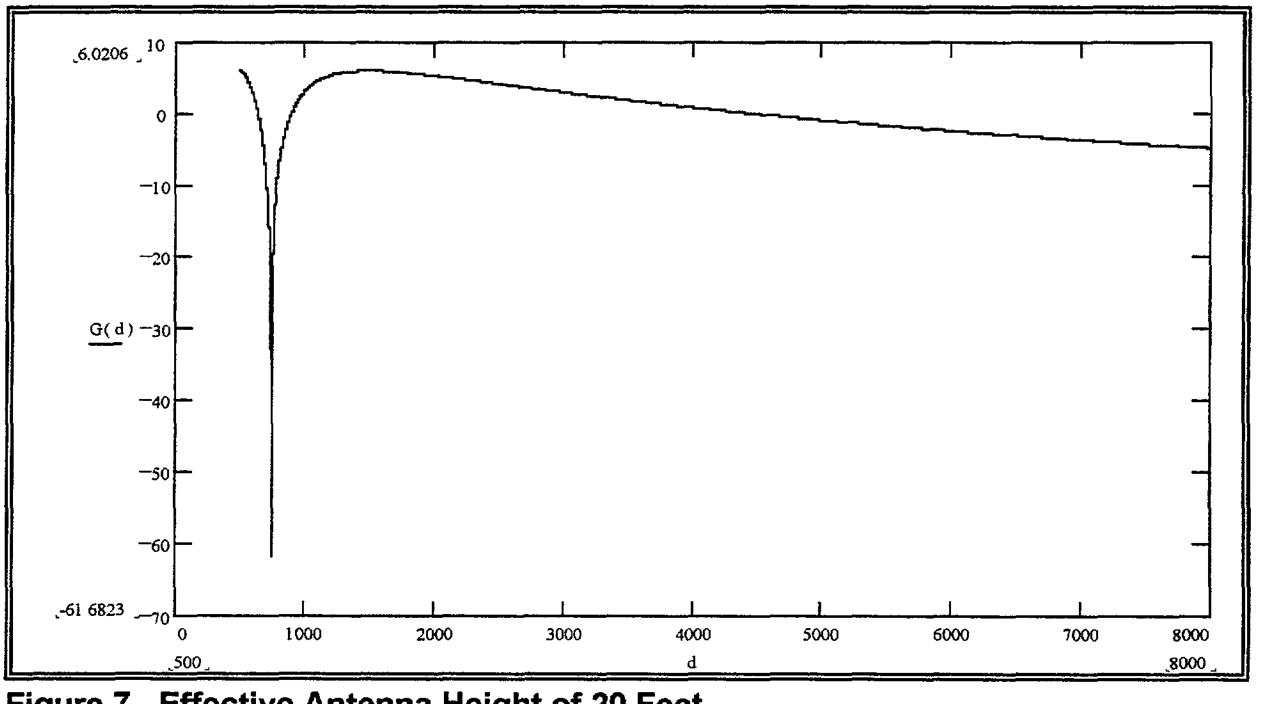


Figure 7 Effective Antenna Height of 20 Feet

The problem that was observed on I-94 was associated with multipath caused by the vehicles. Figure 8 represents the same radio wave in Figure 5 when it is reflected off of a vehicle. The reflection will change the free space path length and the apparent gain. As depicted in the figure, the vehicle reflection is equivalent to changing the equivalent height of the antennas. In this case, the apparent height of the antenna is the difference between the original height and the height of the truck.

For the traffic management environment, the effect of the reflections off of the moving vehicles is similar to the multipath effects of moving vehicles with signal fading. In this case, however, it is the characteristics of the propagation that are changing and not the position of the mobile antenna. It cannot be assumed that the stochastic characteristics of the associated channels are equivalent. In addition, it should be noted that there can be a strong correlation between a significant fade in the signal and the presence of congestion. Stated differently, the probability that there will be a loss of signal is proportional to the probability that the system operators will be using the field elements requiring the signal path.

Continued investigations and field tests should be conducted to further refine the deployment models. There have been several investigations into developing channel and propagation models for deploying the spread spectrum radios in a factory environment. For these applications, multipath is an issue, but the distance characteristics are different than those observed in the Smart Work Zone. Likewise, propagation has been extensively studied for systems operating at 900 MHz. However, in most cases these systems system include mobile or portable units that are in motion. The multipath problem for these systems is characterized by slow and rapid signal fades. For the traffic management environment, the transmitters and receivers associated with the field equipment, are usually in a fixed locations and positions. What is different in these applications is that the reflection points are changing, providing an equivalent slow and rapid fading environment. The research should resolve the stochastic characteristics of this type of channel and the methods that could be used to mitigate the interference problems.

Two other observations should be stated. First, the graphs of the multipath problem are derived from a simple model using a single reflection. In typical applications, such as the work zone, there are multiple reflections from many objects. The results of these reflections cannot be typically identified escept as some form of average. Second, the problems of multipath interference has been identified in many transportation environments. It is most noticeable in data transmissions. For analog voice transmissions, the ear will miss short drop-outs and fill in the gaps. This is not true of data transmission where even a short drop-out can represent a loss of several bits of information and require a re-transmission. As observed on I-94, if the traffic is moving slowly enough, the length of the faded signal strength can seriously affect the system.

5 Conclusions

The tests demonstrated that the wireless networks would provide adequate communications to support the general deployment. However, the focus of the test was on the use of the field equipment and the communications environment was not adequately tested to establish the operational limitations of the deployed system. In general, there were some general results from this test.

- The tests validated the concept that spread spectrum communications will provide adequate communications to support the field infrastructure for the Smart Work Zone.
- There are technical trade-offs between the quality of the video image that is captured by the equipment (size of file), the number of cameras deployed (or being observed at any given time), and the refresh rate of the video (number of frames per second). The current system will not support full-motion video at

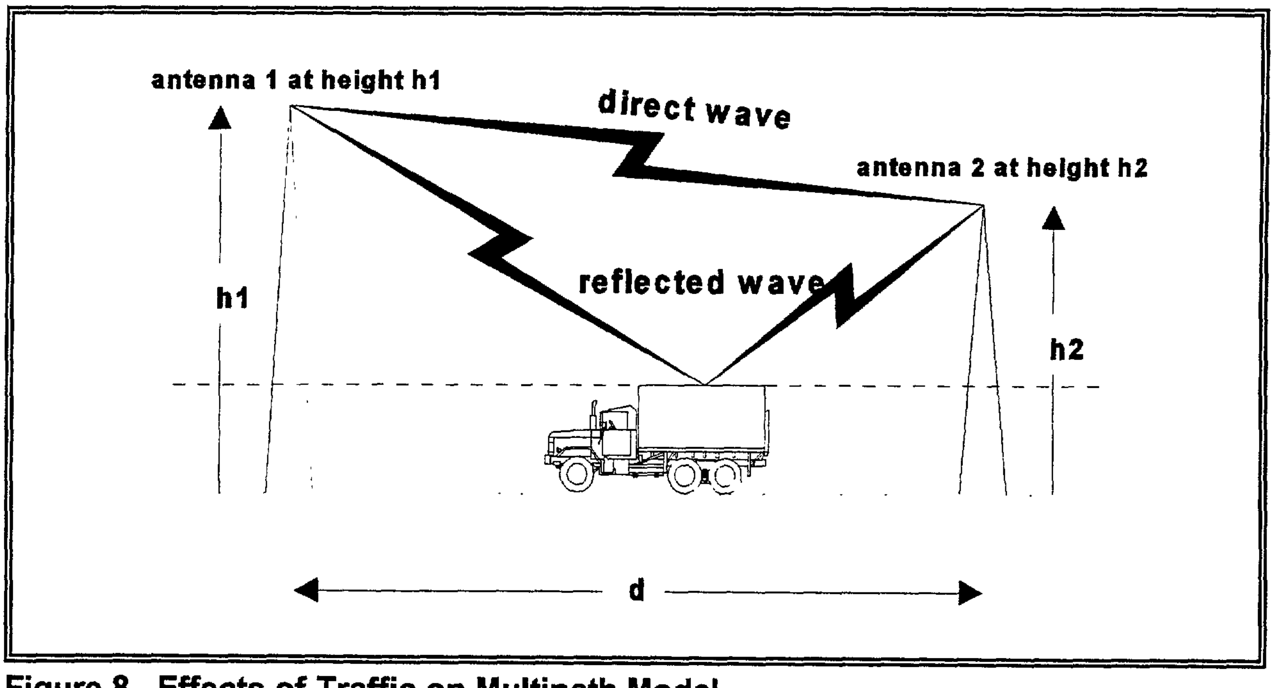


Figure 8 Effects of Traffic on Multipath Model

15 frames per second with ISDN or switched 56 kbps data links. The adequacy of the video depends its operational use. Depending on the outcome of the operational evaluation of the field equipment, the video produced by the operational field test appeared to be adequate.

+ The deployment of the Arlan spread spectrum radios requires additional testing and analysis. The field test demonstrated that the radios will work to two levels lower than the node. The tests were inconclusive at the third and fourth levels as there were problems at this level that could not be analyzed beyond the multipath interference. Even with the counter measures used to eliminate the multipath interference, the links were dropped at times when the radios appeared to attach themselves to a higher level node, thereby eliminating repeaters in the configuration. This remains an issue because without the ability to use repeaters, the there could be a limit on the size of the length of a work zone that could be covered. Based upon the flexibility of these radios, it should be possible change the architecture of the network and use point-to-point links to further disperse the radios. This concept would need to be tested.

+ Further testing is required to establish quantitative limitations on the data rates, refresh times, and number of field elements used for surveillance video.

+ There was no attempt to integrate the data into the existing systems. The ability to place data (video) from the equipment to the Wide World Web, suggests that the equipment should be able to directly interface any system using TCPIIP as its basic protocol. This integration will inevitably require a knowledge of the operational software in the traffic management system. Additional tests will be required with different systems to assess the difficulty of fusing the work zone data into existing traffic management systems.

+ Based upon the results of this test, there is an issue with positioning the radios. For a construction zone, such as the one along I-35, the location of the radios can be determined with a minimum of technical expertise. The envisioned procedure would place the root node transceiver in its location and a portable transceiver would be used to verify the communications links before the skids were deployed. Depending on the provisions of the contract, this could be a significant effort in some projects. In many installations, the contractors may not have the technical expertise to position the radios. The requirement would be for the author of the plans, specifications, and estimate (PS&E) to locate the radios on the plans. Simply requiring the contractor to verify field locations based upon field measurements works well on paper (plans and specifications), but often results in problems when it comes to actual project execution.

+ There is also an potential issue in setting up the network. For both of the field tests, the ADDCO staff had experts that could make the necessary assignments of TCP addresses. While it should be possible to establish procedures that would reduce the amount of expertise required, it is not an obvious that personnel without networking knowledge would be able to set up the equipment.

ADDCO has addressed this issue with the concept of providing technical support out of their distribution network. This concept should be tested to determine its practicality.

+ Based upon the path calculations and the multipath problems, it might be desirable to lower the height of the antennas on the towers. This is not a simple change as interaction between the antenna and the tower can affect the radiation pattern of the antenna if it is not located at the top of the tower. On the other hand, for the surveillance cameras, it is desirable to have the towers as tall as possible.

Overall, the communications equipment and network adequately supported the requirements of the Smart Work Zone project. However, there remain issues that need to be addressed in future tests to verify that the problems on the I-94 deployment were unique to that installation.

APPENDIX C

Motorist Survey

N. K. FRIEDRICHS & ASSOCIATES, INC.
2500 CENTRE VILLAGE
431 SOUTH 7TH STREET
MINNEAPOLIS, MN 55415

_______ (1-4) ___1___ (5)

Project #50-747
Draft #8
August, 1996

INTERVIEWER:______________________ DATE:______________

QUESTIONNAIRE
ADVANCED PTMS WORK ZONE MOTORIST SURVEY

Hello, this is (<u>NAME</u>) from Friedrichs & Associates. We are working with the Minnesota Department of Transportation to conduct a survey with people who drive on Interstate 94 between downtown St. Paul and downtown Minneapolis.

1. We are interested in the area of Interstate 94 between Highway 280 and Riverside. In the past <u>2 weeks</u>, have you or anyone in your household driven either <u>East or West</u> on <u>any part</u> of Interstate 94 between Highway 280 and Riverside?

Yes ....1→ **CONTINUE.**
No ....2→ **DISCONTINUE AND TALLY AT #1 ON CONTACT SHEET.**

2. Are you the person who drives I-94 between Highway 280 and Riverside <u>most often</u>, or is it someone else in your household?

Respondent drives it most often .... 1→**CONTINUE.**
Someone else drives it most often......... 2→**ASK FOR THE APPROPRIATE PERSON AND BEGIN AT INTRODUCTION, OR MAKE APPOINTMENT TO CALL BACK.**

3. About how often do you, personally, drive either East or West on any stretch of I-94 between Highway 280 and Riverside -- **READ LIST:**

(6)

Several times a week ....1 → **CONTINUE.**
Once or twice a week ....2 → **CONTINUE.**
Once every 2 weeks...........................3 → **CONTINUE.**
or Less than once every 2 weeks ....4 → **DISCONTINUE AND TALLY AT #3 ON CONTACT SHEET.**

4-A. In the past <u>2 weeks</u>, have you driven <u>East</u>, toward St. Paul, on any part of I-94 between Riverside and Highway 280?

(7)

Yes .... 1 → **CONTINUE.**
No .... 2 → **SKIP TO Q5.**

B. What time of day do you <u>usually</u> drive East, toward St. Paul, between Riverside and Highway 280? **IF NEEDED, READ LIST: (MULTIPLE ANSWERS ARE ACCEPTABLE)**

(8)

12:01 to 6:30 AM 1
6:30 to 9:00 AM ....$\boxed{2}$
9:01 AM to Noon 3
12:01 to 3:30 PM 4
3:31 to 6:00 PM ....$\boxed{5}$
6:01 to 8:30 PM 6
8:31 PM to midnight 7

5-A. In the past <u>2 weeks</u>, have you driven West, toward Minneapolis, on any part of I-94 between Highway 280 and Riverside?

Yes .... 1 → **CONTINUE.** (9)
No .... 2 → **SKIP TO C.**

B. What time of day do you <u>usually</u> drive <u>West</u>, toward Minneapolis, between Highway 280 and Riverside? **IF NEEDED, READ LIST: (MULTIPLE ANSWERS ARE ACCEPTABLE)**

(10)

12:01 to 6:30 AM 1
6:30 to 9:00 AM ....$\boxed{2}$
9:01 AM to Noon 3
12:01 to 3:30 PM 4
3:31 to 6:00 PM ....$\boxed{5}$
6:01 to 8:30 PM 6
8:31 PM to midnight 7

C. **IF ONE OR MORE ANSWERS ARE CIRCLED IN THE BOXES AT 4-B OR 5-B, CONTINUE. IF NOT, DISCONTINUE AND TALLY AT #5 ON CONTACT SHEET.**

6-A. Still thinking about I-94 between 280 and Riverside -- in the past 2 weeks when you drove either East or West on this stretch of I-94, did you notice any electronic lighted signs on the side of the road that gave messages about traffic conditions in the construction area? (11)

Yes ....1 → CONTINUE.
No 2
Don't Know ....X → SKIP TO PAGE 9, Q14.

B. Do you remember what the lighted messages on the signs said? **RECORD VERBATIM. PROBE UNTIL UNPRODUCTIVE:** Do you remember any other messages? (12-21)

(1.) ____________________

(2.) ____________________

(3.) ____________________

(4.) ____________________

(5.) ____________________

(6.) ____________________

DON'T REMEMBER WHAT MESSAGES SAID ....X → SKIP TO **PAGE 6, Q9**.

7. **IF A MESSAGE IS RECORDED AT #1 ABOVE, CONTINUE TO ASK A-F ABOUT THAT SPECIFIC MESSAGE.**

IF NO MESSAGE IS RECORDED AT #1, SKIP TO PAGE 6, Q9.

A. You said that you saw a message on the lighted signs that said

____________________. (22-30)
(INSERT MESSAGE)

Was this lighted message -- **READ LIST**:

Very easy to read 3 (31)
Somewhat easy to read 2
or Not very easy to read.................. 1
DO NOT READ: DON'T KNOW X

7-B. Was this lighted message easy to understand?

Yes 1 (32)
No 2
Don't Know X

C. Was this lighted message displayed far enough in advance so you were alerted to traffic conditions in the construction area?

Yes 1 (33)
No 2
Don't Know X

D. Did this message give you correct information about traffic conditions that were occuring in the construction area?

Yes 1 (34)
No 2
Don't Know X

E. Was this message useful to you? (35)

Yes ....1 → CONTINUE.
No 2
Don't Know ....X → SKIP TO Q8.

F. **IF YES, ASK:** In what way was this message useful to you? **PROBE AND CLARIFY FULLY.**
IF NO, ASK: In what way was this message not useful to you? **PROBE AND CLARIFY FULLY.** (36-41)

____

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8. **LOOK BACK TO PAGE 3, Q6-B. IF A MESSAGE IS RECORDED AT #2, CONTINUE TO ASK A-F ABOUT THAT SPECIFIC MESSAGE.**

IF NO MESSAGE IS RECORDED AT #2, SKIP TO PAGE 7, Q10.

A. You said that you saw a message on the lighted signs that said

____. (42-50)
(INSERT MESSAGE)

Was this lighted message -- **READ LIST**:

Very easy to read 3 (51)
Somewhat easy to read 2
or Not very easy to read.................. 1
DO NOT READ: DON'T KNOW X

B. Was this lighted message easy to understand?

Yes 1 (52)
No 2
Don't Know X

C. Was this lighted message displayed far enough in advance so you were alerted to traffic conditions in the construction area?

Yes 1 (53)
No 2
Don't Know X

D. Did this message give you correct information about traffic conditions that were occuring in the construction area?

Yes 1 (54)
No 2
Don't Know X

8-E. Was this message useful to you? (55)

Yes ....1 → CONTINUE.
No ....2 → CONTINUE.
Don't Know ....X → SKIP TO Q10.

F. **IF YES, ASK:** In what way was this message useful to you? **PROBE AND CLARIFY FULLY.**
IF NO, ASK: In what way was this message not useful to you? **PROBE AND CLARIFY FULLY.** (56-61)

____

____

____

____

____

G. **SKIP TO Q10.**

9-A Were the lighted messages on the electronic signs -- **READ LIST:**

Very easy to read 3 (62)
Somewhat easy to read 2
or Not very easy to read.................. 1
DO NOT READ: DON'T KNOW X

B. Were the lighted messages easy to understand?

Yes 1 (63)
Some were 2
No 3
Don't Know X

C. Were the lighted messages displayed far enough in advance so you were alerted to traffic conditions in the construction area?

Yes 1 (64)
Some were 2
No 3
Don't Know X

9-D. Did the messages give you correct information about traffic conditions that were occuring in the construction area?

Yes 1 (65)
Sometimes 2
No 3
Don't Know X

E. Were the lighted messages useful to you? (66)

Yes ....1 → CONTINUE.
Some were 2
No 3
Don't Know ....X → SKIP TO Q10.

F. **IF YES OR SOME WERE, ASK:** In what way were the messages useful to you? **PROBE AND CLARIFY FULLY.**
IF NO, ASK: In what way were the messages not useful to you? **PROBE AND CLARIFY FULLY.** (67-80)

____

____

____

____

____

____ (1-4) 2 (5)

10. What did you do in response to the lighted messages? **DO NOT READ LIST.**

Did nothing 1 (6)
Took a different route 2
Reduced speed 3
Became more alert to traffic conditions 4
Other: ______________________________________ 5

____

____ (7)__

(8)B

11. Compared to signs you have seen in other construction areas, would you say that the lighted message signs helped you feel -- **READ LIST**:

Much more informed about traffic conditions............ 4 (9)

Somewhat more informed 3

About the same 2

or Less informed than signs you have seen in other construction areas 1

DO NOT READ: DON'T KNOW X

12. Would you say that the lighted message signs are -- **READ LIST**:

Much more helpful than signs you have seen in other construction areas 4 (10)

Somewhat more helpful 3

About the same 2

or Not as helpful as signs you have seen in other construction areas 1

DO NOT READ: DON'T KNOW X

13. Still thinking of the stretch of I-94 between 280 and Riverside, is there any <u>other</u> information you would like to see on the lighted message signs that would be useful to you? **PROBE AND CLARIFY FULLY.** (11-20)

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14. Now I would like you to think about <u>all</u> the signs, electronic and non-electronic, that you have seen in the construction area on I-94 between 280 and Riverside. Overall, have the signs in the I-94 construction area given you the information you need?

Yes 1 (21)
No 2
Don't Know X

15. Now I have a few questions for classification purposes. This information will be kept confidential. Is your age -- **READ LIST**:

Under 25 .... 1 (22)
25 to 34 2
35 to 44 3
45 to 54 4
55 to 64 5
or 65 or older.......................... 6
DO NOT READ: REFUSED.........................Y

16. When you use I-94 between 280 and Riverside, is your main purpose work related or not work related?

Work related 1 (23)

Not work related 2

17. ASK RESPONDENT'S NAME: ____________________

CITY: ____________________

ZIP CODE: ___ ___ ___ ___ ___ (24-28)

TELEPHONE #: ____________________

18. RECORD RESPONDENT'S GENDER:

MALE 1 (29)

FEMALE 2

19. THANK RESPONDENT AND DISCONTINUE.

20. FILL IN INTERVIEWER NAME AND DATE ON COVER PAGE.

21. TALLY AT #7 ON CONTACT SHEET.

APPENDIX D

VMS Message Scenarios

I-94 EASTBOUND SIGN SCENARIOS
PORTABLE TRAFFIC MANAGEMENT SYSTEM
SMART WORK ZONE APPLICATION

SCENARIO NUMBER	TRAFFIC CONDITION	SEEN FROM	TRAILER MOUNTED VMS	WORK ZONE VMS		
			VMS #3 I-94 EB @ I-35W	WZVMS # 1 I-94 EB @ 25TH AVE	WZVMS # 2 I-94 EB @ MISS RIVER	WZVMS # 5 I-94 EB EAST OF FRANKLIN
EB 1	STOP AND GO (EB @ 25TH AVE)	I-94 (S) 25TH AVE	TRAFFIC DELAY 94 EAST 2 SECOND INTERVALS SLOW DOWN	20 MPH NEXT 2 MILES		END WORK ZONE
EB 2	INCIDENT WEST OF 25TH AVE	I-94 (S) 25TH AVE	ACCIDENT 94 EAST 3 MILES			
EB 3A	INCIDENT BETWEEN 25TH AVE AND FRANKLIN TERRACE	I-94 (S) MISS RIVER	ACCIDENT 94 EAST 3 MILES	ACCIDENT AHEAD		
EB 3B	INCIDENT ON DARTMOUTH BRIDGE	I-94 (S) MISS RIVER	ACCIDENT 94 EAST 3 MILES	ACCIDENT AHEAD	TRAFFIC DELAY 10 MIN	
EB 4A	INCIDENT BETWEEN HURON AND RR BRIDGE	I-94 (N) RR BRIDGE	ACCIDENT 94 EAST 4 MILES	ACCIDENT AHEAD	TRAFFIC DELAY 10 MIN	
EB 4B	INCIDENT BETWEEN RR BRIDGE AND PED BRIDGE	I-94 (N) RR BRIDGE	ACCIDENT 94 EAST 4 MILES	ACCIDENT AHEAD	TRAFFIC DELAY 10 MIN	
EB 5	MAJOR TRAFFIC INCIDENT	CAMERAS, LOOPS, D.P.S.	ACCIDENT 94 EAST 4 MILES 2 SECOND INTERVALS TUNE TO 88.5 FM	ACCIDENT AHEAD 2 SECOND INTERVALS TUNE TO 88.5 FM	ACCIDENT AHEAD 2 SECOND INTERVALS TUNE TO 88.5 FM	

I-94 WESTBOUND AND TH 280 SOUTHBOUND SIGN SCENARIOS
PORTABLE TRAFFIC MANAGEMENT SYSTEM
SMART WORK ZONE APPLICATION

SCENARIO NUMBER	TRAFFIC CONDITION	SEEN FROM	TRAILER MOUNTED VMS							
			VMS # 1 I-94 WB @ LEXINGTON	VMS # 2 I-94 WB @ PRIOR	VMS #4 TH 280 SB @ BROADWAY	WZVMS # 3 I-94 WB @ HURON	WZVMS # 4 I-94 WB @ RR BRIDGE	WZVMS # 6 I-94 WB @ TH 280	WZVMS # 7 I-94 WB @ PASCAL	WZVMS # 8 TH 280 SB @ UNIVERSITY
WB 1	STOP AND GO (WB @ PELHAM)	I-94 (M) PELHAM	TRAFFIC DELAY 94 WEST 2 SECOND INTERVALS SLOW DOWN	PREPARE TO STOP	TRAFFIC DELAY 94 WEST		20 MPH NEXT 1/2 MILE	20 MPH NEXT 2 MILES	TRAFFIC DELAY 10 MIN	TRAFFIC DELAY 94 WEST 2 SECOND INTERVALS WATCH RAMP BACKUP
WB 2	INCIDENT EAST OF TH 280	I-94 (M) PELHAM	ACCIDENT AHEAD 3 MILES	TRAFFIC DELAY AHEAD			20 MPH NEXT 1/2 MILE	20 MPH NEXT 2 MILES	TRAFFIC DELAY 10 MIN	TRAFFIC DELAY 94 WEST
WB 3A	INCIDENT BETWEEN TH 280 ON RAMP AND PELHAM	I-94 (M) TH 280	ACCIDENT AHEAD 3 MILES	TRAFFIC DELAY AHEAD			20 MPH NEXT 1/2 MILE		ACCIDENT AHEAD	TRAFFIC DELAY 94 WEST
WB 3B	INCIDENT BETWEEN TH 280 ON RAMP AND FRANKLIN	I-94 (M) TH 280	ACCIDENT AHEAD 3 MILES	TRAFFIC DELAY AHEAD	ACCIDENT AHEAD 94 WEST 2 SECOND INTERVALS WATCH RAMP BACKUP		20 MPH NEXT 1/2 MILE	TRAFFIC DELAY 10 MIN	ACCIDENT AHEAD	TRAFFIC DELAY 94 WEST
WB 4A	INCIDENT BETWEEN FRANKLIN AND RR BRIDGE	I-94 (N) RR BRIDGE	ACCIDENT AHEAD 3 MILES	TRAFFIC DELAY AHEAD	ACCIDENT AHEAD 94 WEST 2 SECOND INTERVALS WATCH RAMP BACKUP		20 MPH NEXT 1/2 MILE	TRAFFIC DELAY 10 MIN	ACCIDENT AHEAD	TRAFFIC STOPPED AHEAD
WB 4B	INCIDENT BETWEEN RR BRIDGE AND HURON EXIT	I-94 (N) RR BRIDGE	ACCIDENT AHEAD 3 MILES	TRAFFIC DELAY AHEAD	ACCIDENT AHEAD 94 WEST 2 SECOND INTERVALS WATCH RAMP BACKUP		PREPARE TO STOP	TRAFFIC DELAY 10 MIN	ACCIDENT AHEAD	TRAFFIC STOPPED AHEAD
WB 5	INCIDENT ON DARTMOUTH BRIDGE	I-94 (S) MISS RIVER	ACCIDENT AHEAD 3 MILES	TRAFFIC DELAY AHEAD	ACCIDENT AHEAD 94 WEST 2 SECOND INTERVALS WATCH RAMP BACKUP		PREPARE TO STOP	TRAFFIC DELAY 10 MIN	ACCIDENT AHEAD	TRAFFIC STOPPED AHEAD
WB 6	INCIDENT ON TH 280 RAMP	I-94 (M) TH 280 TH 280 (W)			ACCIDENT 94 WB RAMP 2 SECOND INTERVALS WATCH RAMP BACKUP					PREPARE TO STOP
WB 7	BACK-UP ON TH 280 RAMP	I-94 (M) TH 280 TH 280 (W)			TRAFFIC DELAY 94 WEST 2 SECOND INTERVALS WATCH RAMP BACKUP					WATCH RAMP BACKUP
WB 8	MAJOR TRAFFIC INCIDENT	CAMERAS, LOOPS, D P.S.	ACCIDENT AHEAD 3 MILES 2 SECOND INTERVALS TUNE TO 88.5 FM	ACCIDENT AHEAD 2 MILES 2 SECOND INTERVALS TUNE TO 88.5 FM	ACCIDENT AHEAD 94 WEST 2 SECOND INTERVALS TUNE TO 88.5 FM			TRAFFIC DELAY 20 MIN	TRAFFIC DELAY 20 MIN	TRAFFIC DELAY 94 WEST 2 SECOND INTERVALS TUNE TO 88.5 FM

I-35 NORTHBOUND SIGN SCENARIOS
PORTABLE TRAFFIC MANAGEMENT SYSTEM
SMART WORK ZONE APPLICATION

SCENARIO NUMBER	TRAFFIC CONDITION	SEEN FROM	TRAILER VMS	MODULAR VMS		
			VMS #1 Milepost 83	WZVMS #1 1500' SOUTH of CSAH 50	WZVMS #2 NB CSAH 50 EXIT RAMP	WZVMS #3 CSAH 50 BRIDGE GORE
NB 1	FREE FLOW	ALL CAMERAS	WORKZONE 2 MILES AHEAD 2 SECOND INTERVALS SPEED LIMIT 45 MPH	NB 35 MERGE LEFT 2 SECOND INTERVALS RT LANE EXIT ONLY	SPEED LIMIT 45 MPH	SPEED LIMIT 45 MPH
NB 2	STOP AND GO TRAFFIC SOUTH OF SKID 1.	SKID 1	SLOW TRAFFIC AHEAD 2 SECOND INTERVALS PREPARE TO STOP	20 MPH NEXT MILE	20 MPH NEXT 1/2 MILE	SPEED LIMIT 45 MPH
NB 3	TRAFFIC BACKUP SOUTH OF CSAH 50 (30-40 MPH)	SKID 2 Autoscope	35 MPH 2 MILES AHEAD	35 MPH NEXT MILE	SPEED LIMIT 45 MPH	SPEED LIMIT 45 MPH
NB 4	TRAFFIC BACKUP SOUTH OF CSAH 50 (20-30 MPH)	SKID 2 Autoscope	25 MPH 2 MILES AHEAD	25 MPH NEXT MILE	SPEED LIMIT 45 MPH	SPEED LIMIT 45 MPH
NB 5	ACCIDENT SOUTH OF SKID 1	SKID 1	ACCIDENT AHEAD 2 SECOND INTERVALS PROCEED WITH CAUTION	NB 35 MERGE LEFT	SPEED LIMIT 45 MPH	SPEED LIMIT 45 MPH
NB 6	ACCIDENT IN MERGE AREA	SKID 1 SKID 2	ACCIDENT AHEAD 2 SECOND INTERVALS PROCEED WITH CAUTION	NB 35 MERGE LEFT	SPEED LIMIT 45 MPH	SPEED LIMIT 45 MPH
NB 7	ACCIDENT IN SOUTH CROSS-OVER	SKID 2 SKID 3	ACCIDENT AHEAD 2 SECOND INTERVALS PROCEED WITH CAUTION	SLOW TRAFFIC AHEAD 2 SECOND INTERVALS PROCEED WITH CAUTION	PROCEED WITH CAUTION	SPEED LIMIT 45 MPH
NB 8	ACCIDENT IN ONE LANE SECTION	SKID 2 SKID 3	ACCIDENT AHEAD 2 SECOND INTERVALS PROCEED WITH CAUTION	SLOW TRAFFIC AHEAD 2 SECOND INTERVALS EXPECT DELAYS	NB 35 EXPECT DELAYS NEXT 1/2 MILE	PROCEED WITH CAUTION
NB 9	ACCIDENT IN NORTH CROSS-OVER	SKID 4	ACCIDENT AHEAD 2 SECOND INTERVALS PROCEED WITH CAUTION	NB 35 EXPECT DELAYS 2 SECOND INTERVALS NEXT 1 MILE	PROCEED WITH CAUTION	PROCEED WITH CAUTION
NB 10	WORKERS PRESENT	ALL SKIDS	WORK ZONE AHEAD 2 SECOND INTERVALS PROCEED WITH CAUTION	SINGLE LANE TRAFFIC 2 SECOND INTERVALS BE PREPARED TO STOP		