EVALUATION OF ITS TECHNOLOGIES IN RURAL WORK ZONES

Showcase Evaluation #12

Final Technical Report

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DISCLAIMER

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GLOSSARY OF ABBREVIATIONS

AADT	Annual Average Daily Traffic
Caltrans	California Department of Transportation
CMS	Changeable Message Sign
FHWA	Federal Highway Administration
NLOS	Near line-of-sight
ODOT	Oregon Department of Transportation
PTM	Point-to-multipoint
RSSI	Received Signal Strength Indication

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1. INTRODUCTION

There has been a substantial increase in reconstruction and rehabilitation activities on urban and rural highways in recent years. Work zones are a necessary and relatively common occurrence on rural highways in order to preserve and improve the transportation system. The frequency of maintenance activities and the potential severity of work zone crashes have intensified the importance of safe and efficient handling of traffic in work zones.

Recent years have also seen the emergence and mainstreaming of intelligent transportation systems (ITS). ITS uses advanced computer, communications and electronics technologies to save time, lives and money on the transportation system. Many transportation agencies have been using ITS technologies to address transportation challenges (including those related to work zones) in or near urban areas. There has been less attention devoted to how ITS can help address challenges in rural areas. Stakeholders in California and Oregon, working in partnership with the respective state departments of transportation and in concert with the Western Transportation Institute (WTI) at Montana State University, have been researching and demonstrating the application of ITS in a rural context through the Rural California/Oregon Advanced Transportation Systems (COATS) Showcase project.

As a part of the COATS Showcase effort, WTI researchers considered how ITS technologies could be used in rural highway work zones. The California Department of Transportation (Caltrans) Division of Research and Innovation provided funding for such an investigation. The project is consistent with several objectives adopted in the COATS ITS Strategic Deployment Plan (1):

- **Objective 1.2:** Provide systems that advise regional transportation system users of slow-moving vehicles, obstructions and road and weather conditions.

- **Objective 1.3:** Provide systems that advise unfamiliar motorists of alignment and speed conditions, tourist attractions, services, construction, weather, and the ability to request assistance.

- **Objective 1.5:** Reduce the severity of vehicle accidents and their related fatality rates through improved notification and response times.

This report summarizes the findings of this research project, a project which eventually focused on designing and testing a specific ITS application: providing real-time delay information to motorists in a rural two-lane undivided highway work zone with a lane closure (i.e. a pilot car-controlled work zone).

Chapter 2 provides the background of this project along with the context of this study in relation to current practices. Chapter 3 lists user requirements for the proposed ITS system. Chapter 4 describes the methodology used in evaluating the feasibility of such a system and in developing a proof-of-concept prototype. Chapter 5 provides background on the equipment and technology used in the proof-of-concept system and summarizes the associated challenges. Chapter 6 presents background for delay estimation and computation and details regarding several prospective algorithms. Chapter 7 summarizes prospective communication technologies for this system, and describes testing and analysis conducted to evaluate these technologies. Chapter 8 provides a summary of the research conducted in this project and presents recommendations for subsequent research.

2. BACKGROUND AND PROBLEM DESCRIPTION

ITS technologies may be applied to work zones in an attempt to address a variety of challenges. Because of existing work zone-related research and due to project budgetary constraints, the research project focused on applications that are specifically rural and for which little research has been conducted.

This chapter provides background on some of the major issues associated with work zones, to show how the research team selected a specific application on which to focus. First, an overview of work zone challenges is presented. Next, the results of a literature review and a survey of state transportation agencies on the use of ITS applications in work zones are presented and summarized. This is followed by a review of this research project's history, to show how the decision was made to focus on a specific application. The chapter closes with discussion about the vision for this specific application.

The initial literature review of applicable ITS applications suggested that a traveler information system for a two-lane rural highway work zone system was the most promising application that met the overall goals of Caltrans for managing rural work zones. This chapter expands on the specific area of en-route traveler information for a two-lane rural highway work zone. The research team worked closely with the Caltrans personnel to define the user requirements of this system.

2.1. Overview of Work Zone Transportation Challenges

As stated in Chapter 1, there has been an increase in highway work zone activities in recent years, reflecting the needs to maintain the existing roadway infrastructure while providing expansion for increases in highway travel demand. Moreover, work zones are becoming more commonly recognized as a regular aspect of the highway system that, though the locations may change, will never go away. Though they are common features of the highway system, work zones introduce discontinuities into the transportation system with reductions in the number of lanes or lane width available for vehicles, detours, delays, road closures and similar aspects.

There are several challenges that emerge from work zones, which are noted briefly for the purposes of establishing the background for this project. Additional information is available from the Federal Highway Administration's (FHWA's) Work Zone Safety and Mobility Program (2) or the National Work Zone Safety Information Clearinghouse (3).

2.1.1. Safety

Improving work zone safety has become a high priority among state transportation agencies. The U.S. Department of Transportation has stated its goal of significantly reducing the number of fatalities per year from its current level of about 42,000, and has instituted a National Highway Work Zone Safety Program as one means toward accomplishing that goal.

Improving work zone safety can involve numerous approaches. Education approaches can use a variety of outlets (e.g. advanced signage, web pages for highway construction projects) to inform motorists about the existence of work zones and tips for safely driving through them. Engineering approaches seek to design the elements of the work zone to protect worker and motorist safety by fostering safe separation between moving traffic and workers, adding safety appurtenances to protect the perimeter of the work zone, and providing adequate space for motorists to adjust travel speed or change lanes before passing by the work area. Enforcement approaches can be used to ensure that vehicles comply with work zone signage, especially in reducing speeds.

2.1.2. Delay

Travel delay from congestion is recognized as a major and growing problem across the country. Congestion may be either recurrent, such as due to an excess of vehicles trying to use a road, or nonrecurrent, such as due to accidents, weather or work zones. Congestion has significant economic costs - $63 billion in urban areas in 2003 alone (4) – as well as costs related to inconvenience.

Work zone-related delay may be reduced through a variety of means. Public information in advance of and during a construction project can encourage drivers to use alternate routes or alternative transportation. Changes in construction planning – how projects are staged, the use of night-time construction – can also help. Despite these improvements, work zones will likely result in delays.

In some work zones, especially in rural areas where the road geometry is narrow and alternative routes are sparse, delay is unavoidable. These delays can be especially long on rural two-lane highways where traffic flow alternates directions through the use of a pilot car. These delays can increase driver stress and frustration, potentially affecting driver behavior within and after the work zone, which could impact the safety of workers and other motorists.

One way of reducing driver frustration is to provide real-time information on the delays that motorists can expect as they approach a work zone. This information could take the form of a countdown timer, so that motorists know, as they arrive at the work zone, about how long they would need to wait before being able to proceed through.

2.2. Summary of Literature and State DOT Surveys

At the start of this project, the research team conducted a literature review on the use of ITS applications in work zones, and also surveyed transportation agencies regarding their use of ITS in work zones. The goal of this information-gathering was to help direct the types of activities on which the research team would focus in this project.

2.2.1. Literature Review

The existing documented research on traffic control around work zones indicates that travelers would like to have information on delays, alternate routes, and similar information in real time. There are also numerous studies on ITS applications for work zones. In general, the studies found that ITS in work zones help improve the traffic movement, reduce driver frustration, reduce traffic congestion around work zones, and reduce the number of accidents occurring at work zones among other benefits. For example, a simulation study using an ITS Deployment Analysis System (IDAS) found that full deployment of ITS in work zones in the Cincinnati area will result in a benefit-cost ratio of about 11.8 or higher (5).

There has also been research about what elements are vital for ITS applications to be successful. FHWA conducted a cross-cutting study of test ITS applications and identified several factors which contribute to the success of ITS applications at work zones, including reliable communication methods, involvement of other stakeholders, and allowing start-up time for the system (6) .

However, the literature found few documented examples of ITS applications that are applicable for low-volume two-lane rural highways, where the fluctuation in the traffic can be high and delay times for certain time periods of a day can be relatively high. This suggests that further research is required to establish better understanding of pilot car operated work zones, especially on rural two-lane highways. More details on this literature review are provided in the Technical Memorandum 1 (7).

2.2.2. Summary of Agency Surveys

Recognizing that many transportation agencies may implement ITS applications in work zones which are not documented nationally, the research team sought to identify the state-of-the-practice through conducting surveys of agency personnel. As part of documenting the current practices in traffic management in and around work zones, an online survey was created and sent to DOT personnel in all 50 states. Thirty-seven respondents from 29 agencies responded to the survey. Ninety-two percent of respondents indicated that their agency had used ITS to manage the traffic in and around construction/maintenance work zones.

Respondents were asked to select all the ITS systems used in work zones by their agencies from a list of seventeen commonly used ITS systems. Respondents could add other ITS systems if needed. Changeable message signs (CMS) / dynamic message signs (DMS) were the most commonly used ITS technology in work zones with 89 percent of respondents indicating some level of usage. Closed-circuit television (CCTV) cameras and traveler information websites were the next most commonly used technologies; more than 60 percent of respondents reported using each of these two systems.

The conclusions of this online survey indicate that there is broad interest in and usage of technologies to improve traveler information for work zones, such as using CMS or traveler information websites. This is likely influencing driver expectations, so it should be expected that improvements in work zone traveler information accuracy and timeliness will be increasingly demanded by the traveling public. This might eventually include integrating field-based traveler information on delays (en-route) into Internet sites for pre-trip planning purposes.

Since work zone fatalities continue to increase in California, application of technologies designed to protect worker and driver safety in work zones may have some benefits. However, the relatively low level of respondent satisfaction with these technologies suggests that new approaches should be tested and evaluated.

Many respondent comments indicate that certain ITS technologies are becoming standard practice for state departments of transportation in their work zones. This indicates that these ITS technologies can add value to how work zones are conducted in general. This also suggests that transportation agencies are interested in exploring how innovative ITS applications may continue to offer significant benefits to work zone managers and the traveling public.

On the other hand, while there are some standard practices, it is clear that these practices are not well-documented for all states. A state that is interested in using ITS applications for work zones should begin with limited demonstrations of these technologies and move toward standardized practices, including criteria for deployment, location of field elements, message sets, and other factors.

2.3. Project Background

From 1998 until 2001, the California and Oregon Departments of Transportation (Caltrans and ODOT, respectively), with the support of the Western Transportation Institute (WTI) at Montana State University, led the Rural California/Oregon Advanced Transportation Systems (COATS) project. The purpose of the COATS effort was to encourage regional, public and private sector cooperation between California and Oregon organizations to better facilitate the planning and implementation of intelligent transportation systems (ITS) in a rural bi-state area extending between Eugene, Oregon and Redding, California. The purposes of the COATS project were:

- to identify the transportation and information needs within the bi-state study area;
- to determine ITS solutions that would be beneficial, cost-effective, and implementable for demonstration within the study area;
- to identify, design, demonstrate and evaluate initial, small-scale “early-winner” projects/systems; and
- to develop a model deployment and evaluation plan that describes a strategic approach for implementing rural ITS strategies on a larger scale.

COATS Showcase, a subsequent project to COATS, provided additional funding to demonstrate and evaluate ITS technologies in rural areas. COATS Showcase included a number of interrelated efforts which sought to provide data to guide implementation of ITS, and to evaluate the effectiveness of existing ITS deployments.

With the endorsement of the COATS Steering Committee, WTI initiated a research project to examine the applicability of ITS in rural work zones. Based on initial guidance from the project evaluation team, the decision was made to focus on two technology applications: a late-merge application to reduce queue lengths in work zones on multi-lane highways (e.g. interstates) with lane closures, and a project to promote improved real-time delay estimation at two-lane rural highway work zones involving lane closures (i.e. pilot-car controlled). Over the course of the project, project evaluation team members encouraged the research team to focus on the second application, which agrees with the findings of the literature review and agency surveys described in the previous section.

Significant development work for this application occurred between 2002 and early 2004, when the research team relied on in-house expertise in Caltrans Division of Research and Innovation to advance and research alternative concepts. Changes in staffing at DRI, due to other emerging priorities, resulted in a loss of ITS design support for this system, shelving the project. The project was resumed in early 2006 through the use of in-house expertise at WTI.

2.4. Methodology for Application Description

This section provides more detail of the application that was developed through this project.

2.4.1. Statement of Need

Work zones can impose inconvenience on travelers through unexpected delay. These delays can be long and highly irregular in rural areas on two-lane highways where traffic flow alternates directions through the use of a pilot car. These delays can increase driver stress and frustration, potentially affecting driver behavior within and after the work zone, which could impact the safety of workers and other motorists.

There are numerous ITS applications that have been tested and successfully used in work zones in urban and rural settings, such as applications in traffic control and real-time centralized traffic management. There has not been a real-time traveler information system that has been specifically used in a work zone on a two-lane rural highway with one-lane closure where traffic is typically managed with one or more pilot cars.

The initial literature review suggested that rural travelers as well as urban travelers would like more real-time information to facilitate their travel through work zones or alternate routes. This project envisioned the development of a robust, easy-to-use, real-time traveler information system for work zones on two-lane rural highways with one-lane closures. This system will provide real-time estimated delay to the waiting vehicles at both ends of the closure during the hours of pilot car operations.

2.4.2. Project Objective and Approach

The primary objective of this COATS Showcase project led by WTI is to identify different options for ITS applications that can potentially be used in work zone traffic control in rural areas. Based on this research, this project sought to develop a prototype demonstration system for real-time delay estimation and en-route information dissemination for a two-lane highway work zone with a lane closure where a pilot car manages the traffic.

As mentioned in section 2.3, there was only about three months available for the development of a system to fulfill this application. This led the research team to focus on developing a prototype system that could be tested in a controlled fashion in laboratory conditions. The primary purpose of this prototype system is to serve as a proof-of-concept and demonstrate that this system is feasible. These tests were also used for identifying ways to improve the system to make it deployable with further research and testing.

This prototype system is envisioned to use off-the-shelf components that conform to acceptable ITS industry standards and cater to the primary user requirements in the system input and system communication functional areas.

The methodology used on this project follows the systems engineering model. A system concept is formed to describe the operation and components of the prospective system. High-level requirements are elicited to formalize the parameters within which the system must operate. Design alternatives are considered and formalized to specify the system so that it meets requirements. A proof-of-concept version of the system is then developed to test technologies and algorithms and the results are then used to evaluate the viability of such a system. If the results are promising, subsequent development would be conducted to develop future versions of the system for field testing and, if successful, production deployment. Each development phase can be considered part of an iterative, or spiral, process that helps to identify and mitigate risk as early as possible, and to accurately capture user requirements.

2.5. System Concept: Rural Two-Lane Highway Work Zone Delay Estimation System

The system was envisioned to have the following components and capabilities:

- One or more signs positioned near the ends of the work zone, each capable of displaying delay estimation messages.
- Controllers at or near each sign, each capable of changing the message on the sign.
- Receivers at or near each controller, each capable of receiving data messages from the pilot car.
- A data logger in the pilot car, capable of determining and logging the duration in which the pilot car is in various states: i.e., waiting at each end point, or traveling between each end point.
- A transmitter in the pilot car, capable of transmitting data messages to the sign controllers.
- Programmable logic at the sign controller and/or in the pilot car to calculate delay estimates.

The system would use these components and capabilities to calculate, transmit, and display delay estimates to drivers waiting at each end of the work zone.

3. USER REQUIREMENTS

After developing a vision for the application, the next step in the systems engineering process is to develop user requirements that can guide system design. User requirements for a real-time traveler information system were developed in consultation with Caltrans personnel, to reflect Caltrans practice in managing work zones. These practices include the following:

- Caltrans has adopted a policy to keep the wait times not to exceed 15 minutes.
- All vehicles that have come to a stop before the pilot car is ready to leave for the other end are allowed by flaggers to go through the work zone before they close it off.
- Pilot cars are instructed to follow the posted speed limit as closely as possible.

The user requirements are divided into functional areas for the ease of correlation with the methodology and other sections of this report. The prototype system was designed to accommodate most of these requirements with further research and testing.

3.1. Delay Estimation and Display Requirements

The overall system purpose is to accurately measure the stopped delay for each end of the pilot car managed traffic through a two-lane rural highway, and to display this information to motorists to reduce motorist frustration. Requirements governing information display include the following:

1. The system should be able to display one of the following three time measurements
    a. Time before the first car in the queue starts to move through the work zone
    b. Time for the first car in the queue to get to the other end of the work zone
    c. Delay due to the work zone (i.e. the difference in travel times between any two points encompassing the work zone with and without the work zone)
2. The accuracy of the displayed time measurement (i.e. either total delay or stopped delay) should be within the range of ±2 minutes. New policies for stabilizing the cycle times of the pilot car operation may also be used to meet this requirement.
3. Display messages must be able to be defined by the system user. Users are the district maintenance personnel corresponding to the highway location of the work zone.
4. To the extent possible, the displayed time measurement should be updated every two minutes to reflect the time measurement with respect to that instant in time.
5. The displayed time measurement shall be rounded up to the nearest whole number of minutes.

3.2. Placement Requirements

The system is to display estimates of delay at both ends of the work zone. The following general requirements govern the placement of field elements involved in making this system function.

1. The location of the signs will vary based on the design of the work zone. Signs may be located at the first vehicle of the queue or at half to two-thirds length of the estimated

longest queue length for a 15-minute closure for the given highway location. In other words, the location of the flagging station can be different from that of the time measurement display. These locations are shown in Figure 3-1.

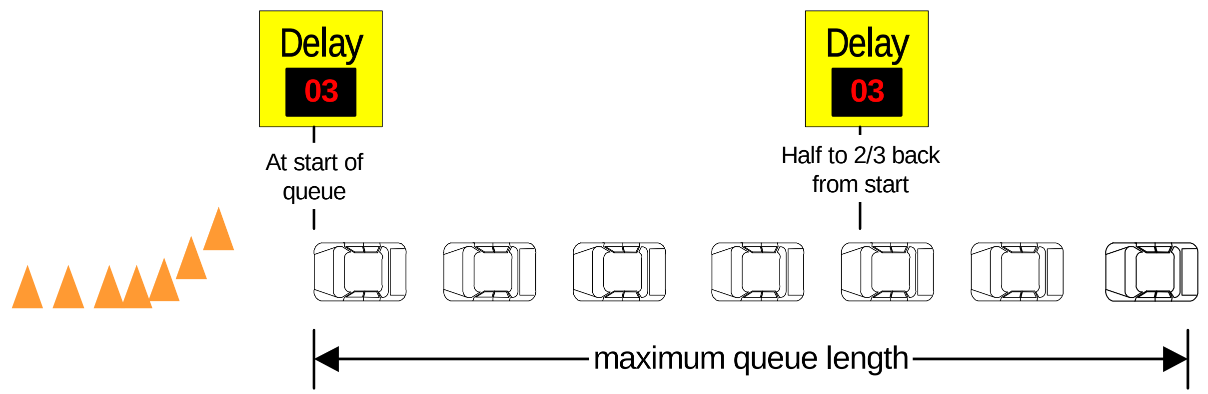


Figure 3-1: Schematic Showing Placement of Signs

2. The system should be designed such that the display and other system components could be placed when there are no paved or unpaved shoulders available at the work zone ends

3.3. Communication Requirements

Caltrans District 2 and other districts have highways that pass through terrain where there are numerous communication challenges. Therefore, the communication system chosen for this system should meet the following requirements.

1. The system should be able to work at work zones with no line of sight between ends.
2. The system should be able to work at work zones where there is either poor or no cell phone coverage.
3. The system should preferably use a type of communication that has the least amount of recurring costs per use.
4. The system should be able to overcome any communication hindrances from roadsides or other vehicles passing through the work zone.

3.4. Input Requirements

In order to help ensure its stability, the system should be designed to require a minimal amount of human input and customization specific to the work zone sites. The following requirements are based on this vision.

1. The system should account for possible manual errors whenever there is a manual input required, using appropriate error-checking and quality control mechanisms.
2. Use of manual inputs should be minimized and avoided if possible.
3. Automation of vehicle location as an input to the system is preferred.

3.5. Ease-of-Use Requirements

A typical work zone is expected to be set-up within two hours. Therefore, it is expected that the set-up requirements of this system should not add too much additional effort; otherwise it will not be used.

1. The system shall require no more than 30 minutes to be set-up at the work zone location.
2. The system shall not require commercial power sources.
3. The system shall not require more than nominal repair and regular maintenance.
4. The system shall be portable comparable to other work zone traffic control elements (e.g. cones, temporary traffic signal controls)

These user requirements guided the research team through the remaining aspects of designing this application. Continuing evaluation of user requirements is an integral part of system development using a systems engineering process. Therefore, these user requirements will have to revisited and modified, if necessary, throughout the progression of the stages of system development.

4. METHODOLOGY

As the user requirements suggested, there were several functional areas for this system, and the system had to be designed in an integrated fashion while meeting the user requirements or allowing for meeting the user requirements in the future with further research and testing in each of the functional areas. For the purpose of documenting the design and testing efforts of this prototype system, this process is generally categorized into three major functional areas. It should be noted that these three major divisions intersect and interact in numerous ways all along this process.

4.1. Systems Engineering Process

For successful design and implementation of a complex system in a team environment, the systems engineering process model has been extensively employed. The systems engineering process model, as illustrated by the "Vee" Model in Figure 4-1, was followed in designing and developing the proof-of-concept system for this project. A systems engineering approach increases the likelihood that the system will work, satisfy customer needs, and meet acceptable cost and schedule constraints.

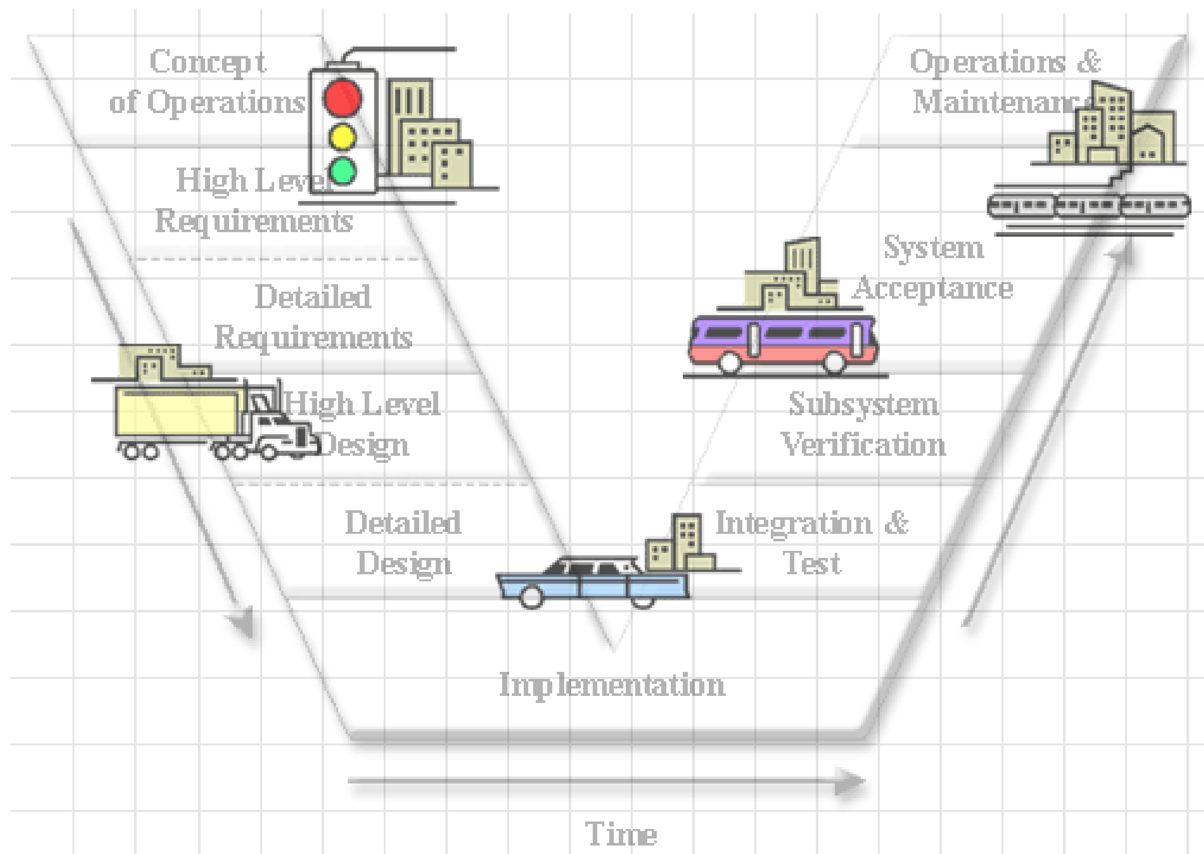


Figure 4-1: "Vee" Model for Systems Engineering

4.2. Caltrans Stages of Research Deployment

Caltrans has identified five stages for developing initial concepts that will help Caltrans conduct projects that are well-researched and deployed in a sound fashion. The five stages are:

1. Concept Stage
2. Laboratory Prototype Stage
3. Controlled Field Demonstration Stage
4. First Application (Contract) Field Pilot Stage
5. Specification & Standards with Full Corporate Deployment Stage

The systems engineering process model can be used iteratively to conduct research and development through these phases. Following such an approach allows for requirements, design and the system itself to evolve progressively toward deployment for production use.

Due to the limited time available for design and development within this project, the goal of this project was to develop a system that corresponds to Stage 2 (Figure 4-2), the Laboratory Prototype Stage. If the developed system shows promise, then it would be recommended that research and development be conducted to evolve the system to subsequent stages eventually leading to production.

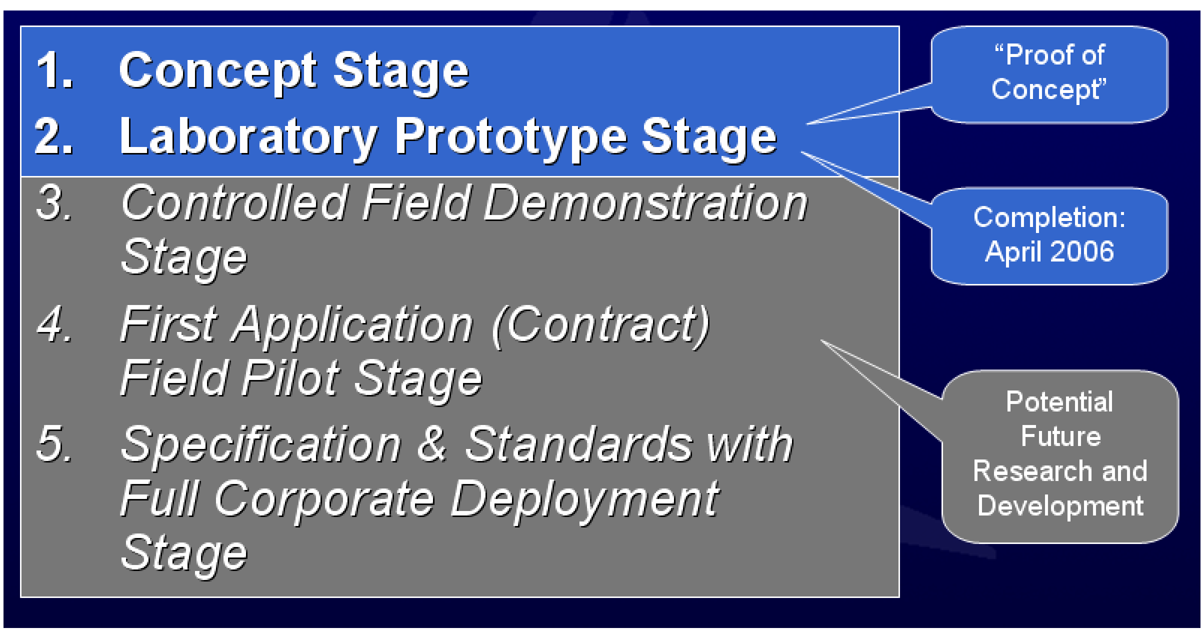


Figure 4-2: Alignment with Caltrans Stages of Research Deployment

4.3. Laboratory Prototype System Plan, Primary Research Components and System Design

The goal in the development of the laboratory prototype system was to develop a “proof-of-concept” that could be evaluated in a laboratory setting and that could be used to evaluate prospective system components and algorithms.

Based on the identified user requirements, the development of a laboratory prototype system was divided into equipment and technology, communication technologies, and delay estimation and computation. These three distinct areas were researched in a collaborative way for the development of a proof-of-concept system and for the evaluation of technologies and techniques for prospective subsequent application to this problem.

The end product of this project would be the proof-of-concept system, assuming it could be successfully built, and recommendations for further development and eventual production use.

5. EQUIPMENT AND TECHNOLOGY

5.1. Background

There are a number of technologies that could be applied as components within a solution system for this problem. The basic logical components that a solution system might include are:

- signs (changeable message signs) to display delay information to drivers at both ends of the work zone;
- controllers (computing devices used to control sign displays);
- transmitters (telecommunication devices to transmit information);
- receivers (telecommunication devices to receive information);
- data loggers (computing devices to log information such as pilot car location and speed);
- location sensors (used to determine the location of the pilot car [i.e., GPS units]); and
- user interfaces, used to provide information and retrieve input from system users.

Other components such as traffic counters might also be considered.

It was not feasible to evaluate all possible component combinations for viability within the scope of this project. Instead, efforts were focused on one configuration of components that appeared promising and that could be constructed and lab-tested prior to project completion. This approach should be characterized as a “proof-of-concept.” By no means is it implied that this configuration is ready for production deployment. In fact, extensive further testing and development of this system and evaluation of alternatives would be necessary prior to production deployment. However, this test configuration does demonstrate the potential viability of such a system.

5.2. Challenges

The biggest technological challenge is data communication, which is addressed in Chapter 7. Other general challenges include hardening equipment for field use, and addressing user interface and setup issues. These challenges should be addressed in subsequent research.

Supplying power to equipment is yet another challenge. For the purpose of this study, it was assumed that equipment could reside within vehicles and that vehicles could supply power via 12V DC. Ultimately, consideration would need to be given to integrating components into vehicles, onto signs, and perhaps onto other field-ready units. The challenge of integration is non-trivial and would require significant further investigation.

5.3. Components

The proof-of-concept system consists of components separated into two modules, the pilot car module and the endpoint module. The pilot care module (as seen in Figure 5-1) contains:

- Combined Data Logger and User Interface (Notebook PC)
- Combined Transmitter and Receiver (Wi-Fi Interface)
- Location Sensor (GPS)

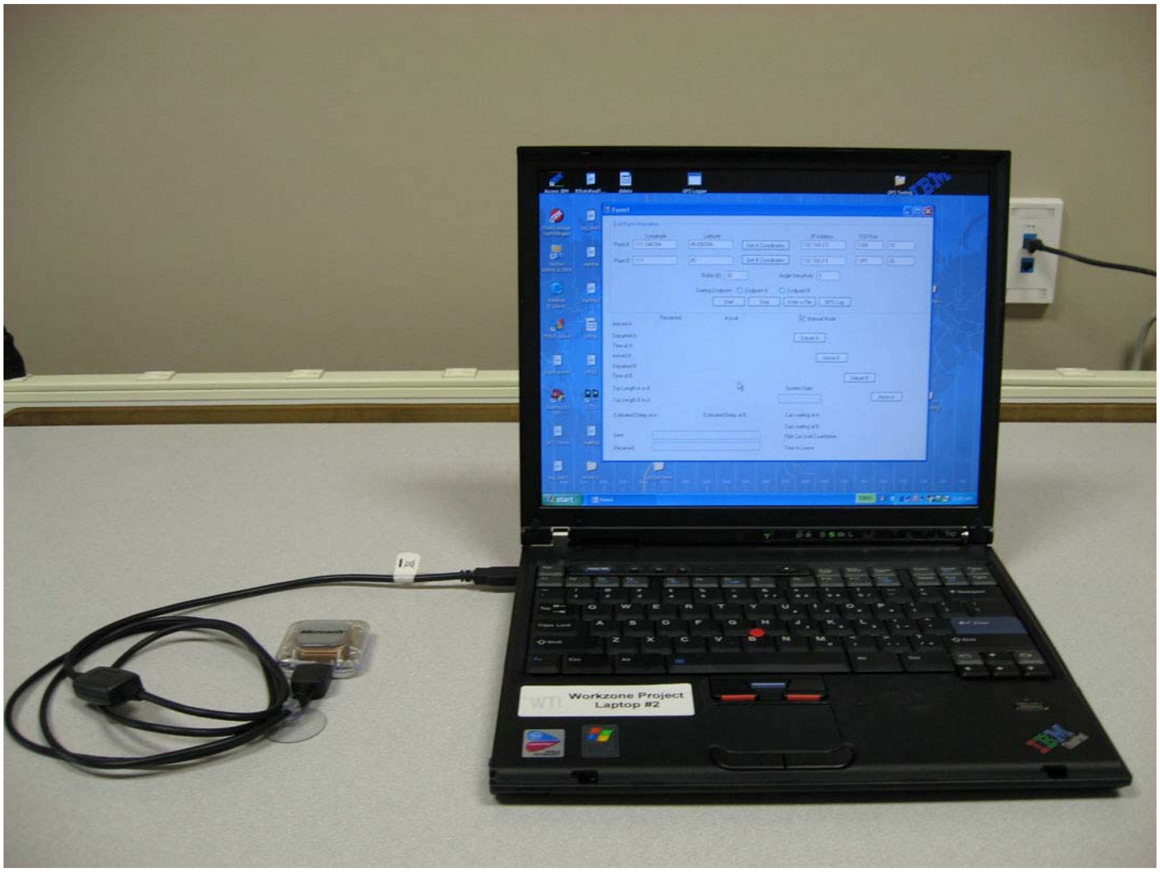


Figure 5-1: Pilot Car Module Equipment

The end point module (as seen in Figure 5-2) contains:

- Signs (LED Changeable Message Signs)
- Combined Data Logger, Controller, and User Interface (Notebook PC)
- Combined Transmitter and Receiver (Wi-Fi Router, Wi-Fi Interface)

Figure 5-2: End Point Module Equipment

The specific components used are described in the following sections.

5.3.1. Notebook PC

A notebook PC is used in both the pilot car and at end points of the work zone. In the pilot car, the notebook PC serves as both a data logger and user interface. At the end points, the notebook PC serves as a data logger, user interface and sign controller. The notebook PC was chosen because it provides sufficient computational power and known compatibility with all of the other components. Other versions of the system may employ a different device for the same functions.

An IBM ThinkPad T42 PC is used in the proof-of-concept system. It contains an Intel Pentium Mobile processor operating at 1.7GHz and 256 MB of memory. The ThinkPad operating system is Microsoft XP Service Pack 2. Interfaces include two USB 2.0 Hi-Speed ports.

5.3.2. Wi-Fi Interface

A Wi-Fi interface is used in both the pilot car and end points to send and receive data from one computer to another. Wi-Fi was chosen for simplicity and for its ability to meet the relatively light data size requirements for the demonstration system. Standard network communications protocols (specifically TCP/IP) can easily be implemented over the Wi-Fi interface. Other versions of the system may employ a different device or communications scheme.

An 802.11g Wi-Fi network adapter is integrated into the ThinkPad Notebook PC. The interface is an Intel PRO/Wireless 2915ABG Network Connection. A Microsoft XP wireless service, Wireless Zero Configuration, automatically controls the wireless adapter. The wireless antenna is integrated into the screen of the laptop and is not visible.

5.3.3. GPS

A GPS device is used in the pilot car to determine the location of the pilot car and each end point. GPS was chosen for its known effectiveness and ease-of-use. Other versions of the system may employ a different device or method of determining location.

The proof-of-concept system uses a Pharos iGPS-360 device. The unit has an integrated antenna and connects to the notebook PCs via a Serial-to-USB converter. The unit automatically outputs standard NMEA-0183(V2.3) strings approximately once per second.

5.3.4. Signs

A LED changeable message sign was used at the end points to display wait time and other messages to motorists. The sign uses a standard computer interface (RS-232) and documented method of communication via computer code. The sign was chosen for its simplicity, ability to prove the concept, and ease of procurement. Other versions of the system may employ different signs for displaying information.

The demonstration system uses an Adaptive Microsystems BetaBrite message sign. The BetaBrite is a one-line LED sign capable of displaying 14 characters per line. Its character array is a 5-inch by 7-inch LED pixel matrix. The sign uses a standard serial communications interface (RS-232) and a documented message protocol (ALPHA Protocol). The sign is connected to the computer via a Belkin Serial-to-USB converter (#F5U109).

5.3.5. Wi-Fi Router

A Wi-Fi router was used at the end points to facilitate data transfer between the pilot car and the end points. The router was used for its simplicity in establishing network associations between wireless adapters and for its ease of administration. Other versions of the system may employ a different means of facilitating data transfer.

The proof-of-concept system uses a D-Link 802.11g wireless router (Di-634). The router contains four antennae (two external and two internal). The router automatically uses the antenna with the best signal strength. In addition, the router contains several Ethernet jacks for wired network communication, although all communications are wireless. The demonstration system uses WPA TKIP encryption.

5.4. System Design

Each module of the demonstration system – the pilot car module and the end point module – contains a software application to control the flow of data and ultimately allow the delay estimation algorithms to be implemented. The major goal of the modules is to provide the proper inputs to the delay algorithms and manage their outputs. Management of the outputs may include displaying messages on the signs or simply storing the results. Each application uses the components available in its corresponding module to accomplish this goal. The applications run concurrently and interact when appropriate.

The module applications must be able to respond to certain events accordingly by transferring data to each other, recording data, and making computations. Due to the nature of the communications scheme, communication only between an end point and pilot car (discussed further in Chapter 6), there are four such events. Assuming end points are labeled A and B, the events are as follows:

- Pilot car arrives at A,
- Pilot car departs A,
- Pilot car arrives at B, and
- Pilot car departs B.

Correspondingly, there are four possible system states for the pilot car application:

- At A,
- Moving from A to B,
- At B, and
- Moving from B to A.

The relationships between these events and the four possible system states are shown in Figure 5-3. The system is in only one state at any given time, and the states must follow a logical sequence. For instance, the system cannot change from state "At A" directly to state "At B" without first entering state "Moving from A to B". State changes are triggered by the four events above. When a state change is detected, data must be recorded, transferred, and computed such that estimation algorithms will have the correct inputs and their outputs are managed effectively.

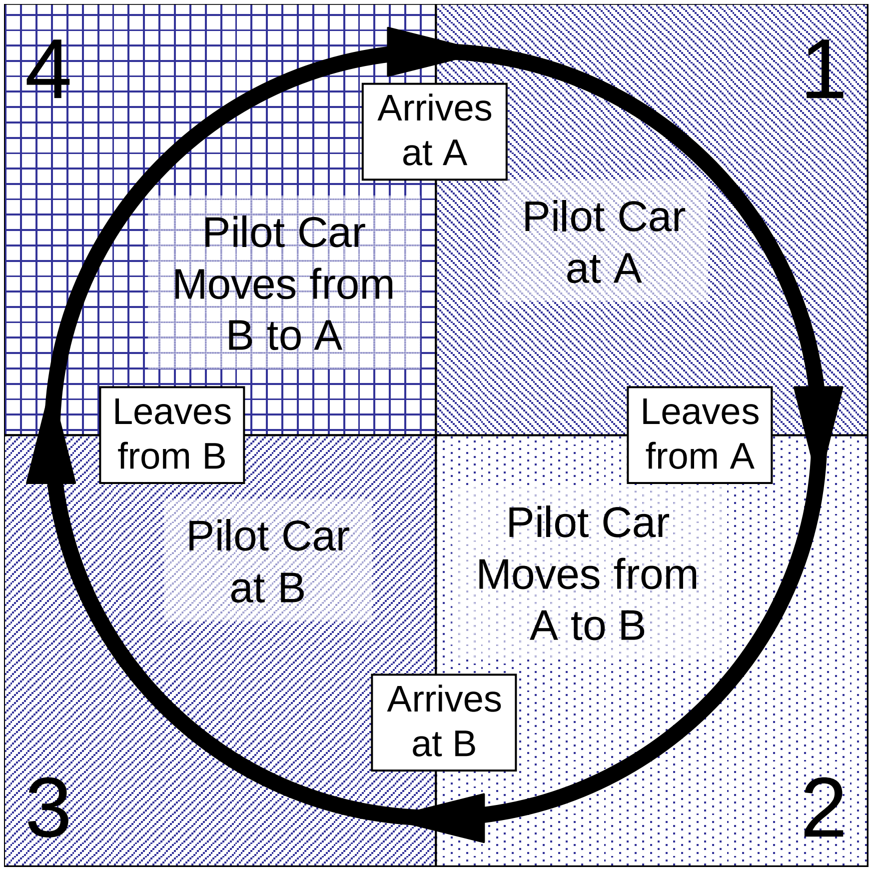


Figure 5-3: Relationship of States and Events in Work Zone

A general flow of data is shown in **Table 1**. Each cell shows the required actions taken by the modules upon transition into a new state.

Table 1: Summary of Data Flow

Component	State 1 At A	State 2 A to B	State 3 At B	State 4 B to A
Pilot Car	• Record time • Calculate trip length • Send data to A	• Record Time • Calculate wait length • Send data to A • Receive data from A	• Record Time • Calculate trip length • Send data to B	• Record Time • Calculate wait length • Send data to B • Receive data from B
A	• Receive data from PC • Update sign message	• Receive data from PC • Estimate delays • Send data to PC • Update sign message	N/A	N/A
B	N/A	N/A	• Receive data from PC • Update sign message	• Receive data from PC • Estimate delays • Send data to PC • Update sign message

The general flow of data above highlights several key functions of both the end point and pilot car applications. Support of the estimation algorithms depends on the effectiveness of each application accomplishing these functions.

Pilot Car Application

The application in the pilot car performs several functions.

- State Determination. The application determines if the pilot car is at end point A, end point B, en route from A to B, or en route from B to A. State determination is accomplished through GPS interpretation, assuming that the locations of both A and B are known. State determination involves several factors including velocity, direction of travel, and distance from the pilot car to the end points. It may also involve recording the path of the pilot car.

- Time Span Calculation and Storage. The application stores timestamps corresponding to times at which the pilot car transitions from one state to another. Using these timestamps, the application must calculate state durations. For example, the length of time at end point A is determined using the timestamp for both the arrival and departure at end point A.

- Data Transfer. State durations are automatically transferred to and received from each of the end point software applications when communication is possible.

- User Interface. The application provides a Graphical User Interface (GUI) to the driver of the pilot car. The GUI facilitates system initialization, allows the user to manually control the sign, and provides real-time status information (such as “Waiting at A”). The interface may also provide manual override of current state information and user confirmation prompts if necessary. (Note that a GUI was chosen to expedite research and development. For production deployment, it may be desirable to implement a hands-free system. Further investigation would be necessary to implement such a system.)

End Point Application

The application at each work zone end point is identical and performs several functions:

- Sign Control. The application displays a message on the sign dynamically and is aware of the sign’s current message.

- Time Span Calculation and Storage. The application stores timestamps and determines time spans for all time segments of the delay algorithm.

- Data Transfer. The application automatically transfers data to and receives data from the pilot car application and perhaps from the application running on the other end point.

- Delay Time Algorithm. The application determines the delay at its end point using a combination of current cycle times spans, historical data, and estimates traffic volumes. The output of the delay algorithm is displayed on the sign.

- User Interface. The application provides a GUI to a user at the end point (such as the flagger). The GUI facilitates system initialization, allows the user to manually control the sign, and provides real-time status information. The application may also provide manual override of state information and user confirmation prompts if necessary. The GUI will allow (and may require) the flagger to indicate the time when the end point is closed for a particular cycle. (Note that a GUI was chosen to expedite research and development. For production deployment, it may be desirable to implement a hands-free system. Further investigation would be necessary to implement such a system.)

5.4.1. State Determination

The pilot car application automatically determines the state of the system by detecting when the pilot car arrives and departs the end points. The system uses GPS coordinates of both the pilot car and the end points to determine system state. Assuming that the end point locations are known and that GPS data for the pilot car is readily available, the system compares pilot car location with that of the end points to determine state. Three components necessary to determine state are interpreting the GPS, calculating the distance between two points (namely the location of the pilot car and that of an end point), and calculating the direction of travel.

Interpreting GPS Data

The GPS device outputs NMEA-0183 standard strings about once per second without being polled. Information pertaining to the longitude and latitude coordinates and velocity are included as well as information about the satellites from which the location is calculated. Code was written to extract the latitude and longitude coordinates when provided by the GPS device.

Initial tests showed that the location of the device could be determined effectively and archived. Locations pertaining to several driving and walking tests were plotted on a map and were shown to represent the actual path traveled.

Calculating Inter-Point Distance

The distance between two latitude and longitude coordinates must be calculated in real-time to determine the distance between the pilot car and an end point. The formula used is:

$$dist = 2\arcsin\sqrt{\left(\sin\left(\frac{lat_1 - lat_2}{2}\right)\right)^2 + \cos(lat_1)\times\cos(lat_2)\times\left(\sin\left(\frac{lat_1 - lat_2}{2}\right)\right)^2} \qquad (5\text{-}1)$$

where lat_x = latitude of point x
lon_x = longitude of point x

The formula was tested using stationary, sample points with known distances. Tests showed that the formula effectively determined the distance between the stationary points. Further tests were performed using a stationary point and a moving point. These tests showed that the distance between a stationary point and a moving point can be effectively determined by the formula in real-time. Since this configuration of points, one stationary and one moving point, resembles that of the work zone, the formula is sufficient for use in the work zone demonstration system.

After the distance procedure was shown to be useful, it was then used to test whether the system could determine if the pilot car had arrived at an end point with a known location. This determination is not as simple as detecting when the distance between the pilot car and end point is zero feet, since GPS readings are accurate only within ±10 meters. Therefore, the system may never detect that the pilot car has reached the end point. A buffer zone surrounding the endpoint was employed to compensate for the inaccuracy. The buffer zone is illustrated in Figure 5-4. Locations with green icons are within the buffer zone while locations with red icons are outside the buffer zone.

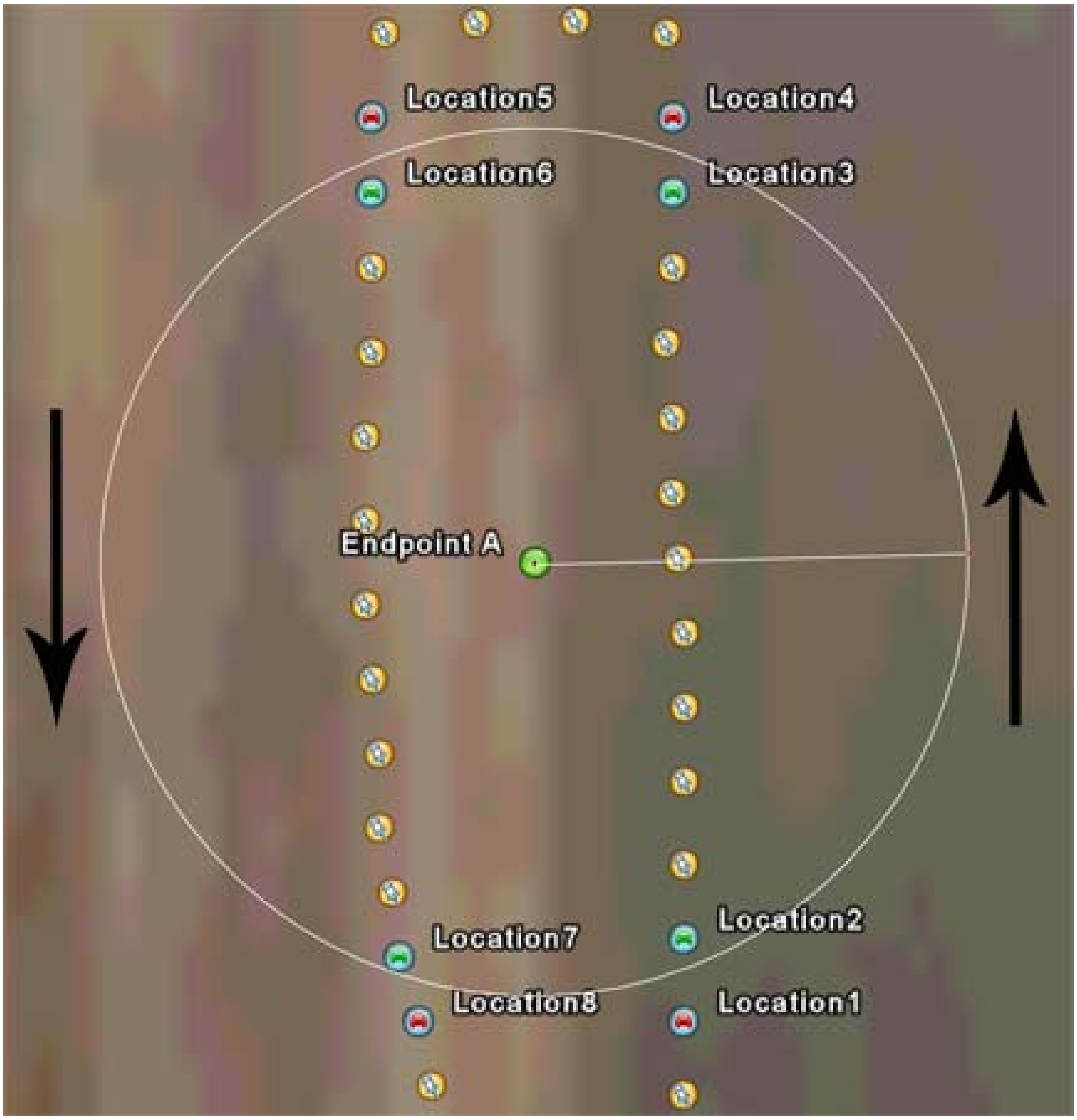


Figure 5-4: End Point Buffer Zone Illustration

The size of the buffer zone is important to the effectiveness of the system. If the buffer zone is too small, there is a risk of missing when the pilot car arrives at or departs from an end point. However, if the event is detected using a small buffer zone, it will be detected close to the actual time that the pilot car arrived at the end point. Conversely, making the buffer zone too large will increase the likelihood of the system detecting when the pilot car arrives and departs an end point, but there will be a larger error between when the event is detected and when it actually occurred. Testing of the system to determine a sufficient buffer showed that a distance of 125 feet is adequate. At this distance, the system was consistently recognizing pilot car arrivals and departures. The difference between when the arrivals and departures actually occurred and when they were detected were generally about 10 to 15 seconds. This error is reasonable compared to the anticipated duration of delay at a work zone (10-15 minutes). However, the limited testing only involved arriving at an end point, turning around at the end point, and departing the end point along the same path. Attempts to arrive at the end point, continue outside the buffer zone, turnaround, and travel back through the buffer zone, as illustrated by Figure 5-4, produced poor results. This issue is addressed in the next section.

Calculating Direction of Travel

Calculating the distance between the end points and the pilot car alone is not sufficient to determine state. A pilot car arriving at an end point must turn around to return to the other end point. However, the location of the turnaround is not consistent for all work zones. Therefore, the pilot car driver might choose to travel well past the end point to perform the maneuver, as is illustrated in Figure 5-4. If distance alone were used to determine state, the system would have incorrectly identified the pilot car, intending to turn around past the end point, as departing the endpoint. Using Figure 5-4 as an example, the system would first correctly detect that the pilot car has arrived at the end point at Location 2. However, as the pilot car passes through Location 4, the system would incorrectly detect that the pilot car has departed the end point based on distance alone. After the pilot car completes the turnaround maneuver, the system would incorrectly detect that the pilot car has arrived at the end point at Location 6. The system would then correctly detect that the pilot car has departed the end point at Location 8. Based on this behavior, timestamp and subsequent time span calculations would not be correct.

A two-dimensional approach employing distance and the relative direction of one point to another is employed to determine system state. The pilot car application stores both the current and the last latitude/longitude coordinates pertaining to the location of the pilot car. When the system detects that the pilot car has entered the end point buffer zone, the direction of the current point (first point inside the buffer zone) relative to the last point (last point outside the buffer zone) is recorded. When the system detects that the pilot car is outside the buffer zone, the direction of the previous point (last point within the buffer zone) relative to the current point (first point outside the buffer zone) is recorded. If this direction is similar to the first recorded angle, it can be assumed that the pilot car is traveling in roughly the opposite direction as when it arrived. Based on this fact and the fact that the pilot car is now outside the buffer zone, the system then determines that the pilot car is departing the end point. If the directions are not similar, it can be assumed that the pilot car is traveling outside the buffer zone, but is not heading back in the general direction from which it arrived. Therefore, no state change is necessary.

Again referring to Figure 5-4, the system detects that the pilot car has arrived at the end point at Location 2. Therefore, the direction of Location 2 relative to Location 1 is recorded. The system then detects that the pilot car moves outside of the buffer zone at Location 4. Then, the direction of Location 3 relative to Location 4 is compared to the direction of Location 2 relative to Location 1. The directions are not similar (in fact, nearly opposite); therefore, no state change is detected. The system detects that the pilot car has re-entered the buffer zone at Location 6, but the arrival to the end point does not represent a state change since the system state indicates that the pilot car is already at the end point. Therefore, the arrival at Location 6 is ignored. The system detects that the pilot car has traveled outside the buffer zone at Location 8. The direction of Location 7 relative to Location 8 is compared to the direction of Location 2 relative to

Location 1. Since the directions are similar, the system determines that the pilot car has departed the end point.

Tests were performed to determine how similar directions would have to be to determine if the pilot car is indeed departing or simply moving away from the endpoint but not departing. Too small of a similarity between directions (< 10˚) would require the pilot car to arrive and depart at nearly the same angle, a requirement that may not be met due to pilot car path randomness and GPS error. Setting the value too large (> 180˚) may allow the pilot car to falsely trigger a departure. The tests showed that a value of 170˚ was effective in determining when a pilot car was actually departing an end point versus driving past the end point to turn around outside the buffer zone.

The pilot car application can determine states sufficiently, without user interaction, for the testing of the proof-of-concept system. Further work is needed to determine if the methods used are robust enough to succeed in subsequent versions of the system and in a real-world testing situation. The current method was chosen because it is sufficient for the controlled testing purposes and is simple to set-up and use. Other technologies may be used instead of or in combination with the current methods. A possible alternative is to use signal strength of the communications mechanisms as an indicator of the location of the pilot car in relation to the end point. However, additional work must be done to investigate the effectiveness of such a method. Also, more GPS data could be employed to determine system state, such as velocity and historical path information.

5.4.2. Time Span Calculation and Storage

Inputs to the estimation algorithms include information concerning the length of time required for the pilot car to wait at the end points and travel from one end point to another. The ability to accurately record times corresponding to certain events and store these times is important to the effectiveness of the estimation algorithms. Times corresponding to when the pilot car arrives at and departs the end points are essential. Also organizing the times and storing them is necessary to provide a historical profile of pilot car activities.

There are two methods for recording and using times. First, timestamps pertaining to the actual time of day that an event occurred can be used. The system would then keep a record of the times when states changed. Alternatively, the system could use the timestamps to calculate time spans. Whereas using timestamps alone associates a time element with events, the use of timestamps to determine time spans associates a time element with the duration the system remains in a state.

The proof-of-concept system uses time spans calculated from timestamps derived from the system clock. The time spans are transferred from one computer to another every time the pilot car arrives at or departs an end point. Using time spans removes the requirement for system clocks on different computers to be synchronized. Testing showed that timestamps could be temporarily stored using a system clock and that a time span can be calculated using two timestamps and subsequently stored. Time span information is consistent and accurate despite discrepancies in individual system clocks and with no further configuration by the user.

5.4.3. Data Transfer

The system incorporates three concurrently running software applications: one for the pilot car and two identical applications for the endpoints. The applications must transfer data to each other to provide the estimation algorithms with the proper inputs. Since there is only communication between an end point and a pilot car, the only means of communication between end points is through the pilot car. When the pilot car arrives at or departs from one end point, data is exchanged. An efficient mechanism for data transfer is needed to facilitate the exchange. The system uses TCP/IP over 802.11g Wi-Fi to exchange data.

Wi-Fi 802.11g networks were chosen for simplicity and ease-of-use. A network can be easily configured using standalone routers and wireless adapters that are already integrated into the notebook computers. Therefore, extraneous wires and antennas are not required and setup may be as easy as providing power to the routers and laptop computers. The Zero Configuration Service automatically handles associations with new access points and the ability to restrict connections to certain access points. The system is configured to only associate with the specified network(s) corresponding to the end points. In addition, static addressing is activated to save time in the association process. It is noted that Windows XP Firewall and any antivirus programs are deactivated. While these can be configured to work with the system, they were unnecessary and caused minor communications difficulties.

The system employs standard TCP/IP network protocols for data communications over the Wi-Fi network. This provides standard means of establishing connections and transferring data between one computer and another. Tests were performed using two computers, in close proximity, wirelessly connected to the same network. Tests showed that data can be consistently transferred from one computer to another. Also, data can be transferred and manipulated back and forth.

While the use of a Wi-Fi network requires minimal setup and hardware overhead, the usable range of the network is relatively short compared to other communications mechanisms. Tests showed that usable signal strengths were retained as far as 850 feet from a wireless router inside a building. However, these results were obtained placing the wireless router close to the window, with no major obstructions between the router and the test computer, and with a test computer in the open (not in a vehicle). Altering the test conditions produced significantly different results. For instance, using the test computer in a car and having several walls between the computer and the router decreased the useable range to about 200 feet. It cannot be assumed that even this range can be maintained for all situations, but it is acceptable for demonstration and testing of the system. The pilot car is not required to communicate with the end points until it is within the buffer zone of the end point. Assuming that the buffer zone is 125 feet, the range of the wireless router is sufficient for testing.

Though transferring data between two computers that were previously connected to the same wireless network was successful, the proof-of-concept system requires automatic association of a new network and subsequent data transfer to reliably occur in the correct order and in a predictable fashion. Tests involving a pilot car starting out of range of the end point router, arriving at the end point, and attempting to transfer data initially produced mediocre results. While it was known that the pilot car was well within range of the end point router, the association of the pilot car computer to that router occurred at seemingly random times. Further investigation revealed that the Windows Zero Configuration service only polls for new access points once per 60 seconds. As a result, the pilot car may take up to 60 seconds to associate with the network once the car is within range of the network. This delay would then require that the pilot car be stationed at an end point until the data is transferred, a requirement that may or may not be feasible. However, a workaround was employed that simply forces the Wireless Zero Configuration service to associate with the new access point once the system detects that the pilot car is within the buffer zone of the end point. Tests showed that the association process occurred reliably within 8-10 seconds after entrance to the buffer zone, at which point data is consistently transferred to the endpoint. This association mechanism is sufficient for demonstration testing, but further investigation is necessary to determine a robust method of access point polling and subsequent association.

A key requirement of the proof-of-concept system is that data be automatically and reliably transferred to and from system computers. Tests have shown that Wi-Fi 802.11g is a suitable communications medium for such transfers. Data can be successfully transferred between computers within a range that is suitable for the demonstration system. Users are not required to interact with the system for data to be transferred.

5.4.4. Sign Control

An essential feature of the proof-of-concept system is a public interface to real-time travel information in the form of a dynamic message sign. The system must automatically display real-time delay information. Therefore, the sign must have a standard hardware interface and documented communications protocol with which to control the information displayed. The sign primarily investigated for the proof-of-concept system, the BetaBrite, meets these requirements.

The BetaBrite uses a standard RS-232 communications interface for connectivity to a computer and the ALPHA protocol as a message protocol. Tests showed that a computer can successfully communicate with the sign and cause the sign to display a predetermined message instantly. The message on the sign can be changed at any time. In addition, the memory of the sign is sufficient to store and display the messages necessary for the work zone system.

Although the use of a BetaBrite is not suitable for use in a deployment system, the sign does demonstrate that the system can integrate a visual display device. The underlying interaction between the proof-of-concept system computers and the BetaBrite through serial communications via the ALPHA protocol is similar to the interaction between Caltrans' Sign View software, hosted on a computer, and sign controllers through serial communications via the SV170 communications protocol. Assuming that a more suitable sign (larger, field-worthy, Caltrans-compliant LED display) contains a standard computer interface and message protocol, it is reasonable to assume that the proof-of-concept system can integrate the sign.

Additional work involving sign control includes researching and testing the national protocol for communication with field devices (NTCIP), which was too complex to be properly tested in the proof-of-concept system. Future work also involves investigating the use of additional signs at each end point, including their placement and messages. The research into power supply and end point-to-sign communication is also of interest.

5.4.5. User Interface

The proof-of-concept system employs a user interface in both the end point and pilot car applications. The user interface allows operators to view system information in real-time. Such information includes current and historical timestamps and time spans, the message on the sign, the contents of the messages being transferred between applications, and system state. In addition, the interface provides users the ability to interact directly with the system. This interaction is required for two processes: initialization and testing. During initialization, communication parameters, such as TCP ports and IP addresses, are specified, as are the latitude and longitude of the end points. Testing requires the user to indicate when arrivals and departures actually occur. Users indicate these times using the interface and the values are compared to system measurements. A voice interface is employed to notify pilot car drivers of a state change. Tests showed that all information available via the user interface is consistent to the underlying system values.

Although the proof-of-concept system employs a user interface, the shape of an interface in future systems is unclear without further investigation. Initialization is an essential function and will likely require an interface. However, other information, such as timestamps and time spans, may not serve a purpose in a deployment system resulting in a smaller user interface. More work must be done to determine the degree of control a user may be able to exercise over the system. The results of such work will influence the components of the interface.

5.4.6. Delay Time Algorithm

The proof-of-concept system must allow the delay time algorithms to be implemented in real time. The system is designed such that different algorithms may be “plugged” in when needed without causing instability to the rest of the system. The modular design allows for the addition of new algorithms or for using a variety of algorithms during the course of the day. Tests showed that the algorithms could be coded and integrated with no difficulty. Given the proper inputs, the algorithms can produce expected outputs.

5.4.7. Proof-of-Concept System

All individual components necessary to test the delay estimation algorithms were created and tested as discussed above. A complete proof-of-concept system was created, integrating all of the components. The system was designed in a modular fashion, using object-oriented principles, to accommodate new equipment and technology decisions. For instance, using a new sign or GPS device does not require a complete redesign of the system. Rather, only a new module for the specific device must be developed to integrate with the change. It should also be noted that several estimation algorithms were integrated into the system in a similarly modular fashion.

5.5. Equipment and Technology Testing

The complete proof-of-concept system was tested in and around the parking lot of the WTI facilities for several hours. The 0.5-mile-long testing site was chosen for convenience and the relatively light traffic conditions during the test. The site is shown in Figure 5-5. Approximately

22 complete trips between end points were traveled. The purpose of the tests was to investigate the effectiveness of a complete system using all of the equipment and technology components and the effectiveness of the algorithms. The system tested contained an end point module located in the WTI Systems Engineering Laboratory. The pilot car module was housed in a private vehicle. It was not feasible to setup an end point module at the end point site far away from the building. Therefore, the end point application was run concurrently on the pilot car module computer, minus a display sign. More information concerning the testing in reference to the estimation algorithms is discussed in Chapter 6.

Figure 5-5: Aerial Photo Showing the Path of One Test Run

5.6. Equipment and Technology Findings and Recommendations

A complete proof-of-concept system, upon which the estimation algorithms could be implemented, was designed and built using several components. The system uses two main applications and associated hardware. The pilot car module records timestamps, calculates time spans, transfers/receives data, and determines the system state. The end point module transfers/receives data, estimates delay times, and controls the sign. Both modules also involve a user interface for initialization and system monitoring.

The controlled lab tests showed that all components of the complete proof-of-concept system performed properly. The system was able to initialize properly and detect all arrivals and departures. Communication between computers encountered no difficulties. All time span recordings were properly completed. As a result, the estimation algorithms received the proper inputs and were able to perform calculations effectively.

In short, the limited tests showed that the proof-of-concept system could support the estimation algorithms and display useful information using LED message signs. The system involves minimal user input or external data to run properly. The hardware components are relatively easy to set-up and to use. In short, the system serves as a “proof of concept” showing that technology can be used to effectively convey relevant information at work zones.

Although the controlled test results of the proof-of-concept system were promising, it should be noted that the system is not ready for deployment. Further investigation involving several areas of the system is needed to determine the optimal configuration.

While the system used two notebook computers for many tasks, it may be possible to use other, lightweight devices instead. For instance, an alternate configuration may defer all calculations to the end points, allowing the pilot car system to be little more than a GPS device continuously transmitting its location. Other configurations include using embedded controllers at the end points that would handle control of sign or any other devices.

The proof-of-concept system uses GPS to determine pilot car arrivals and departures relative to end points. While this was adequate for use in the controlled lab test, GPS is not suitable for use in all topographical or environmental conditions. Effective use of GPS assumes a clear view of the sky. However, such conditions cannot be guaranteed for deployment. Dense overhead foliage or other obstructions may be common in the field. Therefore, other methods of state determination must be researched and possibly used with GPS to provide a more robust system. In addition, the test site contained relatively straightforward approaches to the end points while deployment requires that the state determination mechanism perform well in any circumstance. Work zone site geometry and pilot car driver behavior influences the effectiveness of state determination. Additional work must be done to provide a state determination mechanism that is relatively immune to driver behavior and road geometry.

Wi-Fi 802.11g is used as a communications medium between computers in the proof-of-concept system. This means of communication was sufficient for testing in the lab but other technologies may be needed for deployment. If Wi-Fi is used in subsequent versions of the system, an investigation concerning the range of the Wi-Fi router must be performed to ensure effective field communications, especially in rugged areas with many obstructions. The system uses a workaround to poll for the access point once the pilot car has arrived at an end point. An investigation of a more robust method of access point polling should be undertaken. A closer look into security issues and solutions concerning Wi-Fi should also be taken.

The user interface allows users to glimpse underlying system values for testing and initializing the system. Further work should be done to determine the role of the user interface in future systems. Other systems may include increased or reduced user involvement or the addition of historical data. The user interface must be able to facilitate these changes. It may be of interest to investigate a voice interface for initialization of system override functionality. For instance, the pilot car driver may simply say “At A” to indicate that the pilot car has arrived at end point A.

As both real-time and historical data are available, the role of an interface to the data collected by the system must be further investigated.

The proof-of-concept system uses a BetaBrite LED message sign to visually convey delay information. While this sign is not intended for use in the field, it does have a standard computer interface and a documented communications protocol. These two attributes are required for use by this system and are essential for operation with Caltrans' Sign View software. The use of field-appropriate signs, their interfaces and protocols, must be investigated for a deployable system. However, the underlying computer-to-sign communications principles are similar to those employed by Sign View to control Caltrans' CMS devices. Given the modular nature of the demonstration system, it seems reasonable to assume that a more appropriate sign can be "plugged-in" in the future without too much difficulty. Further investigation concerning NTCIP compatibility must be completed to further evaluate the system's integration potential. Furthermore, more research concerning the use of multiple signs, their placement, and the synchronization of their messages should be undertaken.

6. DELAY ESTIMATION AND COMPUTATION

Based on the experience of Caltrans personnel, there are typically variations in a pilot car's cycle length throughout a day in a two-lane rural highway due to the following reasons:

- Interruptions in the pilot car progression through the work zone due to work zone activities (e.g. temporary heavy equipment movement encroaching the traffic lane);
- Unavoidable variations in the traveling speed of the pilot car through work zones; and
- Variations in the arrival rate of vehicles for different hours of the day.

The variations in wait times between cycles add to driver frustration when they are not informed of how long the wait will be. As explained earlier, the user requirements for the Delay Estimation and Display functional area of the system states that the accuracy of the displayed time measurement (i.e. either total delay or stopped delay) should be within the range of ±2 minutes.

This chapter summarizes how algorithms for estimating and computing delay were developed and tested. Due to the fact that there were only three months available for the design and testing of the prototype system, testing of the accuracy of the following algorithms was limited and allowance to meet the user requirements in the future were made in general design of algorithms.

6.1. Background

6.1.1. Policies

Caltrans and other agencies may have policies that affect how the system's estimation of delay may work. Typical work zone delays range between 10 and 15 minutes, as Caltrans has adopted a policy to keep the wait times to no more than 15 minutes. All vehicles that are stopped at one end of the work zone will be allowed to exit during one cycle; in other words, a flagger will not stop traffic in the middle of a queue of vehicles starting to move through the zone. Pilot cars will also generally follow the posted speed limit through the work zone.

6.1.2. Definition of Delay

Generally, the delay caused by work zones can be seen in two different ways. The total delay caused by the presence of work zone on highways includes the stopped delay and the delay due to lower speeds in the sections leading up to the work zone. As stated in the user requirements (Chapter 3), three options for the type of delay estimation to be displayed were considered.

1. Time before the first car in the queue starts to move to go through the work zone

2. Time for the first car in the queue to get to the other end of the work zone

3. Delay due to the work zone (i.e. the difference in travel times between any two points encompassing the work zone with and with out the work zone)

The research team decided to estimate delay according to option 1, as this was considered to be the most relevant information sought by the waiting public. It should be noted that these three measures are related, and the general design of the system will be able to accommodate the other options with only limited changes.

6.1.3. Terminology

The first step towards measuring the wait time (i.e. the time before the first car in the queue starts to move to go through the work zone) was to define one cycle of pilot car operations, since the pilot car's operations for the whole day are essentially repetitions of one complete set of operations. Generally, the total cycle length is defined as the time difference between the times of two consecutive departures of the pilot car from any clearly defined location along its path through the work zone. For the purposes of the prototype system, using a work zone whose endpoints are defined as A and B, the cycle length has been defined as the time difference between two consecutive departures of the pilot car from end A of the work zone.

Following this definition of the cycle length (also referred to as cycle time or cycle duration), one cycle of pilot car operation consists of a series of four states: the pilot car waiting at A (State 1), the pilot car traveling from A to B (State 2), the pilot car waiting at B (State 3), and the pilot car traveling from B to A (State 4). These were shown in Figure 5-3. The pilot car wait times at the ends are defined as the time between when the pilot car arrives at and leaves from an end. This includes the turnaround time of the pilot car.

For this chapter, assuming a work zone with two ends of the work zone defined as A and B, the following expressions are used:

C_i = Time length of cycle i
T_{ADi} = Time of departure of pilot car from end A of work zone in cycle i
T_{AAi} = Time of arrival of pilot car at end A of the work zone in cycle i
T_{BDi} = Time of departure of pilot car at end B of the work zone in cycle i
T_{BAi} = Time of arrival of pilot car at end B of the work zone in cycle i
T_{AFi} = Time when the flagger closes the traffic at A
T_{BFi} = Time when the flagger closes the traffic at B
L = Work zone length
v = Average pilot car speed

Figure 6-1 details the travel through the work zone from the perspectives of the pilot car, the first car in line at both ends and the other cars in line at both ends. These perspectives are as follows.

- Pilot car. As stated earlier, it is assumed that the cycle length begins when the pilot car departs from point A and ends when the pilot car next departs from point A. After traveling from A to B, the pilot car waits at end B until all the cars it is leading have passed it, and left the work zone. At this point, the pilot car turns around, and returns to A. At point A, the pilot car waits for all vehicles which followed it from B to pass through the work zone. This completes the cycle.

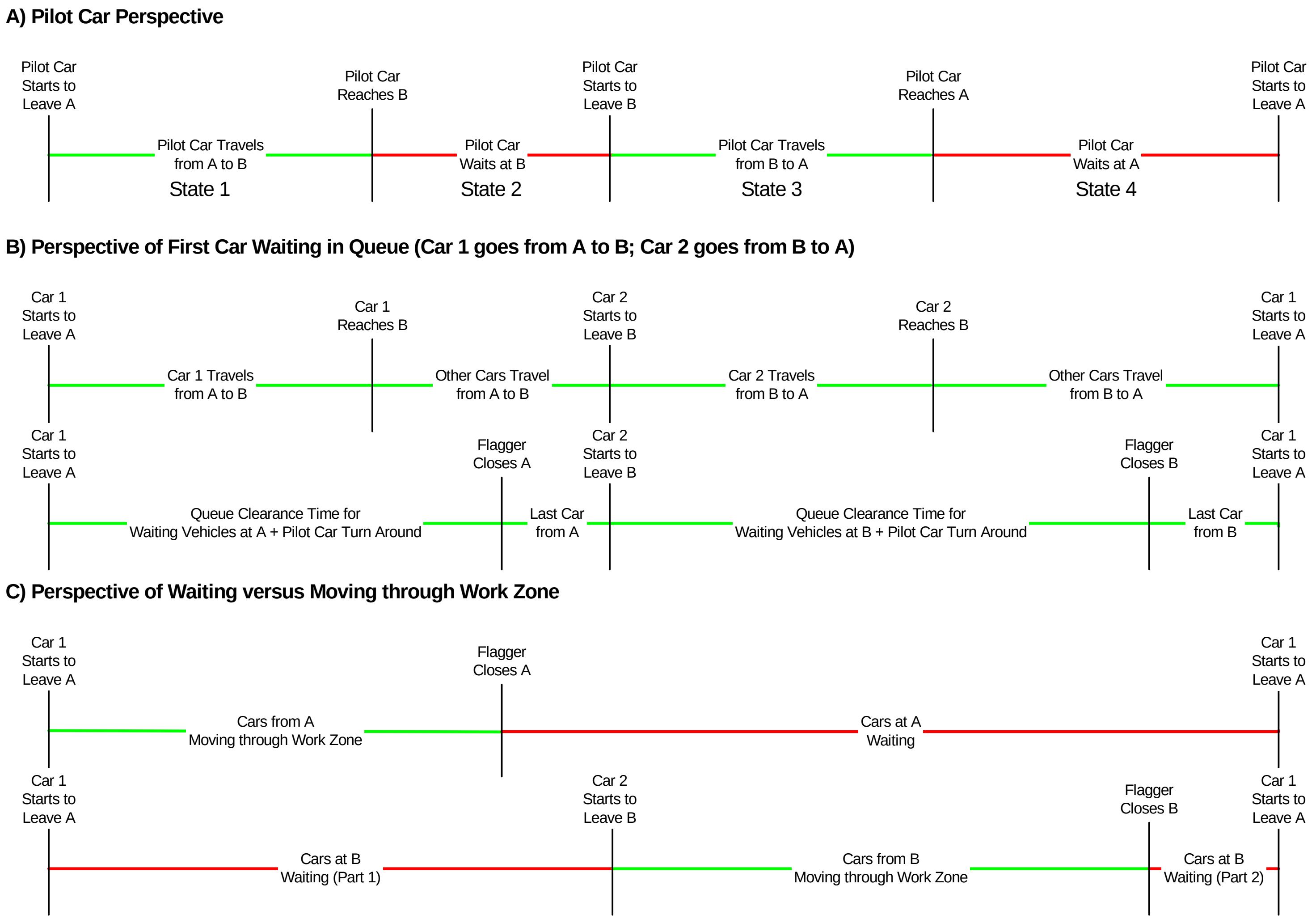


Figure 6-1: Timeline of Vehicle Operations inTwo-Lane Rural Highway Work Zones

- First car waiting. The first car waiting at either end will proceed toward the other end of the work zone once the pilot car moves; this can be seen in Figure 6-1 where the events are shown simultaneously. Once the queue of cars has exited the work zone and the pilot car has turned around, traffic switches directions.

- Waiting versus moving. These concepts may be combined to show how stopped delay may be calculated. For vehicles moving from A to B, the waiting time starts once the flagger stops traffic at end A, no longer allowing vehicles to enter the work zone. The waiting time ends at the start of the next cycle, when the pilot car starts to leave end A. The same is true for traffic leaving end B. Figure 6-1 shows two different components of waiting time for vehicles at end B, but it is conceptually identical to what is occurring at end A.

The different states of the pilot car and its operations can also be explained using the Figure 6-2. shows one pilot car operation cycle in terms of four states of pilot car operations.

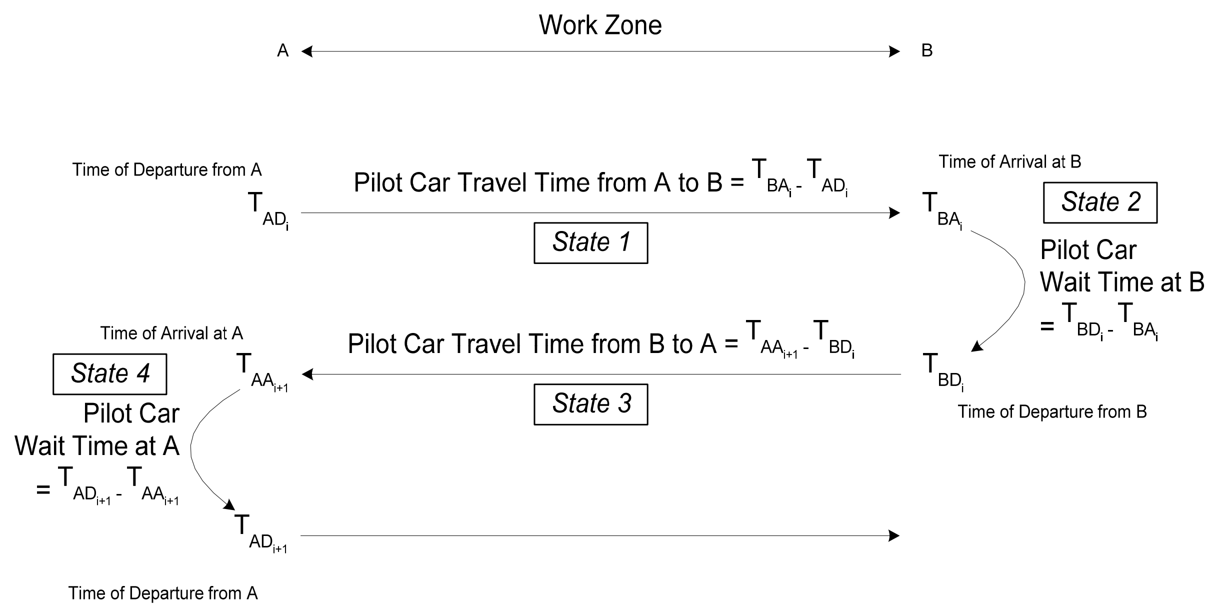


Figure 6-2: Components of Cycle Duration

To simplify the notation, let the following be defined:

AB_i = Travel time (for pilot car) from A to B during period i (= $T_{BAi} - T_{ADi}$)
BA_i = Travel time (for pilot car) from B to A during period i (= $T_{AAi+1} - T_{BDi}$)
B_i = Wait time (for pilot car) at B during period i (= $T_{BDi} - T_{BAi}$)
A_i = Wait time (for pilot car) at A during period i (= $T_{ADi+1} - T_{AAi+1}$)

The following sections use these terminologies and definitions for explaining the wait time estimation algorithms developed.

6.1.4. Challenges

To accommodate the user requirements, the following constraints were considered in the development of wait time estimation algorithms.

1. No site-specific traffic characteristics (e.g. real-time traffic data through detection equipment) are available as inputs to the algorithm.

2. Only minimal human inputs and verification are possible.

3. Cycle time variations between consecutive cycles of pilot car operations are expected.

4. Traffic conditions for the first run of pilot car for the day are not known.

5. Technology (e.g. in-pavement sensors) to determine the queue length at the work zone ends is not used.

6. Communication between the pilot car and the wait time estimation systems (i.e. end point applications) is limited to the times when the pilot car is at the ends of the work zone. In other words, end-to-end communication for the length of the work zone is not assumed to be available.

7. There is a possibility that there are failed communication attempts between pilot car and wait time estimation systems.

8. The time at which the flagger closes an end point to traffic is unknown.

6.1.5. Assumptions

The following assumptions were made in the selection of algorithms for the prototype system to determine the wait times at both ends of the work zone.

1. Wait time estimation is performed at the applications at the end points.

2. Communication between the pilot car and end point applications occurs only at the end points. (However, further research may make end-to-end communication and multiple communications from various points along the work zone.)

3. Archived information is available for at least the ten previous cycles.

4. The wait time displayed by the system will indicate the time for the first car in line to start entering the work zone.

6.2. Algorithm Development

Based on the challenges and assumptions described above, a set of algorithms was chosen for further exploration in this study. The simplest of these algorithms was to use a moving average approach to estimate the wait time to be displayed. Four different ways of estimating moving averages were explored and are discussed in this section. A methodology to improve the moving average was developed and is discussed below, although this methodology was not tested due to time constraints. Alternate methods to moving averages are briefly mentioned here and will need extensive future research before use.

6.2.1. General Wait Time Estimates

Delay for Vehicles Waiting at A:

$$D_{Ai} = T_{ADi+1} - T_{BDi} + \left(T_{BDi} - T_{AFi}\right) \tag{6-1}$$

D_{Ai} should be displayed at the time of flagger closing A. At the time when flagger closes A, only T_{ADi} and T_{AFi} are known, assuming that T_{AFi} can be communicated to the processing unit at A reasonably instantaneously. This means that T_{ADi+1} needs to be estimated when the flagger closes A. For the system to decide when to display the delay time, the system needs to know when flagger closes A. The system needs to know when the flaggers close the traffic or an estimate of when the flagger closes A. The time difference between the pilot car leaving an end and the flagger closing the end is a measure of the number of vehicles queued up at that end (i.e. A). An acceptable estimate of the number of vehicles queued up at that end could be the number of queued vehicles at that end (A) during the last cycle (i.e. the wait time of the pilot car at the other end [B] during the last cycle).

If the time when the flagger closes the traffic at A (T_{AFi}) is known then D_{Ai} can be written in the following terms.

$$D_{Ai} = T_{ADi+1} - T_{AFi} \tag{6-2}$$

Again, when the flagger closes the traffic and triggers an event at the processor at A, only T_{AFi} is known; T_{ADi+1} will have to be estimated.

Delay for Vehicles Waiting at B:

For the purpose of estimating the delay for vehicles at B, a cycle can be defined as the time difference between two consecutive departures of the pilot car from end B of the work zone. D_{Bi} should be displayed at the time of flagger closing B. When the flagger closes B, only T_{BDi} and T_{BFi} are known. This means that T_{BDi+1} needs to be estimated when the flagger closes B as the delay message at the end B of work zone should start when the flagger closes B. For the system to decide when to display the delay time, the system needs to know when flagger closes B.

If the time when the flagger closes the traffic at B (T_{BFi}) is known then D_{Bi} can be written in the following terms.

$$D_{Bi} = T_{BDi+1} - T_{BFi} \tag{6-3}$$

Again, when the flagger closes the traffic, only T_{BFi} is known; T_{BDi+1} will have to be estimated.

The algorithms for the estimation of wait times and cycle times for end B are the same as the ones for end A (i.e. mirror image of the process for end A). For simplicity, the algorithms are discussed only in terms of end A.

This method has some limitations.

- The time that the flagger closes the traffic at end A (T_{AFi}) needs to be estimated if the need for real-time input by the flagger is to be eliminated. This calls for an accurate estimate of the number of vehicles arriving at each end when the traffic is closed at the corresponding end.
- The departure time of pilot car from end A for cycle i+1 (T_{ADi+1}) needs to be estimated at the time when the flagger closes the traffic at A, and similarly for end B.
- T_{ADi+1} and T_{BDi+1} estimates may not be updated during a cycle if communication between ends A and B is not feasible

6.2.2. Moving Average of Wait Times

Unlike the general procedure just described, this method uses archived information on the pilot car's operations to estimate future delay. One method is to estimate the cycle length based on the last i number of cycles.

$$C_{i+1} = \sum_{j=1}^{i} a_j C_j \tag{6-4}$$

where a_j = a weight for cycle j
C_j = cycle length for cycle j

Another way of using the moving average is to average the actual wait times rather than the cycle times:

$$D_{Ai+1} = \sum_{j=1}^{i} a_j D_{Aj} \tag{6-5}$$

Using notation for the time duration of the different states of the pilot car, the time when the pilot car will be leaving end A (T_{ADi+1}) can be measured as follows.

$$T_{ADi+1} = T_{ADi+} AB_i + B_i + BA_i + A_i \tag{6-6}$$

$$C_i = AB_i + B_i + BA_i + A_i \tag{6-7}$$

The only value on the right side of the equation that is known with certainty at point A at all times during cycle i is T_{ADi}. Other values must be estimated and perhaps even updated with actual values as the pilot car progresses. When *the processor at A needs to know the value of C_i*, none of its components – AB_i, B_i, BA_i and A_i – are known. In the case where transmission occurs only at the end points, then values will not be known until the car returns to A. However, in the case where transmission is continuous or even intermittent, these values could be updated with actual values when available.

Delay for vehicles queued up at A:

$$D_{Ai} = C_i - T_{AFi} \tag{6-8}$$

Delay for vehicles queued up at A:

$$D_{Bi} = C_i - T_{BFi} \tag{6-9}$$

This methods also has some limitations.

- The times that the flaggers close the traffic at ends A and B (T_{AFi} and T_{BFi}) need to be estimated if the need for real-time input from the flagger is to be eliminated. This calls for an accurate estimate of number of vehicles arriving at each end when the traffic is closed at the corresponding end.

- The cycle length of cycle *i* (C_i) needs to be estimated at the time when the flagger closes the traffic at A, and it is the same for end B.

- Parts of C_i may not be updated within a cycle if communication between ends A and B is not feasible.

Four methods of moving averages were examined in this study.

Wait Time from Last Cycle. In this method, the actual wait time for the cars for a current cycle is expected to be very similar to the immediate completed cycle. Using equation 6-5, $a_i = 1$ and all of other weights are set to zero (i.e. $a_1 = a_2 = a_3 = a_4 = \ldots = a_{i-1} = 0$). A limited comparison of the performance of this method over the other methods is discussed in the test results section of this chapter.

Average of Last Ten Cycles. In this method, a simple average of the wait times from the last ten cycles is used as the estimated wait time for the current cycle. Ten cycles were chosen to represent a two-hour time period, with an average cycle length of about 12 minutes. In the moving average calculation, all of the weights are set to 0.1 (i.e. $a_1 = a_2 = a_3 = a_4 = \ldots = a_9 = a_{10} = 0.1$). A limited comparison of the performance of this method over the other methods is discussed in the test results section of this chapter.

Exponentially Decaying Weights for Last Ten Cycles.

In this method, a weighted average of the wait times from the last ten cycles is used as the estimated wait time for the current cycle. Instead of equal weight given to all of the previous ten cycles, the weight exponentially decays as the cycles progress further into history.

In the moving average calculation, $a_n = 1/2^0$, $a_{n-1} = 1/2^1$ (i.e. $a_n = 1/2^{n-1}$ for n = 1-10). A limited comparison of the performance of this method over the other methods is discussed in the test results section of this chapter.

Linearly Decaying Weights for Last Ten Cycles.

In this method, as with the exponentially decaying weights method, a weighted average of the wait times from the last ten cycles is used as the estimated wait time for the current cycle. The weight linearly decays as the cycles progress further into history.

In the moving average calculation, $a_n = 1/1$, $a_{n-1} = 1/2$ (i.e. $a_n = 1/n$ for n = 1-10). A limited comparison of the performance of this method over the other methods is discussed in the test result section of this chapter.

6.2.3. Improved Moving Average of Wait Times

The moving average methods discussed so far are confined to recent work zone operations (i.e. within the last two hours) and as such are relatively insensitive to the specific time of day. Could historical data on pilot car operations – such as consideration of the preceding day's traffic – help to refine the wait time estimate? To answer this question, daily traffic data for a typical two-lane rural highway in Caltrans District 2 was obtained from Bella Vista on State Route 299 in Shasta County (ATR Station 213). A quick analysis of traffic in the two lanes supports one of the basic assumptions of this project that the traffic arrival rate can vary significantly between hours of a day. Figure 6-3 and Figure 6-4 show the variation of lane 1 and lane 2 traffic volumes for different hours of the day. The data used for these figures are for the days between December 14, 2005 and January 17, 2006[1]. These hourly volumes are traffic shown may be assumed to be representative of the traffic volume trends for two-lane rural highways.

As can be seen from these figures, the hour of the day may provide valuable information to improve wait time estimates. Including the hour of day would not require human input, since this could be automatically available from the system clock of the delay estimation application[2].

Other useful information that can help to improve the wait time estimations is the day of the week. It has been established in traffic engineering that the traffic characteristics (e.g. peak hours of traffic) of Tuesdays, Wednesdays, and Thursdays are similar while the weekend traffic, Monday and Friday traffic are significantly different (8). This can also be seen in Figure 6-5. Each curve in this figure represents the hourly volume for one particular hour of the day. This data is for the same dates as Figure 6-3 and Figure 6-4 (i.e. from December 14, 2005 [Saturday] to January 17, 2006 [Tuesday]).

[1] It should be noted that these dates include holiday (i.e. Christmas and New Year) traffic variations.

[2] It is assumed that the system clock is set to the appropriate time zone.

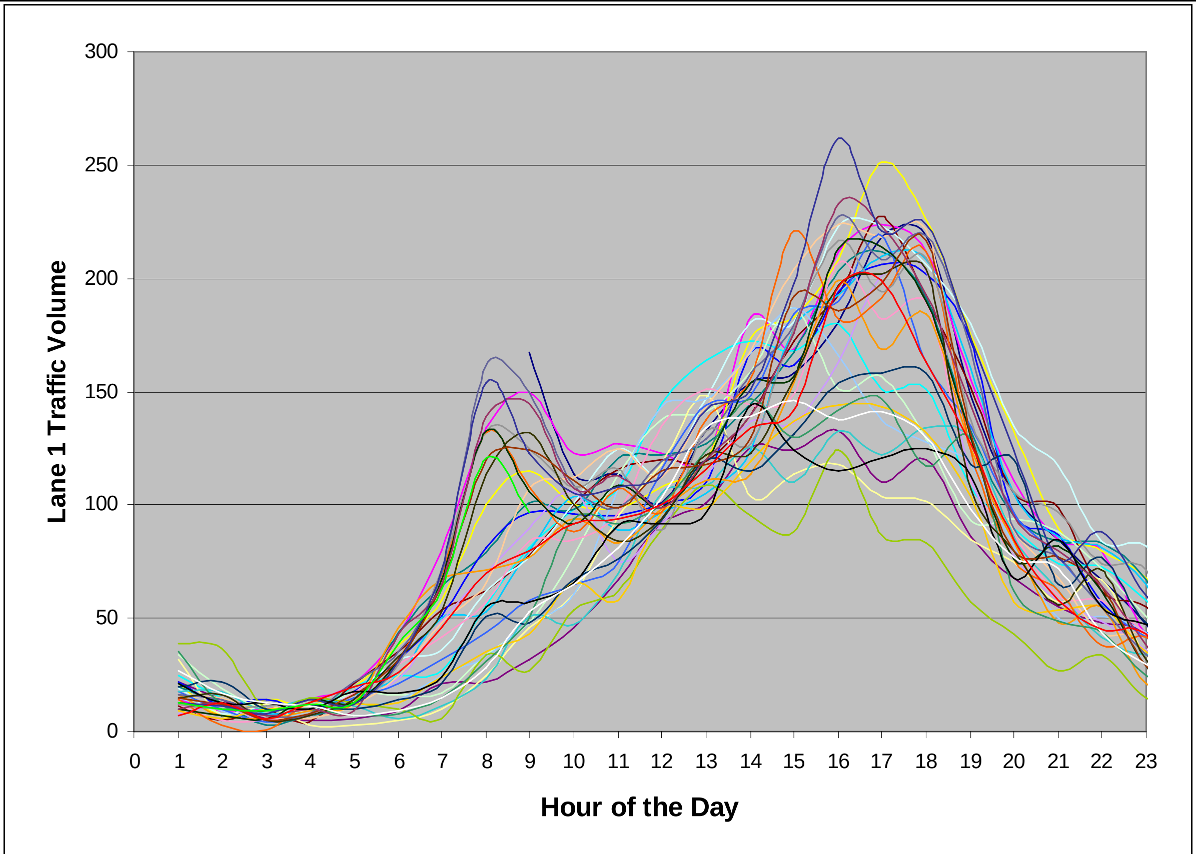


Figure 6-3: Lane 1 Traffic Volume Variations

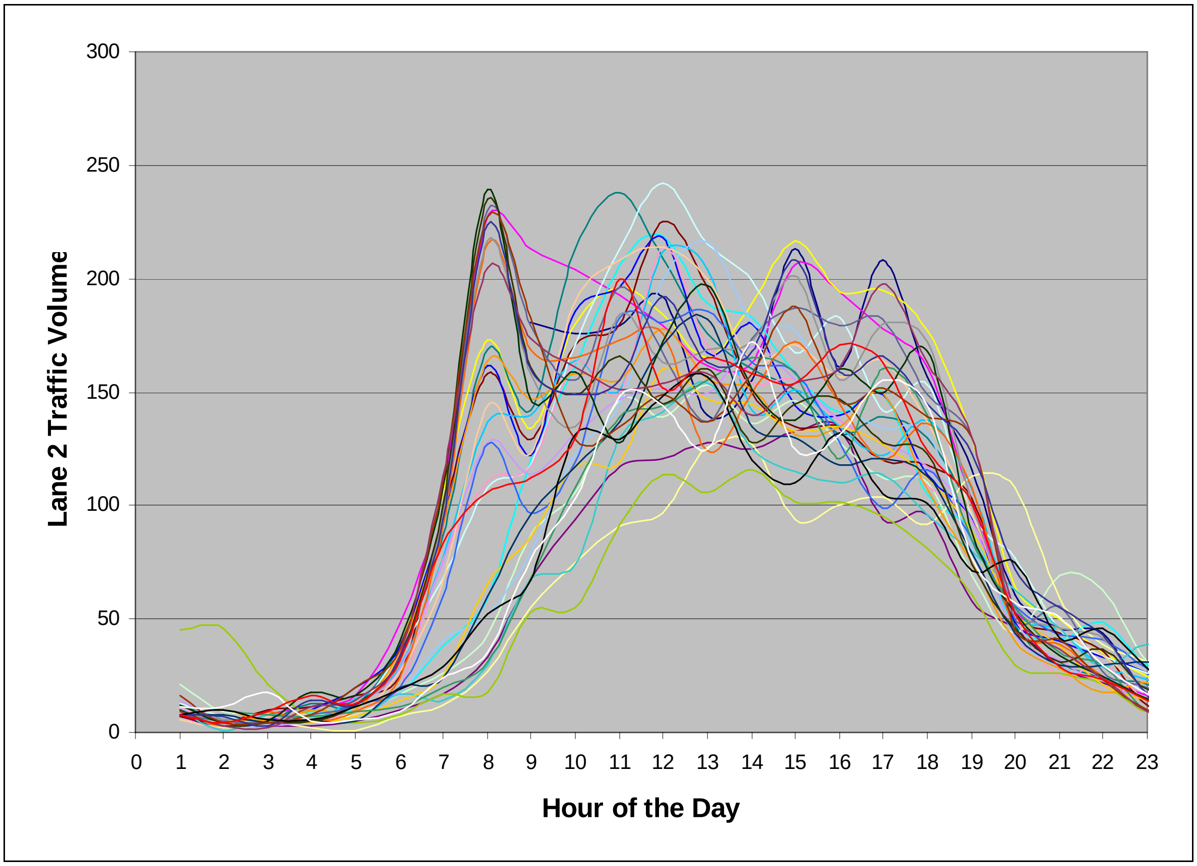


Figure 6-4: Lane 2 Traffic Volume Variations

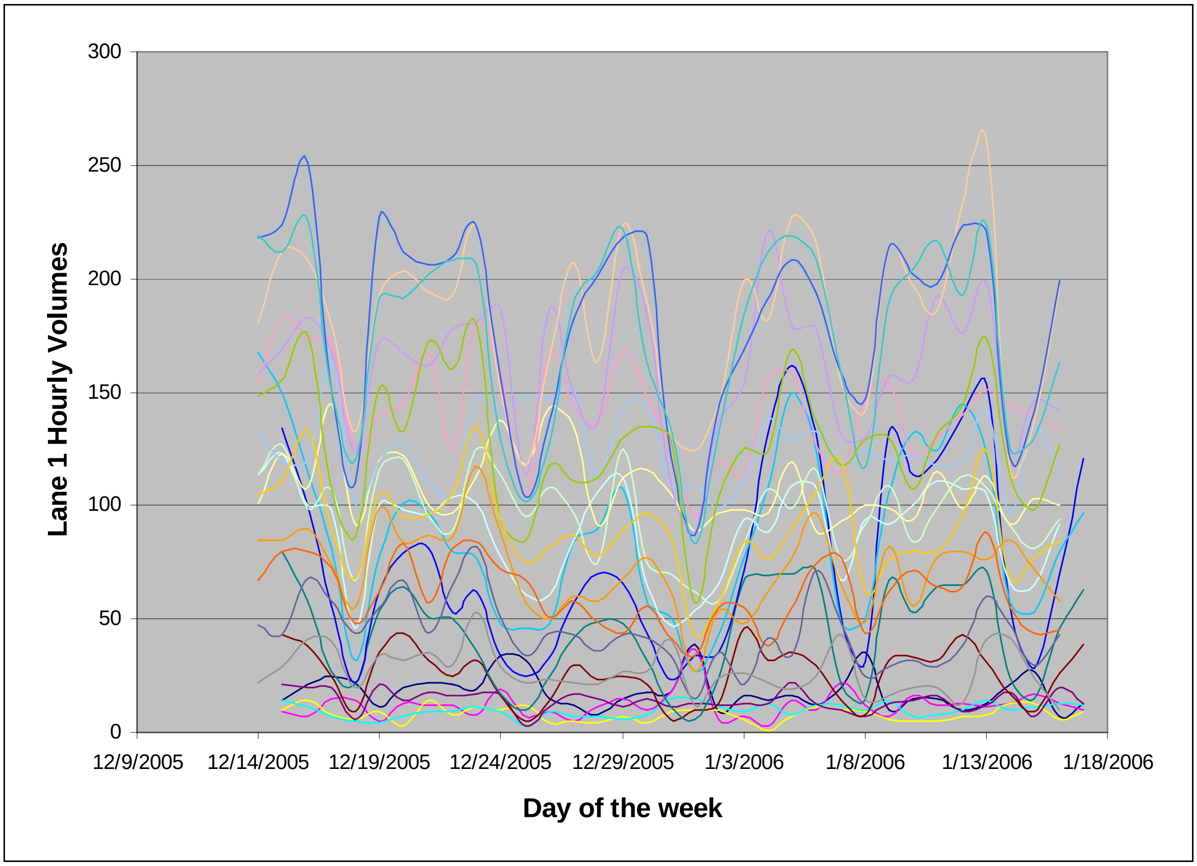


Figure 6-5: Lane 1 Hourly Traffic Volume Variations with Day of the Week

The hour of the day and day of the week information can be obtained from the system clock. A general peak hour trend (e.g. between 7 AM and 9 AM) may be established using regionwide traffic data for rural two-lane highways. (This may be investigated with additional data collection in the future). Using this information and time of day and day of the week from system clock, the following three trends of the traffic volumes can be established.

- Increasing (leading up to the peak hour or pre-peak hour)
- Flat (during the peak hour or during non-peak hours)
- Decreasing (immediately post-peak hour)

Once established, these trends can be used for verification and improvement of the moving average based algorithms.

6.2.4. Other Methods

This system is expected to be used at work zones that typically last for several days. This system is also designed to archive most of its operations. As more and more archived information for the same work zone is available, the following other methods may be useful.

- Time Series Approach. A time series is a set of observations at equally spaced time intervals. Time series are used to separate the general trends from "noise" and predict the future values of the variable observed. In the case of the system in this study, the unit of observation cannot be cycle lengths, as the intervals between cycles (i.e. cycle times) are not equally spaced. The appropriate unit of observation for the context of this study would be the average delay times for each hour for the work zone end of concern. The archived information from previous days and previous hours of pilot car operations at the same work zone can be fit into a time series. This will help identify trends that can be used for predicting the delay time for the next hour. The prediction for the next hour can be translated into the estimated delay time for the next cycle using an appropriate method.

- Fourier Series Approach. Fourier series are generally used to solve arbitrary periodic functions by decomposing the function into simpler functions and solving for those functions. The results are then combined to solve the original function. Non-periodic functions can also be dealt with using Fourier approximations. For the delay estimation system, cycle lengths are expected to be periodic over one day. Therefore, this method may be used for multi-day work zone operations of the system. Since there will only be one lane available for traffic, it may be expected that this lane will have a few hours in the morning and few hours in the evening where the traffic volumes are close to peak-hour traffic volumes. Therefore, the traffic arrival rate at the work zone may be able to be approximated by a Fourier series and modeled.

- Markov Chain Approach. A Markov chain is a sequence of random variables (e.g. x_1, x_2, x_3,…) with the property that the conditional probability distribution of the next future state x_{n+1} given the present and past states is a function of the present state x_n alone. This approach may help improve the delay estimates as it accounts for the stochastic nature of traffic arrivals and disturbances to the pilot car movement through the work zones.

Further research is needed to explore the applicability and subsequently develop algorithms using these methods.

6.3. Testing of Delay Estimation Algorithms

Laboratory-controlled testing of some of the above algorithms was performed. The research team was unable to identify off-the-shelf software that can readily simulate the pilot car operations in a two-lane rural highway work zone without extensive customization. Therefore, SimProcess™, a software program used to simulate manufacturing processes, was used to simulate the pilot car operations and the traffic movement through work zones. A detailed description of the simulation model can be found in Appendix A.

6.3.1. Simulation Analysis

The traffic counts obtained from Bella Vista in Caltrans District 2 were used for this simulation. The start-up delay time for stopped vehicles at each end was assumed to be two seconds and the headway between vehicles while traveling through the work zone length was assumed to be two seconds. The length of the work zone was assumed to be two miles.

Results

Three simulation scenarios were run, and average wait time, queue length and travel time were calculated. Scenario 1 was run to cover traffic for 16 hours between 8 AM and 12 midnight with no warm up. Scenario 2 was run to cover traffic for 24 hours between 12 midnight and 12 midnight with no warm up. Scenario 3 was run to cover traffic between 8 AM and 12 midnight with a 30 minute warm up. The estimates for average work zone travel time and average waiting time for each of the scenarios is shown in **Table 2**.

Table 2: Results of Simulation Analysis

	Average Travel Time		Average Wait Time	
	Lane 1	Lane 2	End A	End B
Scenario 1	5:59	6:08	8:35	8:30
Scenario 2	6:16	6:15	8:15	8:15
Scenario 3	5:58	6:09	8:42	8:35

These simulations are of relevance to subsequent research, because they show the viability of simulating algorithms for delay estimation. As shown later in this report, there are several prospective algorithms for estimation that base their predictions on prior delays. Using simulation would allow for a sufficient number of simulated tests to evaluate algorithm performance. There was not sufficient time to conduct algorithm simulation within the scope of this project.

6.3.2. Lab-Controlled Testing

The objective of this test was to perform a controlled laboratory investigation of the performance of a prototype work zone wait time estimation system designed by the WTI team.

Functionality of the System Tested

This system is designed for rural two-lane highway work zones where one lane is closed and the traffic is controlled by a pilot car. Waiting vehicles at each end are led by the pilot car through the work zone in turns (i.e. cycles). This system records time spans of each state of the pilot car in a cycle, archives the time spans of previous cycles, uses these time spans to estimate wait time for vehicles and displays the wait times and other relevant messages (e.g. pilot car approaching) in a dynamic fashion (i.e. the wait time is updated every two minutes).

Methodology

This test captured data to verify the features of the system listed in **Table 3**.

Table 3: Test Measures for Delay Algorithm Lab-Controlled Test

System Feature	Measure of Effectiveness
recording time spans	actual time spans of pilot car states time spans of pilot car states as determined by the automated detection feature of the system
archiving the time spans	manual or automated count of number of test cycles
estimation of wait times	record of estimated wait times by the system while leaving each ends of the work zone actual wait times (calculated from the actual times of changes in pilot car states)
displaying the wait time message	record of wait time message by the system while leaving each end of the work zone

Test Duration

The test was conducted in the parking lot of the WTI building for eleven continuous cycles (22 total trips between end points), with a total duration of 1.5 to 2 hours. The absence of waiting cars at each end was dealt with by randomizing the wait time of the pilot car at each end. To simulate a one-hour peak period of a typical two lane rural highway traffic, a Wednesday hourly traffic volume from the Bella Vista ATR station at 5 to 6 PM was used (219 vehicles in Lane 1, 157 vehicles in Lane 2).

Initialization

The initial number of waiting cars at ends A and B was assumed to be 15 and 20, respectively. The length of the work zone was assumed to be approximately 0.5 miles. Based on this, an approximate cycle can be assumed to be 6 minutes, which was used to define the initial cycle time. For the initial cycle, the pilot car would wait approximately 60 seconds (15 vehicles × 4 seconds per vehicle) at end B and approximately 80 seconds (20 vehicles × 4 seconds per vehicle) at end A.

Estimation

At the end of cycle 1, the actual cycle time was calculated by the system and was used to calculate the number of vehicles waiting at A and B in the following fashion (cycle times and wait times are in minutes):

$$no.\,of\ vehs.\,waiting\ at\ A = 219 \times \frac{last\ cycle\,time\ \text{-}\ last\ wait\ time\ at\ B}{60} \times random\ no.(from\ 0.5\ to\ 1.5)$$

$$no.\,of\ vehs.\,waiting\ at\ B = 158 \times \frac{last\ cycle\,time\ \text{-}\ last\ wait\ time\ at\ A}{60} \times random\ no.(from\ 0.5\ to\ 1.5)$$

6.4. Results of Laboratory-Controlled Testing

The controlled lab tests were performed, resulting in 11 complete cycles of data (22 complete trips between end points). The results of the testing indicating the cycle lengths and cars waiting at each end point for each cycle are shown in **Table A-** of Appendix A. The results are summarized in **Table 4**.

Table 4: Summary of Cycle Lengths and Number of Cars Waiting.

	End Point A		End Point B	
	Cycle Time(s)	No. of Cars Waiting	Cycle Time(s)	No. of Cars Waiting
Mean	390	17	390	13
Maximum	411	22	429	20
Minimum	355	9	362	7

The proof-of-concept system equipment and technology worked without failure as expected to facilitate the estimation algorithms, as discussed in Section 5.6. Resulting time spans were output as a comma-separated-file and analyzed to evaluate overall system effectiveness according to the measures discussed in Section 6.3.2.

Accuracy of Automated Time Interval Recording

The system measured and recorded time intervals pertaining to the length of time the system remained in all states of a given cycle as per the automated state determination mechanism. In addition, the pilot car driver indicated, via the user interface, all actual arrivals to and departures from end points. A comparison of the actual cycle times, as indicated by the pilot car driver, and measured cycle times, as measured by the system, is in **Table A-** of Appendix A and summarized in **Table 5**.

Table 5: Differences between Actual and Measured Cycle Lengths

Measure (sec.)	End Point A	End Point B
Mean	1.09	1.27
Maximum	6	6
Minimum	0	0

The results in **Table 5** show that the discrepancy between actual cycle times and those measured by the system is low. The average difference is close to one second, which is quite small considering cycle lengths averaged 6½ minutes. This indicates that the system was recording overall cycle lengths well and was consistent with reality. Since the delay estimations are based largely on the overall cycle lengths, the results show that the system is capable of providing accurate inputs to the algorithms.

Since each cycle length is comprised of the span of time spent in each of the four system states, a closer look at the component time spans is warranted. The actual time spans pertaining to all components of the cycles appear in **Table A-** of Appendix A. The results are summarized in **Table 6**.

Table 6: Summary of Time Span Results for Each Cycle Component

Measure (sec.)	State 1 At A	State 2 From A to B	State 3 At B	State 4 From B to A
Mean	67.27	121.09	79.91	122.82
Maximum	89	127	98	127
Minimum	48	118	60	120

Note that the actual time that the pilot car waits at end point B, on average, is longer than the pilot car wait time at end point A. The difference is due to the fact that the length of time that the pilot car remained at an end point is related to the number of cars behind the pilot vehicle at the time of arrival. **Table 4** shows that there were more cars, on average, waiting at A than at B. Consequently the pilot car has to wait longer at B, on average, for the cars waiting at A to clear the work zone. Also, note that the trip times from A to B are very similar to those from B to A. This is expected since the trips are mirror images of each other. Also, there was not prohibitive traffic or other obstructions during testing.

The difference between the actual values of the pilot car wait times at the end points and those measured by the system during testing are shown in detail for every cycle in **Table A-** of Appendix A. These results are summarized in **Table 7**. Note that these are not absolute values.

Table 7: Summary of Differences between Actual and Measured Pilot Car Wait Times

Measure (sec.)	Endpoint A	Endpoint B
Mean	7.82	16.82
Maximum	10	21
Minimum	6	15

The test results in **Table 7** show that at both A and B there is a difference between system measured and actual pilot car wait times. Furthermore, **Table A-** shows that, for each endpoint and in each cycle, the measured pilot car wait time span is greater than the actual pilot car wait time span. This consistent overestimation is likely due to the fact that the state determination mechanism uses a buffer zone surrounding the endpoint. Therefore, the system detects that the pilot car arrives at the point before the pilot car actually arrives. Similarly, the system detects that the pilot car departs the point after the pilot car actually departs. Measuring arrivals too early and departures too late results in a time span measured that is longer than reality, hence the test findings.

Table 7 also shows that the difference between pilot car wait times at end point B is larger than that of end point A, on average, despite the fact that both end points use the same size buffer zone. This may be due to the fact that end point B resided in close proximity to several buildings. The pilot car driver indicated that the system detected arrivals and departures at roughly the same location every cycle for each endpoint. The initialization may have used a slightly errant GPS reading to set the location for end point B. Such an errant reading is possible due to the nature of the GPS device. The chance of the errant reading is increased at end point B because of the proximity to the buildings. As stated in Section 5.5, more work is required to determine the effect of obstruction on GPS readings and subsequent state determination.

The difference between the actual values of the pilot car trip times between the end points and those measured by the system during testing are shown in detail for every cycle in **Table A-** of Appendix A. These results are summarized in **Table 8**. Note that these are not absolute values.

Table 8: Summary of Differences between Actual and Measured Trip Times

Measure (sec.)	A-to-B Trip(s)	B-to-A Trip(s)
Mean	-12.45	-13.54
Maximum	-10	-11
Minimum	-17	-19

The test results summary in **Table 8** show that there was a difference in measured versus actual trip times both from A to B and B to A. **Table A-** shows that the system consistently measured the trip times to be less than the actual trip times. Considering that the measured overall cycle lengths closely resembled the actual cycle lengths and that measured pilot car wait times were always larger than actual pilot car wait times, this is an expected result. Measured trip times are always less than actual trip times because the state determination mechanism consistently detects arrivals to end points too early and departures from end points too late.

Overall, the limited laboratory tests showed that the system's ability to record timestamps and calculate the associated time spans in response to system state changes is promising and worthy of further investigation. Measured cycle times were close to the actual cycle times. The individual components of the cycles differed from actual values in an expected manner due to the details of the state determination mechanism. GPS error due to the close proximity of one of the end points to a building may have caused an increased difference between actual and measured pilot car wait times for that end point. Differences in the state determination algorithm will likely have an effect on the accuracy of the measured cycle components. More rigorous testing of the system is needed to determine if measured values truly are accurate in all situations, as the limited nature of the tests does not provide enough evidence to support or refute the claim.

<u>Accuracy of Archiving</u>

The system was able to automatically count the number of cycles in real time and display the number to the pilot car driver via the user interface. In addition, the end point applications each kept track of the number of cycles. The values were monitored and verified throughout testing and were found to be accurate. Upon conclusion of the testing, the cycle counts in all system applications were consistent with reality. Furthermore, statistics concerning the timestamp when the cycle ended and times spans for all cycle components, both actual and measured, were archived in real time and verified after testing. The system appears to be able to successfully keep track of cycles and archive statistics for each cycle.

Accuracy of Estimated Wait Times

Throughout the controlled laboratory tests, the system estimated wait times for each cycle based on previous cycles alone. Four estimation methods, discussed in 6.2.2, were calculated and recorded simultaneously. As discussed in Chapter 6, the actual wait time for a given cycle consists of the cycle time minus the time span between when the pilot car leaves an end point and when the flagger closes the end point. This is the time during a cycle when cars cannot move through the work zone and must wait. The time span between pilot car departure and the flagger closing the end point is not known and, therefore, is estimated to be equal to the time that the pilot car waited at the other end point in the last cycle (which is related to the number of cars waiting during the previous cycle). **Table A-** of Appendix A shows the actual, measured and estimated wait times using the four estimation algorithms for all test cycles at end point A while **Table A-** of Appendix A shows the results for end point B.

Table 9 shows a summary of the difference between the estimated wait times, derived from the four estimation algorithms, and the actual wait times at end point A, while **Table 10** shows the same set of results at end point B. Note that these results are not absolute differences.

Table 9: Summary of the Differences between Delay Estimation Algorithms, End Point A

Measure (sec.)	Last Cycle	Simple Average	Exponential Decay	Linear Decay
Mean	-12.5	-25.3	-17.6	-18.03
Maximum	76	53	57	56
Minimum	-83	-83	-71	-72

Table 10: Summary of the Differences between Delay Estimation Algorithms, End Point B

Measure (sec.)	Last Cycle	Simple Average	Exponential Decay	Linear Decay
Mean	-11.6	-21.1	-15.4	-16.0
Maximum	63	38	56	55
Minimum	-105	-105	-105	-105

The results in **Table 9** and **Table 10** show that wait time estimations performed similarly at both end points. The simple averaging of the last five cycles performed worst and deriving the wait time directly from the last cycle's wait time performed best. Exponential and linear decay both offered improvements over the simple average algorithm but did not perform as well as the last cycle wait time algorithm.

The results show that these algorithms were promising in that they provided relatively small average discrepancies between estimated and actual wait times. However, further investigation is necessary to determine the effectiveness of each algorithm in wait time estimation. While the average discrepancies appear promising, there is a substantial degree of variability among them. For instance, estimates at end point A were as far off as 83 seconds and estimates at end point B were as far off as 105 seconds. A more comprehensive set of test data is required to analyze the algorithms.

Accuracy of Display Messages

The message displayed on the sign was informally checked several times during the testing. Observations confirmed that the sign displayed the expected message. A more rigorous test of the display message is necessary to evaluate the accuracy of the display messages. Such a test would involve recording all sign messages and associated times during a laboratory test. Initial tests of the computer/sign interaction, however, seem to show that the sign appears to function as expected in all cases.

Summary

The controlled lab testing produced several promising results. The proof-of-concept system appears to be able to support estimation algorithms. Further refinement and research based on the findings in this test will likely result in a more robust, deployable system in the future. Similarly, results show that the use of these estimation algorithms to predict work zone wait times dynamically is reasonable. Further refinement and fine-tuning of these and other algorithms will likely result in a more accurate estimation system.

6.5. Findings and Recommendations

The results of this brief research into the delay estimation algorithms for a two-lane rural highway work zone with a lane closure are encouraging. Several methods to estimate the work zone delay were identified. The moving average algorithms were implemented and integrated into the proof-of-concept system. The algorithms were tested in a controlled laboratory test and with modeling software. The results of each of these testing methods were promising.

The controlled laboratory tests evaluated the performance of the algorithms in the context of the proof-of-context system. The results showed that the system was able to support the algorithms by providing the proper inputs by accurately recording cycle times and the number of cycles. The system was able to properly manage the algorithm outputs by accurately displaying messages on the sign. Furthermore, given the proper inputs, the algorithms produced the expected delay time estimates. However, further investigation is necessary to determine the effects of inaccuracies of cycle components to the moving average and other estimation algorithms.

Although implementation of the algorithms in the system is feasible, more work must be done to determine the effectiveness of the algorithms' ability to estimate delay information. Further development on delay estimation using the other methods (Time Series, Markov Chain, and Fourier Series) is recommended. Development should include identifying traffic volume trends and their correspondence to times of the day or days of the week. Further investigation into the use of particular algorithms based on these factors is also recommended. Real data, or more rigorous field testing where possible, should be used to properly test the algorithms. It may not be possible for the delay estimation algorithms to be field-tested to the degree necessary to guarantee their performance in all circumstances. Therefore, it is recommended that the different algorithms be tested using extensive simulation. Even though off-the-shelf traffic simulation software cannot simulate the pilot car operations in a two-lane rural highway work zone without extensive customization, the simple simulation model developed here shows that the pilot car operations can be simulated accurately using SimProcess™.

7. COMMUNICATION TECHNOLOGIES

7.1. Communication Technology Background

There are a number of communication configurations that could be considered for this system. With each configuration, there are a number of technology alternatives. One configuration and technology (Wi-Fi in the pilot car and at the end points) was chosen for lab implementation and testing. This choice was made for practical reasons – there was a high chance of successful implementation using this configuration for lab testing within the limited timeframe of the project. However, other configurations should be considered for further testing and eventual production use, and analysis was conducted using several alternative technologies. Further testing and analysis would be necessary to implement these technologies, but sufficient information was gathered in this study to provide a general indication of what configurations and technologies may or may not be feasible.

The general communication configurations that were considered include:

- At End Points Only. The pilot car can communicate with the end points when in proximity.
- At End Points and from End Point to End Point. The pilot car can communicate with the end points when in proximity and the end points can communicate with each other.
- Complete. The pilot car can communicate with the end points from anywhere within the work zone and the end points can communicate with each other.

These configurations are listed in order of increasing capability. Communication could be bi-directional or unidirectional.

7.2. Communication Technology Challenges

The greatest challenges in terms of communication in this project stem from the System Communication Requirements and the System “Ease of Use” Requirements, as stated previously in this document. In general, the system must be operable in rugged terrain and rural areas, it shall require minimal setup, and it shall not depend on commercial communications services that have recurring service charges. Rugged terrain implies that line-of-sight or near-line-of-sight wireless technology will be of limited use. Rural use implies that existing communication infrastructure (public or private) will be limited and can not be assumed. The requirement of minimal setup further limits options, because certain technologies require careful positioning and configuration of equipment. Constraints are also imposed by power, because it can not be assumed that power is readily available. Finally, the requirement that the system not depend on commercial services eliminates options such as satellite, which would likely come closest to providing full coverage of rural areas.

7.3. Summary of Applicable Communication Technology

Applicable technologies are broken into “wired” versus “wireless.” Wireless is further divided into licensed and unlicensed, and can also be categorized by network topologies.

7.3.1. Wired

Wired technology, i.e. running cable, was considered, but was determined infeasible for this project due to required setup time and potential problems in securing paths to run the cable. There may be applicability of wired communication for short runs between components, but wireless alternatives should be considered for all but the shortest runs. Wireless alternatives will provide the greatest flexibility and likely the easiest setup. It should also be noted that if the pilot car is to receive or transmit information, it could only do so using wireless technology.

7.3.2. Wireless

Technologies using licensed and unlicensed frequencies were considered in this project and further investigation of the alternatives would be necessary prior to production deployment.

Licensed frequencies provide the greatest protection against interference. Frequencies in the licensed VHF and UHF bands are more conducive to non-line-of-sight propagation than frequencies in the unlicensed 900 MHz, 2.4 GHz and 5.8 GHz bands. However, licensed frequencies may not be available for this application. The availability of licensed frequencies will depend on location and availability within the Department. RF data modems were examined within the scope of this project using licensed frequencies in the 150 MHz range.

The use of unlicensed frequencies is appealing because of the availability of numerous commercial off-the-shelf alternatives for components and technologies, and because it is not necessary to obtain a license for their use. Alternatives such as Wi-Fi and Zigbee were considered within this project and should be investigated further in subsequent phases to this project. The use of unlicensed frequencies must be carefully weighed against the potential for interference, and security must also be accounted for. Further investigation is necessary in this area.

A number of wireless network topologies were considered within this project including: point-to-point, multi-hop, point-to-multipoint and mesh, as well as fixed versus mobile transmission and reception. The System Communication Requirements and the System “Ease of Use” Requirements impose constraints that make many of the topology options challenging if not impossible to implement. For instance, point-to-point communication is severely impacted by terrain. Multi-hop, which uses a sequence of point-to-point nodes as repeaters, is challenging because of the number of nodes that would be required in rugged terrain and the challenge of determining placement for those nodes. Point-to-multipoint is appealing because of its simplicity and lower relative cost, but it is highly unlikely that such a configuration can be set up quickly and easily to work in a work zone in rugged terrain. Mesh suffers from the same challenges as multi-hop and the associated technology is relatively immature when compared to other technologies.

The technology and configuration used for the implementation within this project, Wi-Fi at the end points only, does appear to show promise. There are still a number of issues in regard to communication that deserve further investigation, including the suitability of using Wi-Fi. But, its use in lab testing is promising enough to say that at least one combination of technology and configuration can be made to work to achieve the goals of this project.

7.4. Testing of Communication Technology

Several tests of communication technologies were conducted in parallel within this project. Propagation studies were conducted to determine the propagation characteristics of various frequencies in rugged terrain. A literature review and vendor contacts were conducted to evaluate several technologies that are currently on the market. Lab and field testing were conducted with a commercial radio system that was optimized for use in rugged terrain. Lab/demonstration unit testing was conducted in the context of the lab/demonstration system. The approach to investigating communication technology lays the groundwork for subsequent study and development.

7.4.1. Propagation Studies

Four initial hypothetical work zone locations were identified for propagation analysis. These hypothetical work zone locations ranged from relatively flat, in which line-of-sight would likely be available throughout, to very rugged, in which line-of-sight throughout the entire work zone would be impossible and line-of-sight along the work zone would be significantly limited. Detailed analysis of a particular rugged area on State Route 70 between Oroville and Quincy at the Butte-Plumas county border (Figure 7-1) was conducted as a worst case or near worst case scenario.

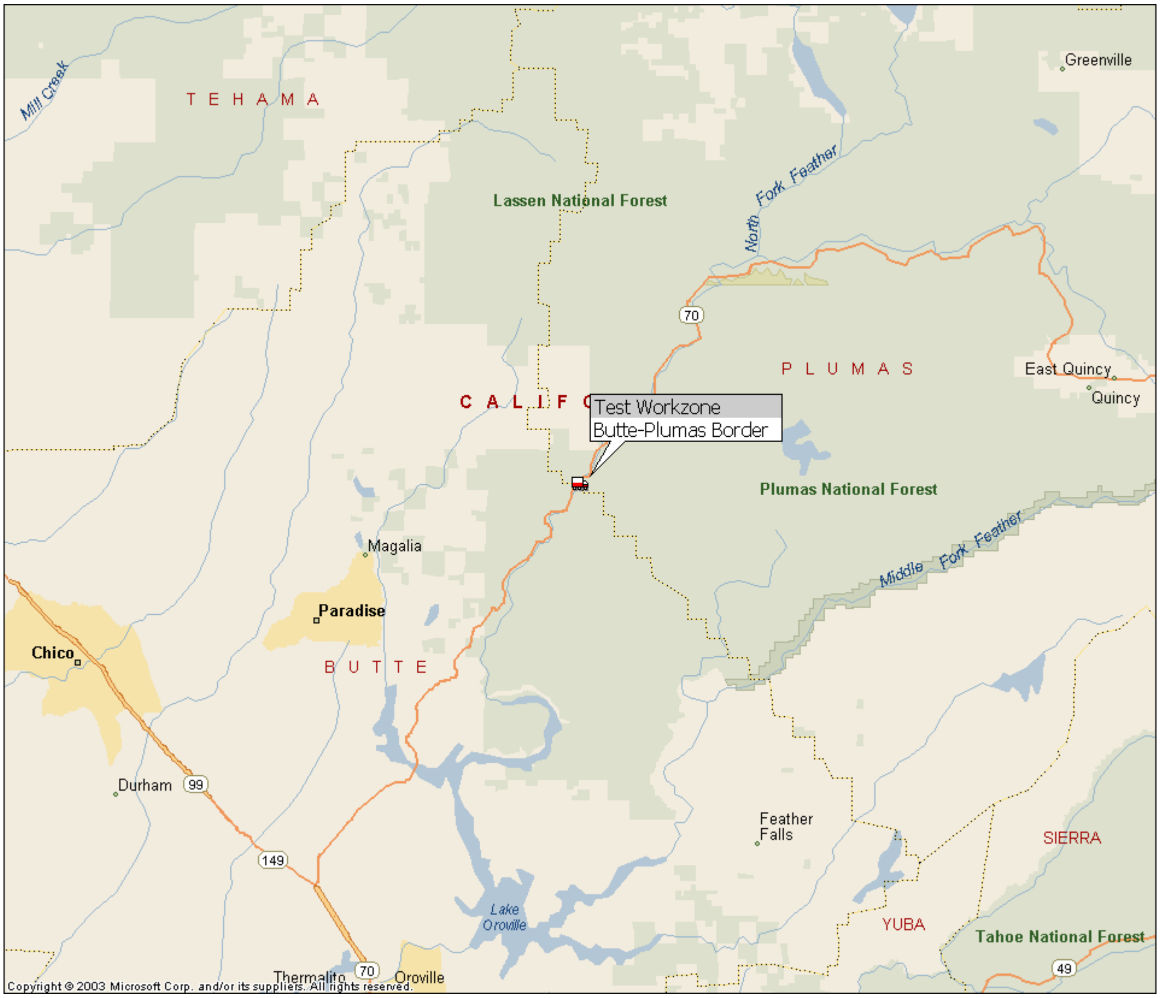


Figure 7-1: Hypothetical Rugged Terrain Work Zone Location for Propagation Analysis

Figure 7-2 shows a 3D aerial view of this hypothetical work zone. Note that terrain causes obstructions throughout the work zone, particularly near the end points at the southwest and to the northeast. In addition to the end points, four intermediate points have been identified for analysis of coverage. The length of the test work zone is approximately 5 miles, and the test points are approximately one mile apart.

Figure 7-2: 3D View of Hypothetical Work Zone

From the southwest end point, labeled Case 1-1 West in Figure 7-2, line-of-sight is very limited, and none of the identified intermediate locations are visible, nor is the other end point, labeled Case 1-6 East in Figure 7-2. The predominant obstruction is the mountain to the northeast of point 1-1. The intermediate portion of the work zone containing points 1-3 and 1-4 has the greatest line-of-sight path, measuring approximately 1.5 miles.

Figure 7-3 shows propagation of a 900 MHz signal originating at point 1-1. Note that this signal may reach point 1-2, but will not reach subsequent locations including the far end point 1-6. 900 MHz is considered near line-of-sight (NLOS), so this result is not surprising.

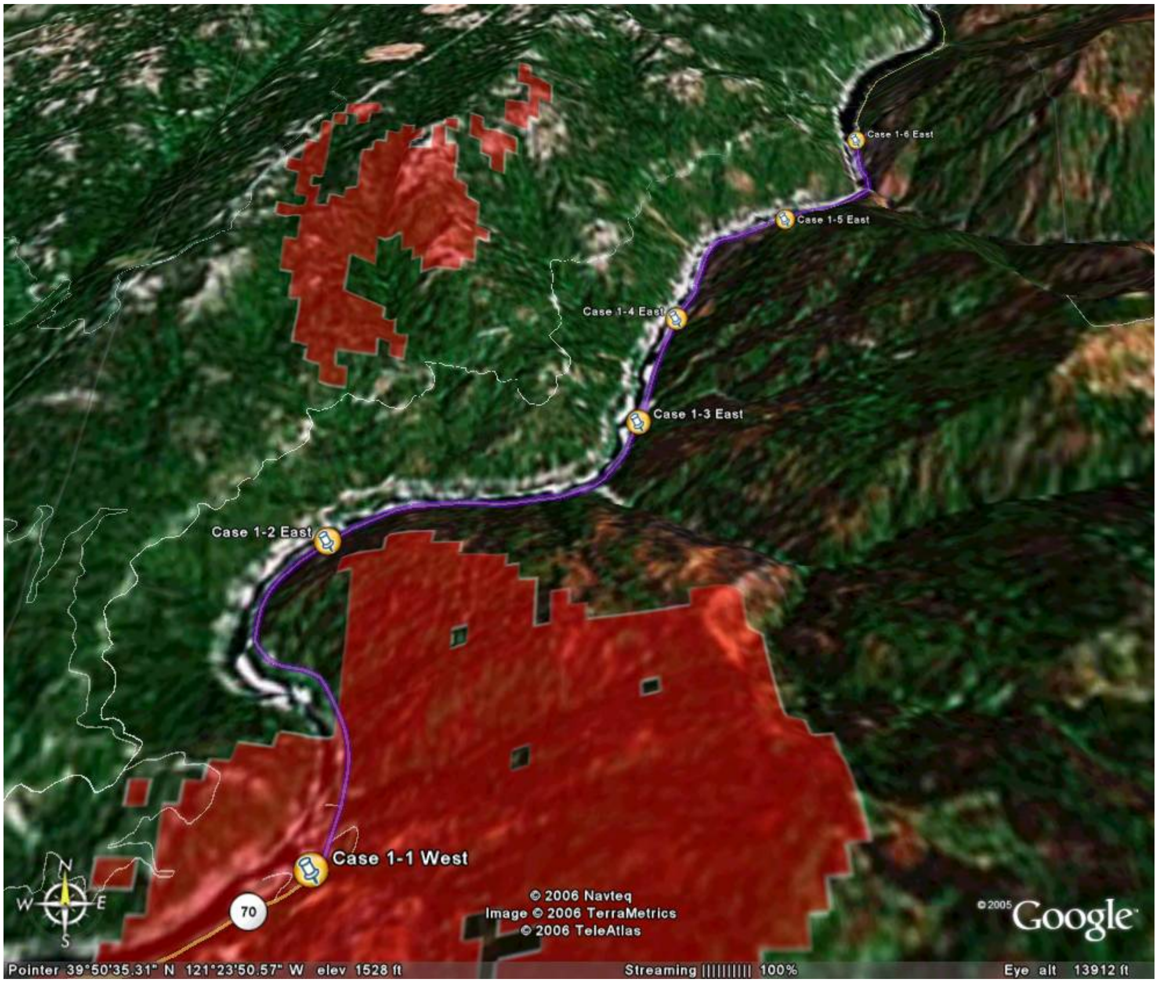


Figure 7-3: 900 MHz Coverage from Point 1-1 – Start of Workzone

Figure 7-4 shows propagation of a 450 MHz UHF signal originating at point 1-1. Note that the UHF signal covers a greater area and the likelihood of coverage at Point 1-2 is increased, but the remaining test points and the majority of the work zone remain uncovered. The 450 MHz signal propagates better than the 900 MHz system and provides better non line-of-sight coverage, but is still not sufficient for extensive coverage of the work zone.

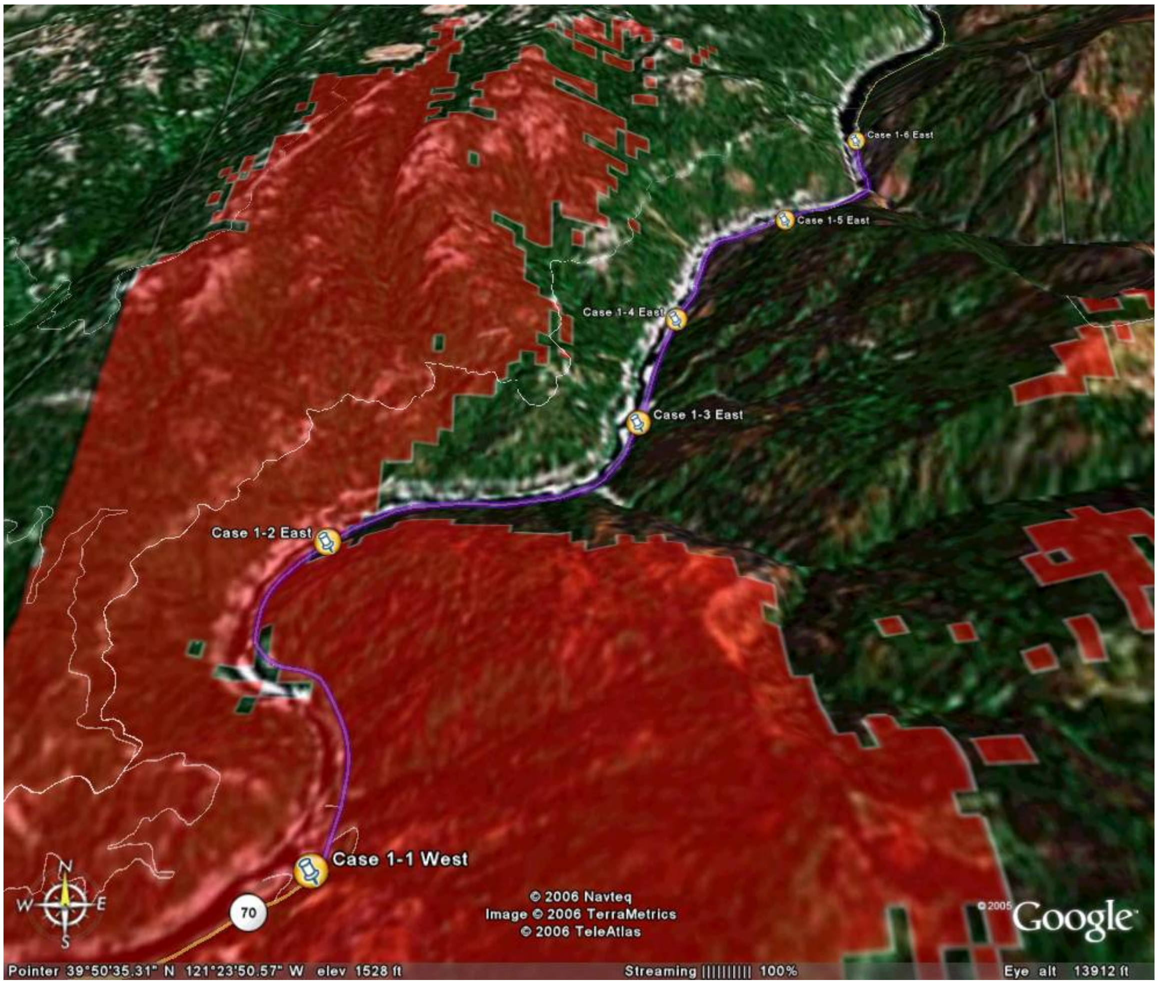


Figure 7-4: 450 MHz UHF Coverage from Point 1-1 – Start of Work Zone

Figure 7-5 shows propagation of a 150 MHz VHF signal originating at point 1-1. Note the dramatic improvement in coverage over the 450 MHz and 900 MHz systems. However, this system does not appear to provide reliable coverage of the entire valley floor where the road, the work zone and the test points are located. Despite the dramatic improvement in coverage, the system appears to guarantee coverage only at point 1-2. Limited coverage may be available at the other test points, but it certainly can not be guaranteed.

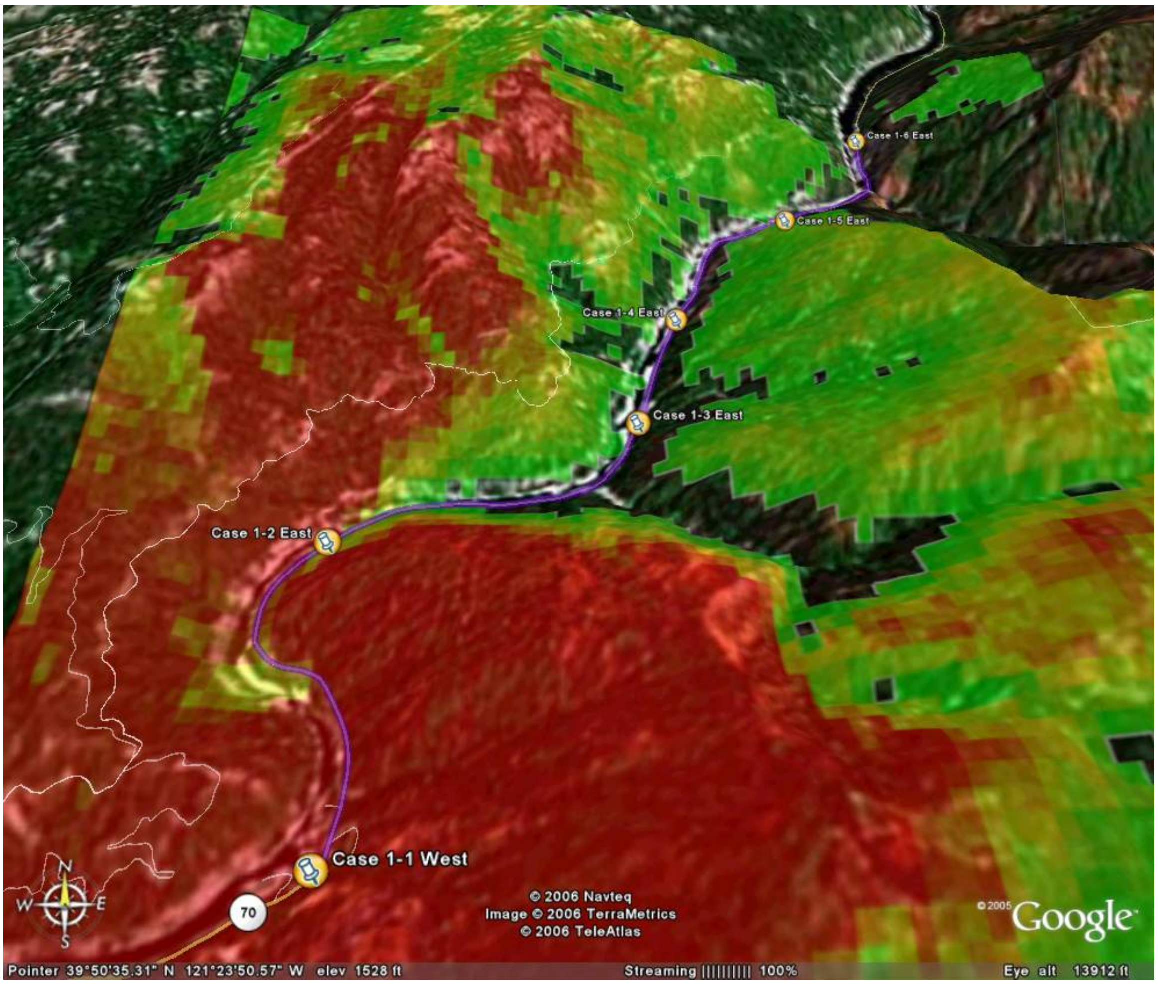


Figure 7-5: 150 MHz VHF Coverage from Point 1-1

Figure 7-6 shows propagation of a 150 MHz VHF signal originating at Point 1-6. This signal covers much of the work zone, but falls short of covering the end of the work zone near Point 1-1. Note that a greater portion of the work zone is covered from this point.

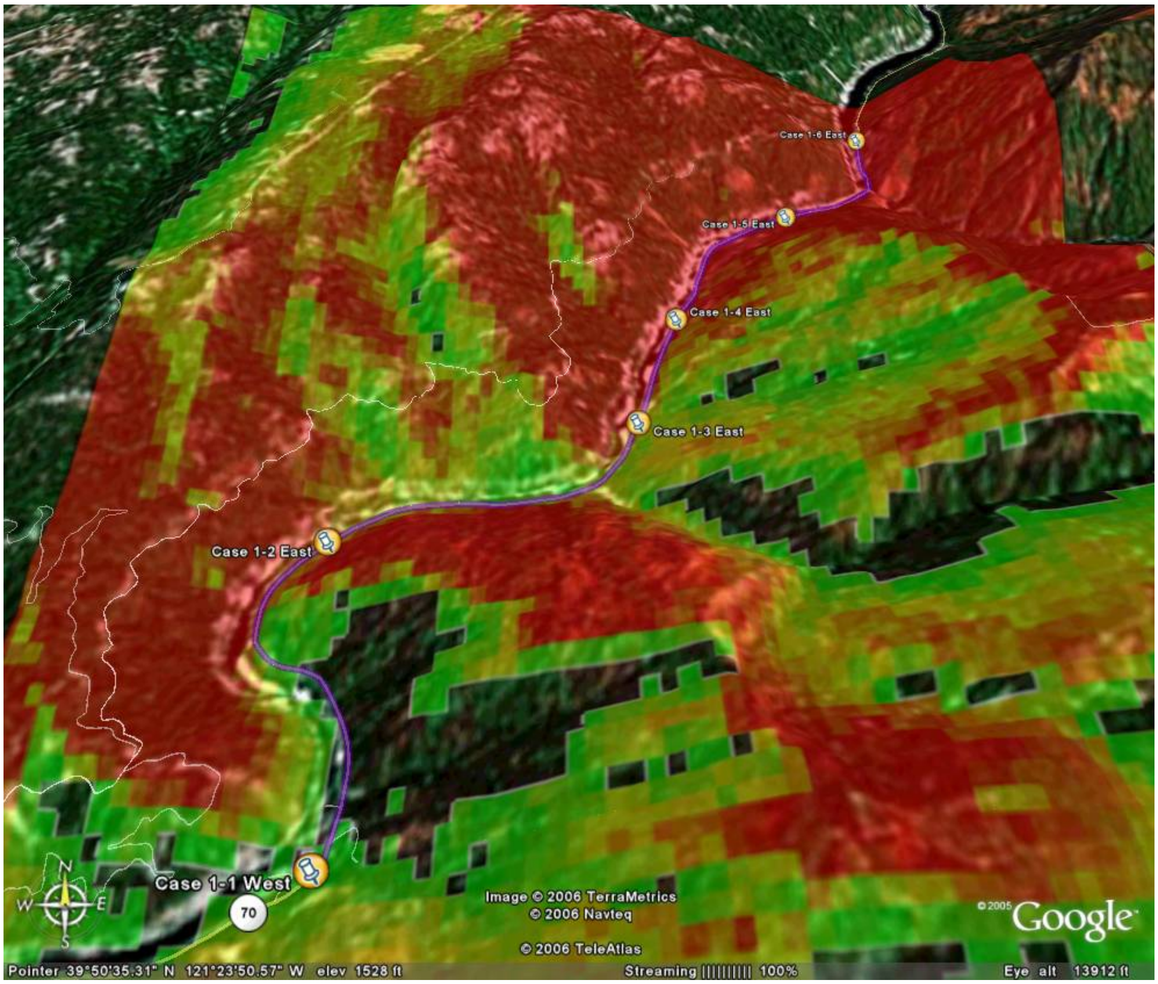


Figure 7-6: 150 MHz VHF Coverage from Point 1-6

Figure 7-7 shows propagation of a 150 MHz VHF signal originating in the middle of the work zone, at point 1-3. Coverage does not reach the ends of work zone near point 1-1 and point 1-6. Thus, it does not appear that a point-to-multipoint system could be implemented at a single point along the work zone to provide coverage of the entire work zone.

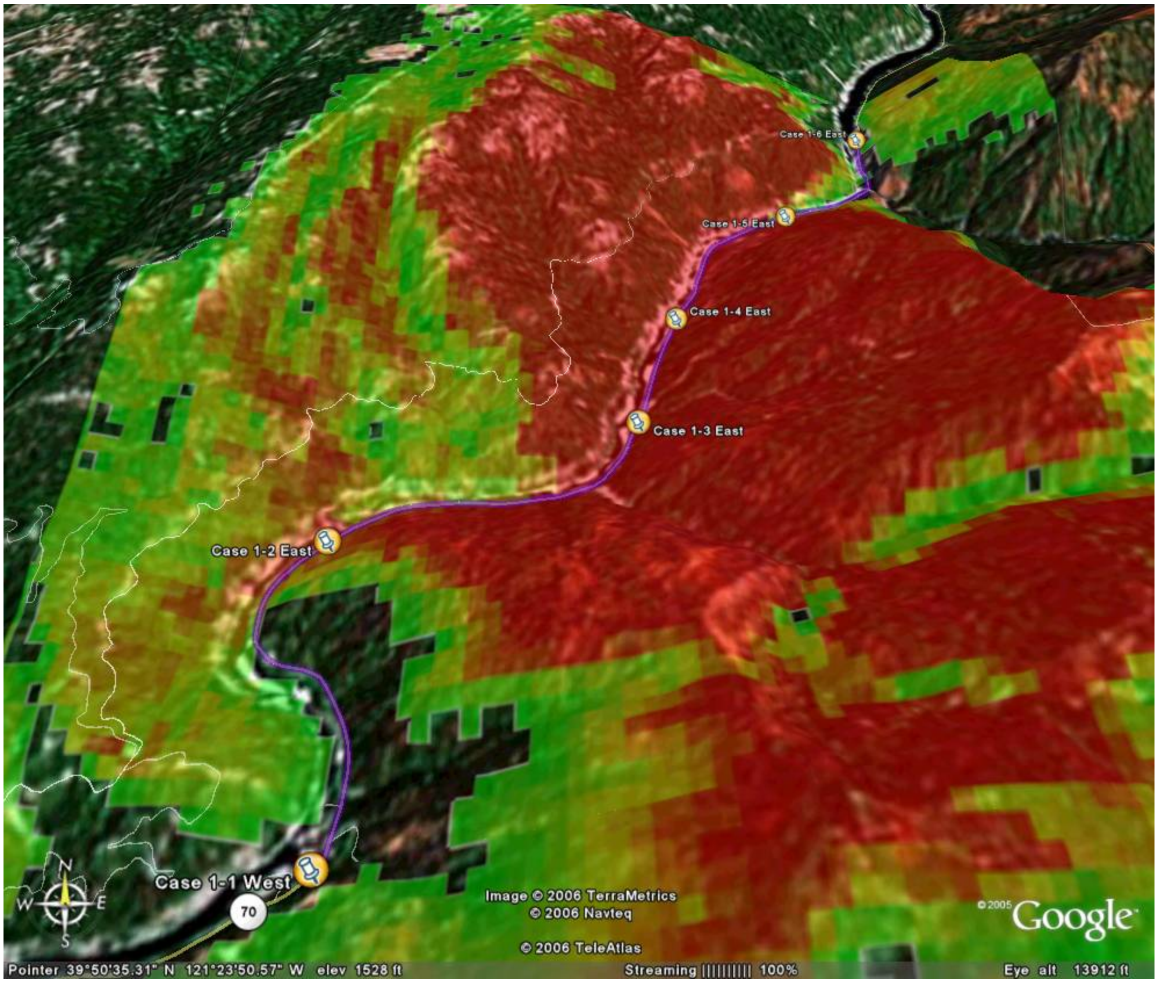


Figure 7-7: 150 MHz VHF Coverage from Point 1-3

Further investigation of technologies and scenarios should be conducted, but the propagation analyses reveal that it is highly unlikely that any system satisfying project requirements will be able to provide complete coverage of this work zone. End point-to-end point coverage under all circumstances, particularly within work zones in rugged terrain such as this, is highly unlikely. However, the scenario of communication between the pilot car and the end points when in proximity is not only achievable, but the project team was able to show reasonable success under this scenario in lab testing. This may be the only case under which we can demonstrate reasonable confidence in operation given the requirements associated with this project.

7.4.2. Literature Review and Vendor Contact

Several prospective systems were reviewed in literature and through communication with vendors. These include:

- Multi-hop using a system such as MeshDynamics multi-hop system,
- Multi-hop using ZigBee (802.15.4); and
- Point-to-multipoint using 900 MHz systems such as Trango Broadband or Motorola Canopy systems.

It was determined that the multi-hop systems would be cost-prohibitive and would require too much set up time to make them feasible for use in a work zone. In rugged terrain, these systems would require an excessive number of repeaters to cover a work zone such as the hypothetical State Route 70 work zone. Generally, these systems operate on frequencies requiring line-of-sight. Note however that such systems might be viable for the deployment of permanent communication infrastructure in such areas. In fact, they may be the only viable alternative in certain circumstances. Systems such as MeshDynamics could be used for this purpose.

A novel multi-hop configuration was considered using a relatively new technology, ZigBee, which operates on top of the 802.15.4 standard. ZigBee is promoted as offering mesh capability and requiring minimal power in low-cost, compact devices. While ZigBee technology is just reaching the market and would require significant investigation for application to this project, one can envision a self-forming ZigBee network made up of ZigBee transceivers deployed throughout a work zone, perhaps in conjunction with traffic cones. Power could potentially be supplied by small solar panels, and the resulting network could provide coverage over the area in which cones are deployed. It should be noted that cones are not typically deployed to cover an entire work zone in which a pilot car is used. Thus, this system would not be feasible to provide complete communication coverage for a work zone.

Point-to-multipoint technologies such as Trangobroadband and Motorola Canopy were also considered. These systems are appealing because their overall cost would be less than that of a multi-hop system. However, it is highly unlikely that a single point along a work zone could be selected for deployment of the central antenna array for such a system in rugged terrain. For the deployment of permanent communication infrastructure in such areas, these systems might prove viable, particularly if equipment could be deployed at high points above the road way. Other issues with these systems include questions as to whether or not they could be used for mobile communication.

7.4.3. Lab and Field Testing

A pair of Microwave Data Systems MDS 1710 transceivers (Figure 7-8) were field tested in the Gallatin Canyon along US Route 191 south of Bozeman, Montana. This area is characterized as rugged terrain, and is similar to many areas in northern California, particularly the State Route 70 hypothetical work zone. The objective was to field test the performance of a VHF system in rugged terrain. The transceivers were configured to operate in the 150 MHz range using asynchronous simplex mode. One transceiver was configured to transmit and the other was configured to receive. Two-way half-duplex communication is possible with these units, but was not used during this test.

Figure 7-8: MDS 1710 Transceivers

Each transceiver was configured in separate vehicles. The transmitter vehicle was parked in a pullout along US Route 191 and the receiver vehicle was driven nearly 10 miles to the south through the canyon. Note that real use would either involve transmission from the moving vehicle or two-way communication. However, it was easier to log signal strength and monitor reception with the given configuration, and it is reasonable to assume that signal strength would be similar to that of normal use.

Notebook computers were used to automate transmission and reception of data. The receiving vehicle computer was configured to read and record signal strength (RSSI) directly from the transceiver. These readings were recorded with latitude and longitude as automatically read from a GPS within the vehicle.

This system was chosen as representative of a best case for a mobile system requiring minimal setup. Setup, aside from prior configuration of modems for frequency, power and transmission mode, involved connecting the modems to power, external magnetic mount antennas, and the computers. See Figure 7-9, Figure 7-10, Figure 7-11 and Figure 7-12 for pictures from the field test.

Figure 7-9: Stationary Transmitter Vehicle at US 191 Pullout

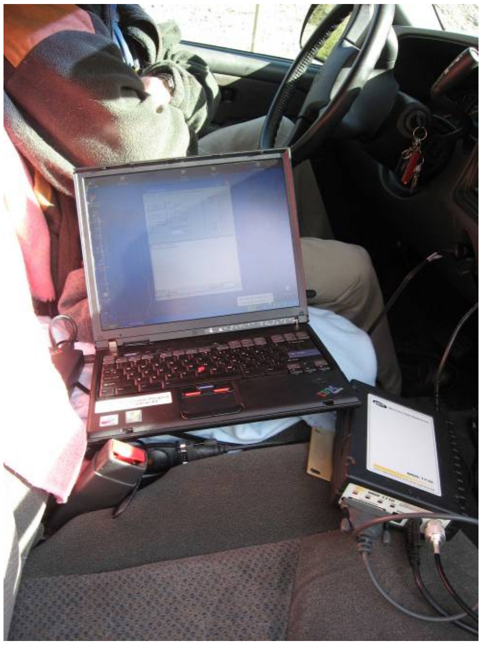


Figure 7-10: Transmitter and Computer

Figure 7-11: Receiver Vehicle and Southbound US 191

Figure 7-12: Receiver and Computer

Propagation characteristics for the 150MHz data modems were anticipated to be good, but still limited by terrain. Figure 7-13 shows a propagation map for the Gallatin Canyon test area, with transmission from the pullout.

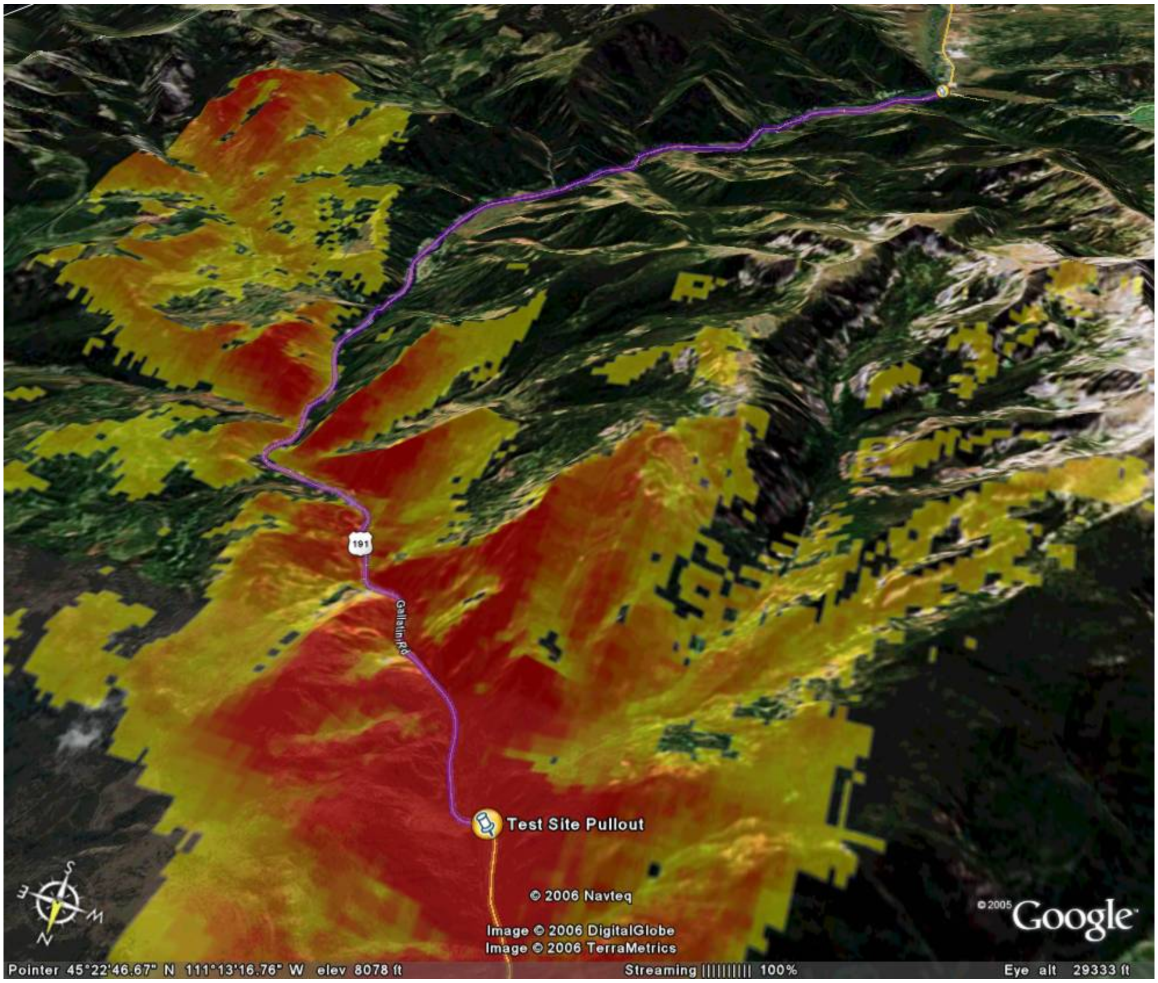


Figure 7-13: Propagation Map for 150 MHz VHF South of Transmitter

Legend:
Red = excellent (20 dBu and above)
Yellow = good (10 dBu and above)
Green = acceptable (0 dBu and above)

The test route, shown in purple, is approximately 13 miles in length. Note that coverage is predicted approximately 3 miles along US 191 from the pullout.

A drive test was conducted along approximately 11 miles of the route, as shown in Figure 7-14. The end of this drive test was approximately eight miles direct distance from the transmission point. Received Signal Strength Indication (RSSI) was recorded from the receiving vehicle while moving continuously along this route. RSSI is indicated by color-coded points in Figure 7-14.

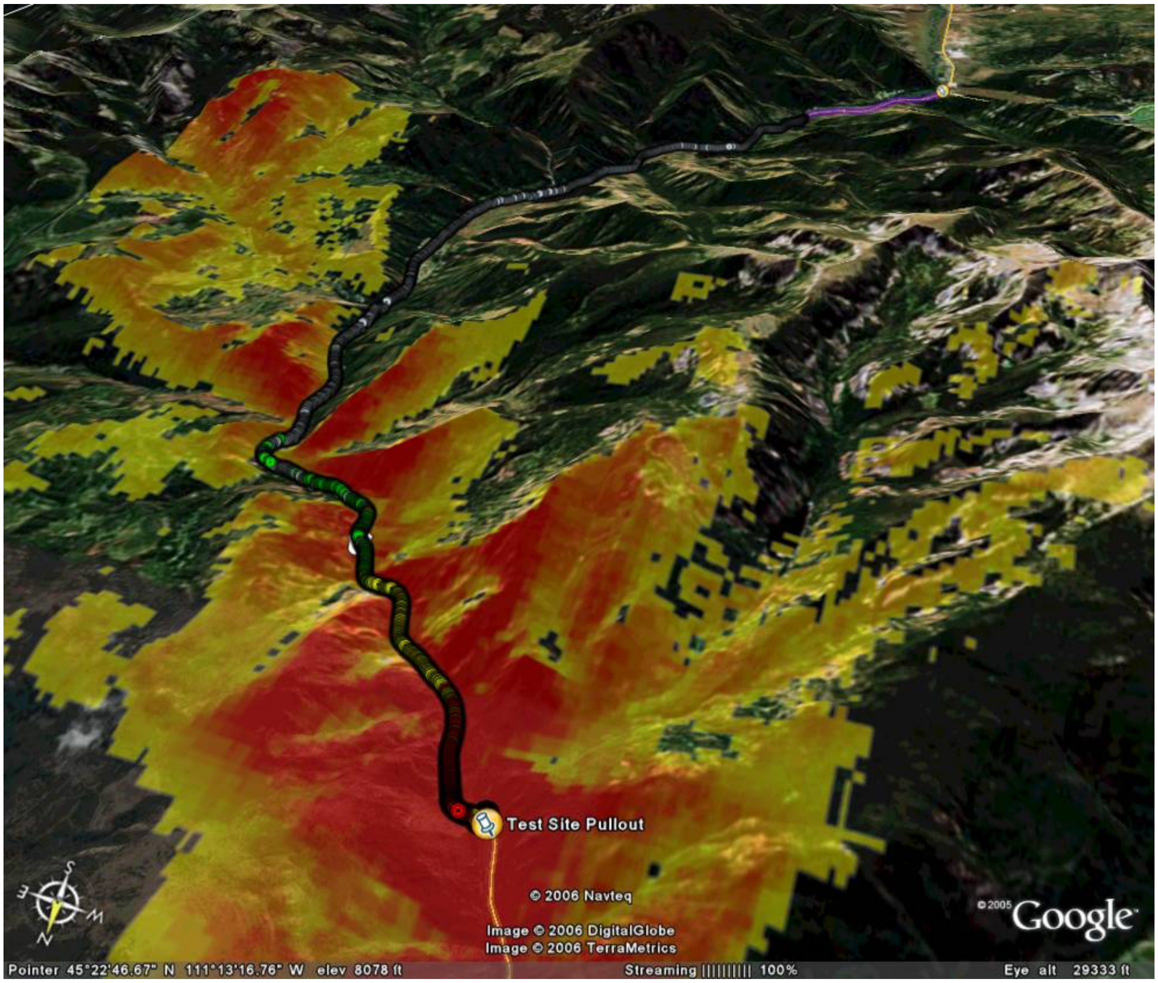


Figure 7-14: Observed RSSI Alongalong US 191 South of Transmitter

Legend:
Red = excellent (0 dBu and above)
Yellow = good (-20 dBu and above)
Green = acceptable (-30 dBu and above)

Note that the points were color-coded using a scale modified from that of the original propagation analysis. Data transmission was manually observed, and the modified scale was derived to correspond to observations of data reception quality.

Data communication was good along the first three miles of the route and dropped off significantly thereafter. Figure 7-15 shows a three-mile radius around the test transmission point.

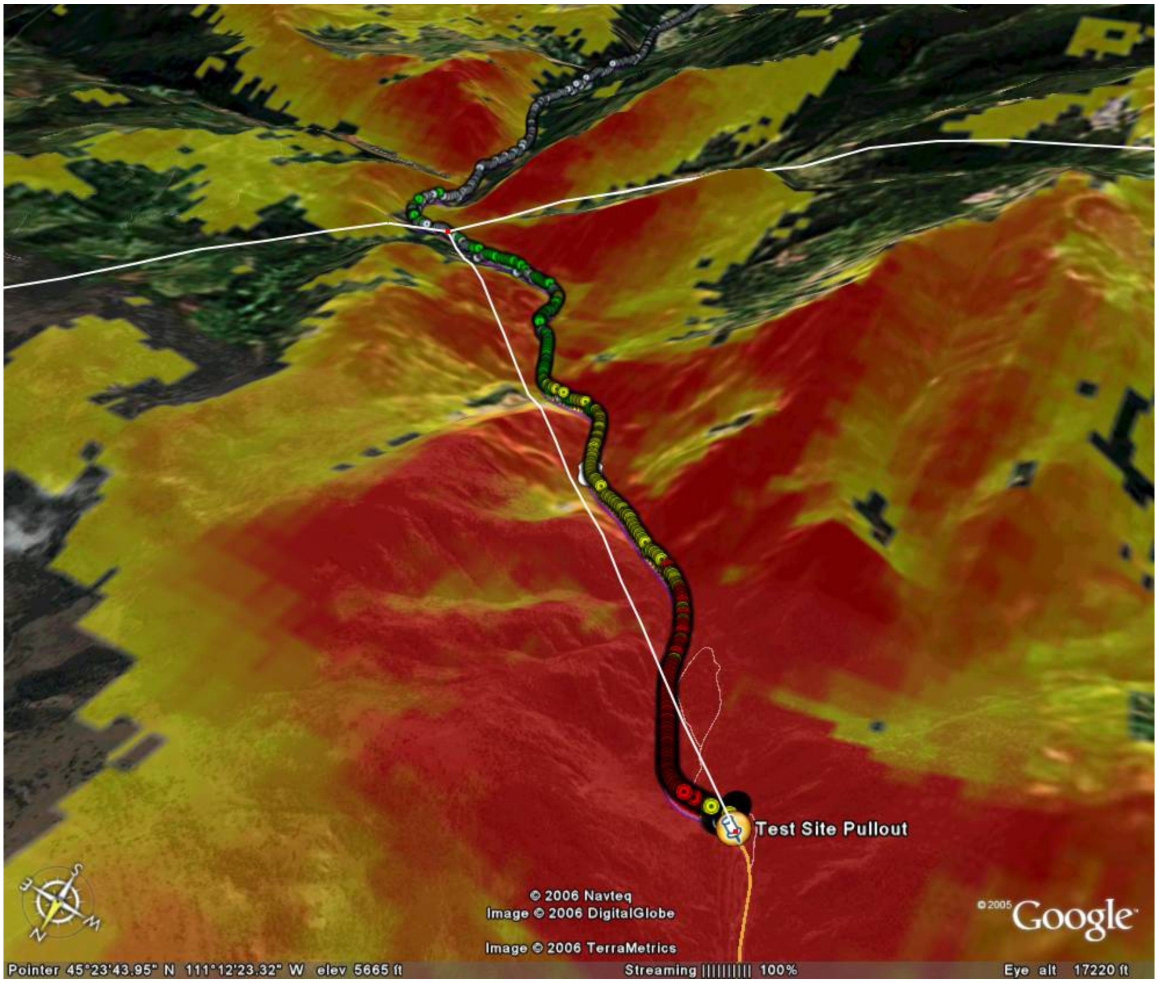


Figure 7-15: Three -Mile Radius from Transmitter

Figure 7-16 shows the degradation of service at three miles from the transmitter. Note that service was observed beyond this point, but not at a reliable level. In fact, data was received at a point beyond five miles from the transmitter, but reception was not reliable.

Figure 7-16: Degradation of Signal at 3 Miles

Figure 7-17 shows the same area three miles from the transmitter from a different view point. Note how the propagation map predicts the impact of terrain on this location. The two mountain ridges shadow the area beyond the three mile point, causing signal strength to reduce dramatically.

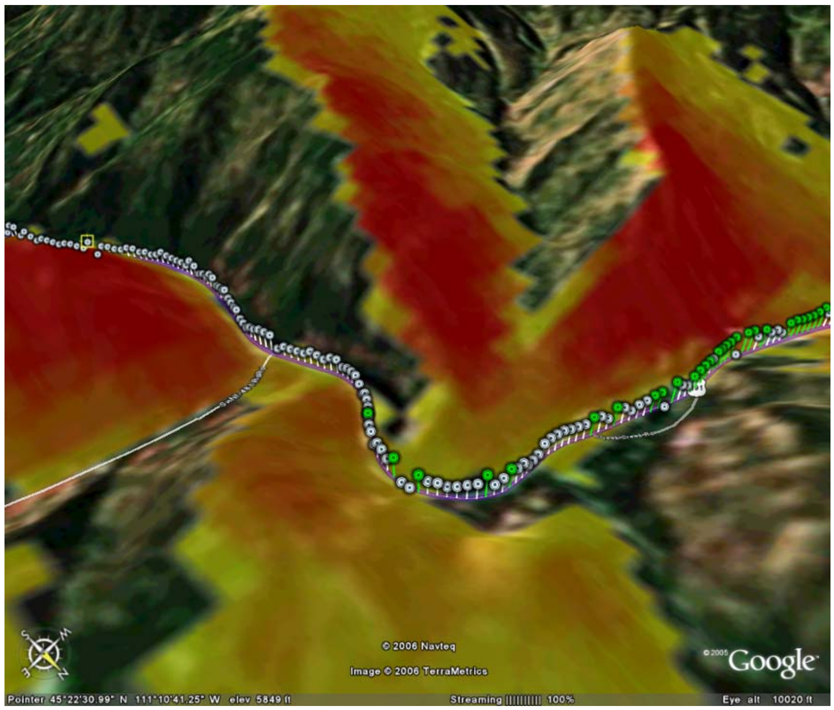


Figure 7-17: Obstruction of Signal Due to Terrain at 3 Miles

7.4.4. Lab/Demonstration Unit Testing

Communication equipment was tested in the lab and in the demonstration system. This equipment is discussed in further detail earlier in this report. The configuration used for lab testing is shown in Figure 7-18. In this configuration, communication is only available at the end points and is provided using Wi-Fi / 802.11. Under this scenario, communication is established in proximity of 802.11 routers at the work zone end points. (The radius in which communication can occur may vary dependent on terrain and equipment power, but should be of sufficient magnitude for this application regardless.)

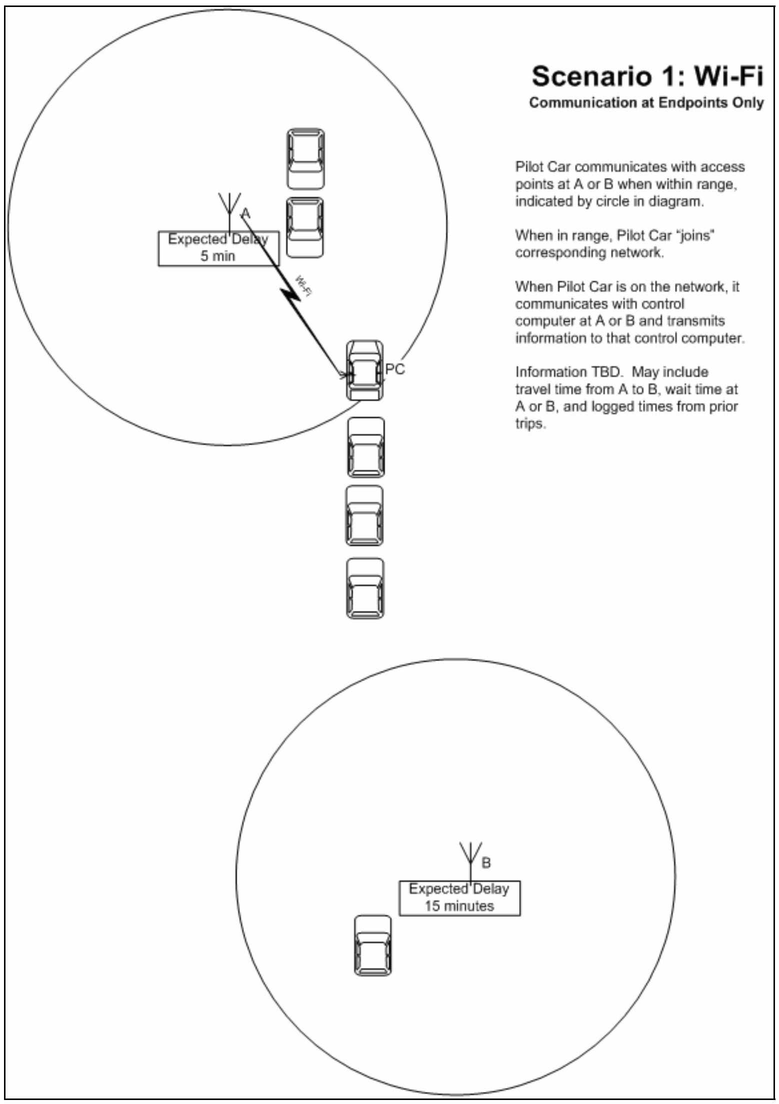


Figure 7-18: Lab Communication Scenario

A D-Link DI 634 108G MIMO Router (Figure 7-19) was used at the end point. Integrated 802.11 capability within the notebook computer was used for transmission and reception within the pilot car. Excellent performance was observed. It must be noted that this configuration was chosen for lab testing only, and that environmental considerations must be taken into account for production use. Rugged equipment would be necessary for field deployment.

Figure 7-19: D-Link DI 634 108G MIMO Router

Several additional components were used for lab testing. A MaxStream XBee-PRO ZigBee 802.15.4 RS-232 RF Modem (Figure 7-20) was used to transmit RS-232 communication via wireless from a control computer to one of the signs. This device proved to be very effective for this purpose. Informal observations indicated that the device was capable of covering a greater distance than the wireless router. Such a device might be used for transmission between a controlling computer and a sign if they can not be collocated. It could also be considered as a possible replacement for the wireless router, although communication capability and bandwidth would be limited greatly when using RS-232.

Figure 7-20: MaxStream XBee-PRO ZigBee 802.15.4 RS-232 RF Modem

A Digi PortServer TS-4 (Figure 7-21) was used to provide serial over Ethernet capability, linking the sign to the wireless router. This device worked well for this purpose.

Figure 7-21: Digi PortServer TS-4

Further investigation of these components and other alternatives would be necessary to determine the best technologies for a production implementation and field deployment.

7.5. Findings and Recommendations

Our propagation studies and corresponding field tests indicate that it would be difficult if not impossible to implement a system that satisfies project requirements for minimal setup and provides continuous communication from end point to end point in rugged terrain. It is also unlikely for the same reasons that such a system could provide communication from end point to end point.

Success was achieved in implementing a system in which communication between the pilot cars and signs occurs in proximity to the signs. Results shown in prior sections indicate that this approach may truly be viable for a production system.

Further investigation into communication alternatives is recommended as a follow up to this project. There are a number of reasonable alternatives, each with positive and negative aspects. The low cost and availability of Wi-Fi equipment makes its use appealing. However, its use of unlicensed spectrum raises concerns about security and the potential for interference. These issues can be addressed by using licensed frequencies, but corresponding equipment is more expensive and it may be difficult to obtain license and permission to use these frequencies. VHF and UHF frequencies have better propagation characteristics in rugged terrain, and could potentially improve accuracy of the system. However, these frequencies are licensed as well.

In addition, significant further investigation is necessary to make such a system field-ready. Hardened components capable of operation in extreme temperature would be necessary. Integration of communication components with other components would have to be considered, as would provisions for power.

8. SUMMARY AND RECOMMENDATIONS

8.1. Proof-of-Concept System Results

A proof-of-concept system was developed that demonstrates the viability of a work zone delay estimation and display system. The system uses communications and computing hardware and separate software applications in the pilot car and at the signs. In controlled lab testing, all components of the system performed properly.

Equipment and technology was evaluated and integrated to create the proof-of-concept system. This equipment proved successful in lab testing. Further research and development will be necessary in order to prepare equipment for field testing and ultimately for production use.

Multiple delay estimation algorithms were identified, researched and tested for prospective use within the system. These delay estimation algorithms were implemented in the proof-of-concept system, proving that the system can support these and other similar algorithms. Further research and development is necessary in order to determine the best algorithm(s) for field testing and production use.

Communication alternatives were identified and tested for use in rugged terrain. While a number of alternatives, including the Wi-Fi configuration used in the proof-of-concept showed promise for use in the system, it was determined that it is highly unlikely that any communication technology would be able to provide complete communication coverage throughout every work zone. Further investigation into communication technologies and configurations is necessary in order to determine the most viable alternatives for field testing and production use.

8.2. Necessary Subsequent Research

8.2.1. Equipment and Technology Research Needs

Further research should be conducted to explore other possible hardware and software configurations – other than notebook computers. Notebook computers were sufficient for rapid development and testing, but likely would not be suitable for production use. Rugged, field-ready equipment must be chosen to withstand extreme temperatures and minimize the possibility that cables become disconnected. It should be taken into account when doing this that the system will likely need to remain portable for use within pilot cars; i.e., permanently mounting the system within pilot may not be an option. Instead, the system might come in a briefcase, in which components can rapidly be connected to power, and antennas can be quickly and easily mounted.

For components used in conjunction with signs, further investigation will be necessary to determine whether these components can and should be attached directly to the signs or whether they should operate separately from the signs, perhaps with a wireless connection to the signs. For instance, the controller might operate as another briefcase within a vehicle that communicates via wireless with a receiver attached to a sign. Alternatively, the controller might also be attached to the sign. It was not possible within the scope of this project to determine which, if either, of these configurations was optimal. Power constraints and the likelihood that a vehicle or trailer could be parked in the right location to house this functionality need to be considered further.

In conjunction, there is a need to further determine the user interface requirements and limitations. A goal of this system is to minimize human interaction and maximize automation. However, there are certain tasks that appear to require manual input such as indicating the starting and ending points of the work zone. This could be accomplished in a variety of ways other than using the GUI that was used on the notebook computer. Indicating/determining when traffic has been closed in one direction by the flagger may also be an issue that requires user input. Further investigation is necessary to determine if the wait time at the other end of the work zone is a sufficient proxy for this measure, eliminating the need for this input.

State determination requires accurate GPS input in the proof-of-concept system. It may be the case that GPS performance degrades to an unacceptable level in rugged terrain, particularly with dense foliage and obstruction of the sky. Further estimation should be conducted to determine the impact and severity of degradation in these circumstances. If the impact is determined to be severe enough to affect system performance, then alternatives should be investigated. There are a number of assisted GPS (AGPS) alternatives that could be considered, as could other RF triangulation methods that do not require a clear view of the sky.

There is a need to test the system with signs that are regularly used by Caltrans and other agencies in the field. Tests were successful with lab signs, and research was conducted into protocols and interfaces used by field-ready signs. A logical next step would be to test the system with such field-ready signs and to enhance the controller application to interface with as many such signs as possible.

Similarly, the possibility that multiple signs are used at each of the end points, in sequence, should be explored further. Inherent in this configuration is the challenge of relaying information to multiple signs using communication technology. It should also be noted that the sign may not be located at the work zone end point, and instead located some distance from the work zone and flagger. Providing communication to control that sign could be a challenge.

In the future, remote posting of real-time delays on the traveler information web pages might also be explored. This information would be beneficial to the public and other public safety organizations. Note that this capability would require further investigation into communication in order to effectively transmit this information to the web and other servers necessary for presenting that information to the public. The communication systems considered for operation within the work zone within this project have largely been considered local area networks within the work zone, with no need to transmit information to or receive information from the outside. It may be necessary to consider commercial providers such as cellular and satellite or consider existing public safety communications infrastructure for this purpose.

Finally, it should be considered whether or not other, related technology will be deployed in pilot cars and/or in the work zone. It may be possible to develop integrated systems that serve a number of applications rather than having separate systems for each. Further investigation would be necessary to determine which alternative is best, depending on the applications. Integration could be beneficial, but it could also unnecessarily tie this system to another system, complicating deployment and use.

8.2.2. Delay Estimation and Computation Research Needs

The different algorithms that are presented here have their strengths and weaknesses. Some of the algorithms perform better in some traffic conditions than the other algorithms. Due to time limitations, it was not possible to compare and contrast these algorithms. As explained earlier, the traffic arrival rate and the traffic arrival trend (i.e. the change in the rate) vary and it may be possible to design the system such that the system picks the best suited algorithm based on the current traffic arrival trend. Further research is needed to verify this concept and to develop an algorithm that will select the appropriate delay estimation method.

Further testing with simulation should be conducted to evaluate algorithm performance. Real traffic counts should be used where possible. The presence of trends or anomalies (sudden spikes or drops) in data as well incorporating events to represent the influence of work zone operations on traffic flow should all be incorporated into testing. Simulation provides a means to test a large number of such scenarios and events that otherwise might not be feasible due to time and budget limitations in field-testing.

8.2.3. Communication Technologies Research Needs

In order to guarantee robust operation in the field, further investigation of 802.11 and alternatives will be necessary. Obvious concerns about the use of 802.11 and other technologies that operate on unlicensed spectrum are the potential for interference and security problems. It should be determined with certainty to what level these concerns can be addressed before deploying such a system for production use.

Technologies using licensed spectrum showed promise for providing better communication coverage of the work zone. These technologies should be further investigated and evaluated to determine if they are viable alternatives to 802.11. There may be challenges in securing frequencies for system use, and equipment will certainly be more costly and perhaps less flexible than 802.11. However, such systems would minimize the potential for interference and would exhibit better propagation characteristics. Thus, they should be investigated further.

8.3. Recommendations

It is recommended that subsequent research and development be conducted as outlined in prior sections to:

- Prepare system equipment and technology for field use
- Evaluate and optimize algorithms to best fit actual traffic patterns including trends and anomalies
- Determine the best communications technologies and configurations for deployment

The system developed within this phase of the project is a “proof-of-concept” system, intended to facilitate lab testing and to demonstrate the potential feasibility of such testing. The system is not ready for field-testing or production use. The system is considered to be at Stage 2, the Laboratory Prototype Stage, of the Caltrans Stages of Research Deployment. Further research and development will need to be conducted to lead system development and deployment through Stages 3-5, preparing the system for production use. In this report, we have outlined prospective subsequent research and development as recommendations for that purpose.

APPENDIX A: CONTROLLED LAB TEST RESULTS

Table A-1: Actual Cycle Times and Number of Cars Waiting for Each Cycle

Cycle #	Actual Endpoint A Cycle Time (s)	Cars Waiting at A	Actual Endpoint B Cycle Time (s)	Cars Waiting at B
1	398	22	429	20
2	410	22	395	14
3	394	20	368	14
4	355	20	377	10
5	402	9	420	10
6	404	9	362	7
7	369	18	408	7
8	411	18	388	13
9	368	22	377	13
10	408	22	390	12
11	370	12	377	12

Table A-2: Actual and Measured Cycle Times for Each Cycle

Cycle #	Actual Cycle Time for A (s)	Measured Cycle Time for A (s)	Difference at A (s)	Actual Cycle Time for B (s)	Measured cycle Time for B (s)	Difference at B (s)
1	398	392	6	429	423	6
2	410	410	0	395	397	2
3	394	394	0	368	367	1
4	355	355	0	377	377	0
5	402	402	0	420	419	1
6	404	403	1	362	363	1
7	369	370	1	408	408	0
8	411	412	1	388	386	2
9	368	367	1	377	378	1
10	408	408	0	390	390	0
11	370	372	2	377	377	0

Table A-3: Actual Pilot Car Wait Times and Travel Times for Each Cycle

Cycle #	Actual PC Wait Time at A (s)	Actual PC Wait Time at B (s)	Actual AB Trip Time (s)	Actual BA Trip Time (s)
1	89	98	126	120
2	65	84	123	124
3	64	62	122	124
4	48	83	118	127
5	78	94	120	121
6	61	60	127	122
7	63	98	119	127
8	74	76	120	120
9	54	83	118	120
10	79	66	120	126
11	65	75	119	120

Table A-4: Actual and Measured Pilot Car Wait Times for Each Cycle

Cycle #	Actual PC Wait Time at A (s)	Measured PC Wait Time at A (s)	Difference (Measured – Actual) (s)	Actual PC Wait Time at B (s)	Measured PC Wait Time at B (s)	Difference (Measured – Actual) (s)
1	89	96	7	98	118	20
2	65	73	8	84	105	21
3	64	71	7	62	78	16
4	48	56	8	83	100	17
5	78	86	8	94	111	17
6	61	68	7	60	76	16
7	63	71	8	98	115	17
8	74	83	9	76	91	15
9	54	60	6	83	98	15
10	79	87	8	66	82	16
11	65	75	10	75	90	15

Table A-5: Actual and Measured Pilot Car Trip Times for Each Cycle

Cycle #	Actual AB Trip Time (s)	Measured AB Trip Time (s)	Difference (Measured – Actual) (s)	Actual BA Trip time (s)	Measured BA Trip Time (s)	Difference (Measured – Actual) (s)
1	126	109	-17	120	101	-19
2	123	108	-15	124	111	-13
3	122	108	-14	124	110	-14
4	118	108	-10	127	113	-14
5	120	108	-12	121	108	-13
6	127	114	-13	122	110	-12
7	119	109	-10	127	114	-13
8	120	108	-12	120	106	-14
9	118	106	-12	120	109	-11
10	120	109	-11	126	113	-13
11	119	108	-11	120	107	-13

Table A-6: Actual, Measured and Estimated Delay under Four Estimation Algorithms (End Point A)

Cycle #	Actual Delay at A (s)	Measured Delay at A (s)	Delay at A From Last Cycle (s)	Simple Average Delay at A (s)	Exponential Decay Delay at A (s)	Linear Decay Delay at A (s)
1	398	392	X	X	X	X
2	324	324	392	392	392	392
3	275	276	324	358	346	347
4	249	250	276	330	306	306
5	323	324	250	310	276	276
6	303	303	324	313	300	301
7	258	259	303	295	300	301
8	335	336	259	282	278	279
9	253	252	336	294	308	308
10	317	317	252	294	280	280
11	271	274	317	293	298	298

Table A-7: Actual, Measured and Estimated Delay under Four Estimation Algorithms (End Point B)

Cycle #	Actual Delay at B (s)	Measured Delay at B (s)	Delay at B From Last Cycle (s)	Simple Average Delay at B (s)	Exponential Decay Delay at B (s)	Linear Decay Delay at B (s)
1	410	404	X	X	X	X
2	299	301	404	404	404	404
3	295	296	301	352	335	335
4	306	306	296	333	311	313
5	364	363	306	326	308	309
6	276	277	363	333	336	337
7	340	340	277	308	304	305
8	317	315	340	316	323	323
9	294	295	315	320	319	319
10	329	329	295	318	307	307
11	290	290	329	311	317	317

APPENDIX B: TRAFFIC SIMULATION ANALYSIS

B.1 Overview of SIMPROCESS

Computer models are widely used in traffic and transportation system analysis. In this project, a work zone traffic simulation model was created using the SimProcess™ simulation tool to study the actual traffic flow patterns at the work zone and to estimate the traffic delay under certain circumstances. SimProcess is a hierarchical and integrated process simulation tool. It provides a fast, flexible, and easy-to-use platform for developing, analyzing, and visualizing dynamic simulations and has been widely used for process and discrete-event simulation.

B.2 Work Zone Description / Traffic Conditions

In order to estimate work zone traffic delay, a hypothetical construction site is assumed on a two-lane segment of rural highway. It was assumed that the roadway maintenance work requires the closure of one lane for two miles, with the remaining one lane open to traffic.

It is more accurate and beneficial to simulate with the real traffic data. Therefore, traffic data from one day (January 4, 2006) at Caltrans’ Bella Vista station was used to simulate the average vehicle approaching rate. The traffic flow distribution is shown in Table B-1 and Figure B-1. The average pilot car speed in the work zone is assumed to be 20 mph. The maintenance activities will be simulated over a period of 16 hours (from 8 am to 12 midnight) or 24 hours (from midnight to midnight), during which the pilot car is assumed to be working all day without interruption. For the 8 am to 12 midnight simulation period, it is assumed that at the each end of work zone A and B, there are already 20 vehicles waiting at 8 am.

Table B-1 Bella Vista Station TR data

Date	Hours	Lane 1	Lane 2
01/04/06	0	14	10
01/04/06	1	3	3
01/04/06	2	1	9
01/04/06	3	13	5
01/04/06	4	13	9
01/04/06	5	32	24
01/04/06	6	69	91
01/04/06	7	132	215
01/04/06	8	108	169
01/04/06	9	88	165
01/04/06	10	107	173
01/04/06	11	97	176
01/04/06	12	138	124
01/04/06	13	156	150
01/04/06	14	221	172
01/04/06	15	182	145
01/04/06	16	191	120
01/04/06	17	212	136
01/04/06	18	124	108
01/04/06	19	76	45
01/04/06	20	62	39
01/04/06	21	38	25
01/04/06	22	42	14
01/04/06	23	22	6

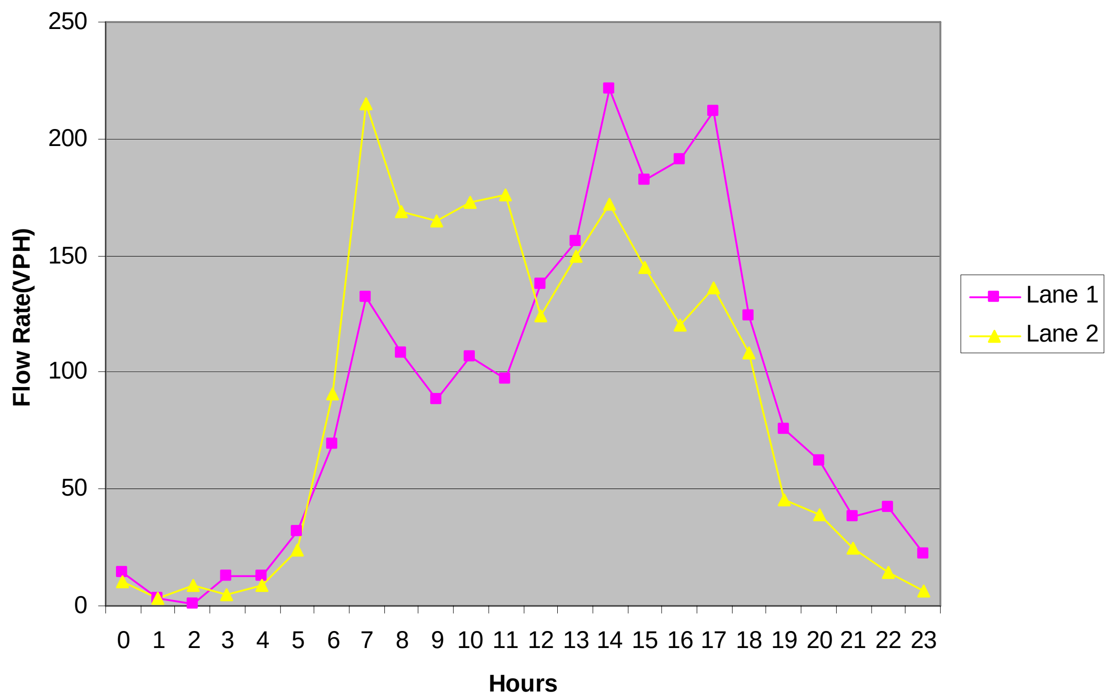


Figure B-1: Traffic Flow Rate over Time

B.3 Methodology

The general logic of the work zone model (shown in Figure B-2) is based on the discrete event simulation principle as well as the building blocks of the SimProcess program.

Two ends of the work zones are named A and B. The pilot car is treated as an entity in the model. Only one pilot car is created at the beginning of the simulation period at **START A** site, and will shift between **FLAGGER A** and **FLAGGER B** stations. The arriving vehicles from each direction (lane 1 and lane 2 from the Caltrans traffic data) are also treated as entities in the model and are generated at **START A** and **START B** and leave at **END B** and **END A** respectively..

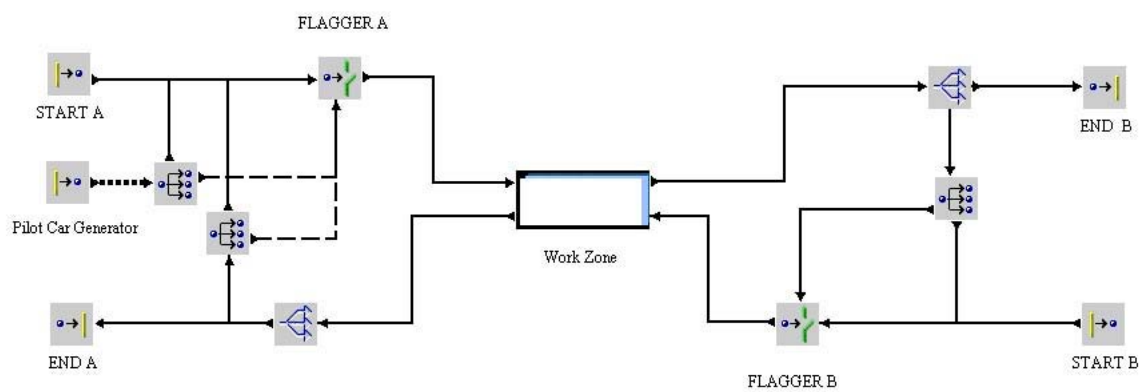


Figure B-2: Work Zone Simulation Model

To simulate the vehicles passing through work zone guided by a pilot car and two flaggers, **FLAGGER A** and **FLAGGER B** stations are modeled as gate blocks in the simulation model. All vehicles approaching work zone will wait at **FLAGGER A** or **FLAGGER B** stations. Once the pilot car and all the following vehicles pass through **FLAGGER A** or **B**, all the vehicles waiting at **FLAGGER A** or **FLAGGER B** will be released. The work zone travel time for each vehicle is defined as the time to move from two miles with a 20 mph speed plus an additional four seconds to startup from a full stop to a speed of 20 mph and then move into the work zone.

The vehicle arrival rate and the work zone travel time are assumed follow the uniform (0.5, 1.5) distribution.

B.4 Analysis and Results

Three different scenarios are studied based on different simulation period and warm up time. Each scenario is simulated using the model defined above and runs with ten iterations. At the end of the each simulation run, a statistics report was generated showing the average waiting time at **FLAGGER A** and **B**, the average travel time in work zone, the average queue length at **FLAGGER A** and **B**. The three scenarios are labeled as follows:

1. 8 am to 12 midnight, with no warm-up

2. 12 midnight to 12 midnight, with no warm-up
3. 8 am to 12 midnight, with 30 minutes warm-up

The results are shown in Table B-2.

Table B-2: Simulation Results

Scenario	Waiting Time (min)		Queue Length		Travel Time (min)	
	Flagger A	Flagger B	Flagger A	Flagger B	Lane 1	Lane 2
1	8.588	8.506	17	16	5.978	6.134
2	8.255	8.248	13	12	6.273	6.253
3	8.705	8.588	17	16	5.968	6.143

APPENDIX C: COMMUNICATIONS ANALYSIS

By Dr. William J. Jameson

As a means of estimating the relative effectiveness of potential RF solutions to communication of the pilot car's location to the traffic message signs at the ends of a highway maintenance project, we have conducted a number of propagation studies. These studies include three options using VHF hi-band (150 MHz) and one each using UHF (450 MHz) and 900 MHz. Studies were conducted over four sets of terrain, two with highly irregular terrain (mountainous), one of moderate irregular terrain and one of relatively flat terrain. Over the last two terrain samples, all of the options appeared to be satisfactory. The first two had similar results relative to all options. Hence, we shall concentrate this report on the first study, referred to as Test 1.

For the VHF studies we used a receiver sensitivity of 0 dBu, a rather conservative figure. (Typically, current systems operate with a receiver sensitivity of approximately -10 dBu.). On the other hand, for the UHF and 900 MHz systems we used state-of-the-art RF modem systems for the comparison. System parameters for the three frequency bands were:

1. VHF (e.g., Data Radio Integra, Kantronics Talon UDC VHF or MDS1710 RF modem)
    a. RX Sensitivity – 0 dBu
    b. TX power in Pilot car – 5 W
    c. RX antenna gain at information sign - 3 dB
    d. RX antenna height at information sign – 6 ft
2. VHF hi-gain
    a. RX Sensitivity – 0 dBu
    b. TX power in Pilot car – 10 W ERP
    c. TX gain in Pilot Car – 3 dB
    d. RX antenna gain at information sign – 9 dB yagi
    e. RX antenna height at information sign – 10 ft
3. VHF 3dB
    a. RX Sensitivity – 0 dBu
    b. TX power in Pilot car – 10 W ERP
    c. TX gain in Pilot Car – 3 dB
    d. RX antenna gain at information sign – 3 dB
    e. RX antenna height at information sign – 6 ft
4. UHF (Data Radio Gemini RF modem with space diversity antenna)
    a. RX Sensitivity – -56 dBu
    b. TX power in Pilot car – 25 W ERP
    c. RX antenna gain at information sign – 15 dB
    d. RX antenna height at information sign – 10 ft
5. 900 MHz (Motorola Canopy system)
    a. RX Sensitivity – -30 dBu
    b. TX power in Pilot car – 4 W ERP
    c. RX antenna gain at information sign – 10 dB
    d. RX antenna height at information sign – 10 ft

Another possible option would be a mesh network. Mesh stations act as network repeaters, which could be a significant advantage. Unfortunately, typical mesh networks sites have a point-to-point range of one mile or less, due primarily to their frequency band (typically 2.4 GHz). For Test 1 several mesh sites would be required along the test path, probably seven or eight and possibly more. Although such site stations could probably be set up in a battery powered “cone”, the time required to set them up (and the RF technical background of the staff individual who sets them up), as well as the cost of multiple units, might make them less than desirable.

Test 1 was based on an approximately five mile stretch of State Route 70 near Redding. At the end of this appendix are five location comparisons of relative system coverage of the five system approaches. The “location” of a pilot car for each of the five comparisons is listed beneath the plot (e.g. for “Test 1-3 UHF” the pilot car is located at the point marked Test 1-3). For each location, one needs to look at whether or not the Test 1 end is covered by a color (red, yellow or green). If so, the location will be adequately covered by the pilot car’s RF signal. The color red indicates exceptional coverage (very high field strength); yellow indicates good coverage and green indicates acceptable coverage. We note that all three of the VHF options provide reasonable or good coverage at the end point (at least green for most or all of the pilot car sample points). Note, however, that neither UHF nor 900 MHz have any yellow or green coverage areas. This is due to their respective line-of-sight limitations – coverage is excellent out to the point where line-of-sight is restricted by terrain. In reality, the performance of the UHF and 900 MHz options was excellent considering the terrain.

The propagation studies do not address possible interference on unlicensed frequencies (interference analysis requires knowledge of the location of all interfering sites). Except, perhaps, in heavily populated areas, it doesn’t seem likely that this would be a significant factor.

For the three VHF systems an RF modem (e.g., Data Radio Integra @ $1,700 or MDS1710 @ $1,100[3]) is a relatively simple approach. It connects directly to a driving device (e.g. laptop). For the UHF option a higher power RF modem would be required (e.g. Data Radio Gemini @ $3,350 – also includes GPS receiver). It, too, connects directly to a driving device. The 900 MHz (based on Motorola Canopy) option may not be satisfactory for mobile use as it is designed for point-to-point operation. Since the subscriber unit and the hi-gain antenna (60^o beam width) are fairly compact, however, it may be possible to mount a system on a pilot car relatively easily. Whether or not it will operate in a mobile mode needs to be determined. The access antenna should be easily mounted on the traffic information sign.

C.1 Equipment Testing

We were able to do extensive highway testing with two MDS 1710 RF modems operating on 151.805 MHz; one served as the transmitter (pilot car), the other served as the receiver site. The tests were conducted on US Route 191 in the Gallatin Canyon, very irregular terrain in the Gallatin Range. Before the tests, we performed a propagation study that allowed us to choose an appropriate section of highway for the tests. The tests actually performed slightly better (over the

[3] List prices. The MDS1710 could be obtained for $979 per unit in reasonable quantities.

entire test run) than we anticipated from the propagation study. (Approximately 42 percent of the test run had adequate coverage, whereas approximately 40 percent of the Run was within the -30 dBu coverage estimates.) We suspect that this may be due in part to ducting along the Gallatin River, which lies within a few hundred feet of the highway for most of the Test Run. Figure C-1 and Table C-1 demonstrate the test results.

C.2 Conclusions

- Highways in regions with highly irregular terrain: In such areas it would appear that a licensed VHF hi-band frequency system would be most viable. The VHF system with a 3 dB gain mobile antenna at both the end points and pilot car would seem to be a relatively logical approach. (Mounting a 9 dB gain yagi at the traffic information sign may be both time consuming and confusing to a non-technician unless, for example, a vehicle, with a pre-mounted yagi antenna that could be easily rotated into position, was to be used.)

- Highways in moderate terrain regions: Any of the options would probably function, assuming, of course, that the 900 MHz option would operate in a mobile situation. (If the 900 MHz frequencies are unlicensed, however, there is some possibility of interference, even though encryption would prevent improper transfer of data.)

- Highways in heavily populated areas: As the use of 900 MHz canopy or similar systems grows in populated areas the potential for significant interference will evolve. In such areas it might be appropriate to use only licensed frequency systems (generally VHF or UHF).

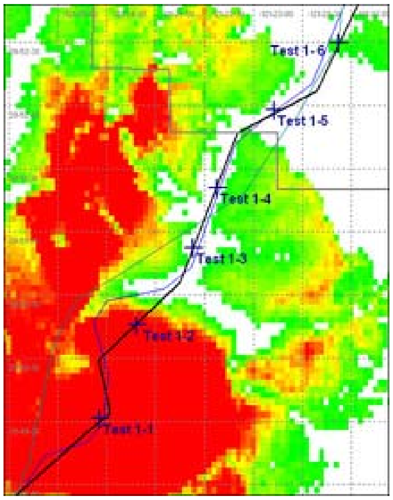
C.3 Propagation Analysis

Legend

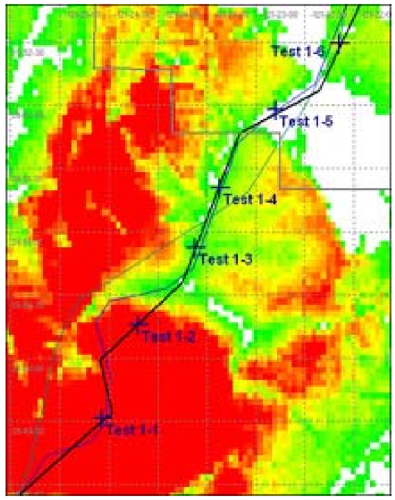
Sensitivity Parameters

VHF	____________________	**20 dBu**
	____________________	**10 dBu**
	____________________	**0 dBu**
UHF	____________________	**-56 dBu**
900 MHz	____________________	**-30 dBu**

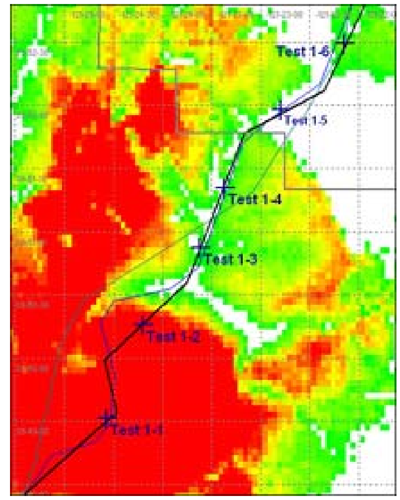
C.3.1 State Route 70 Test 1-1



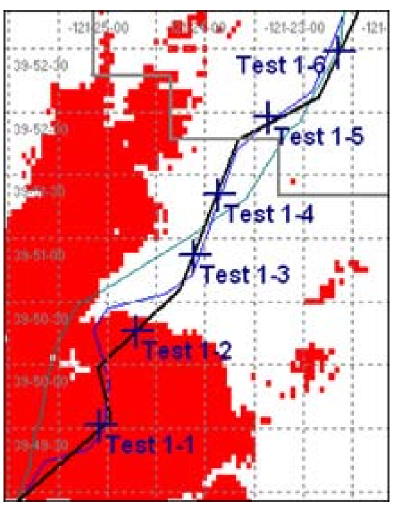
Test 1-1 VHF



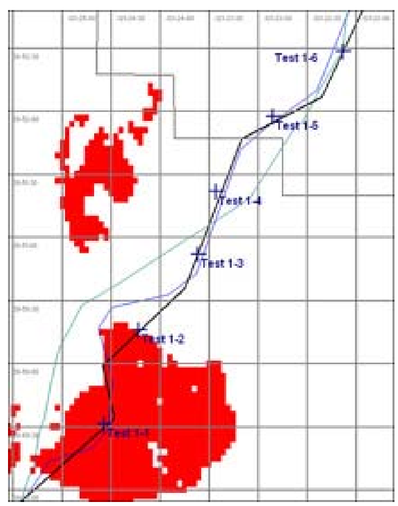
Test 1-1 VHF hi-gain



Test 1-1 VHF 3 dB

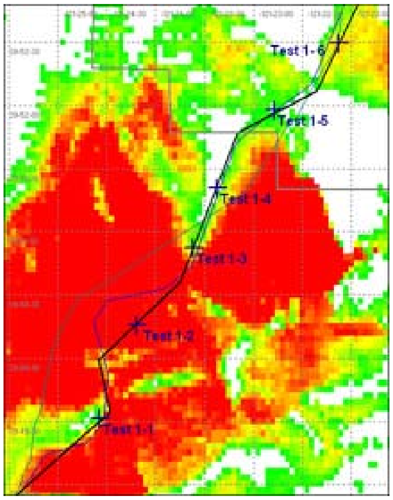


Test 1-1 UHF

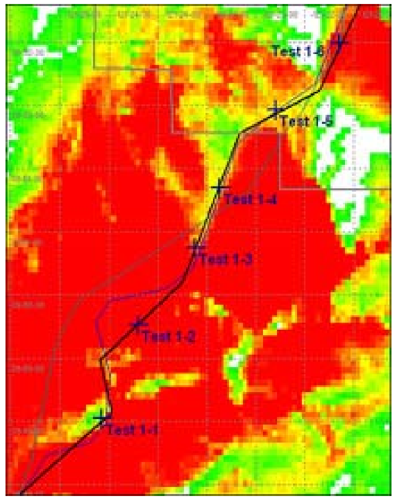


Test 1-1 900 MHz

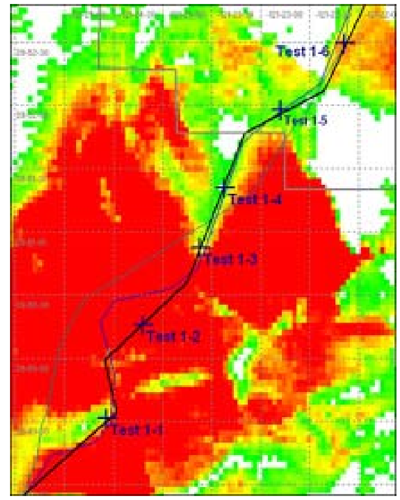
C.3.2 State Route 70 Test 1-2



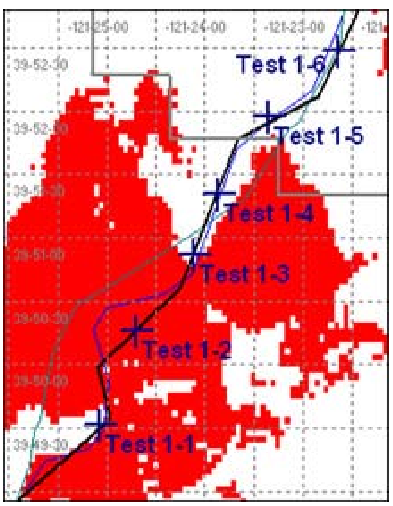
Test 1-2 VHF



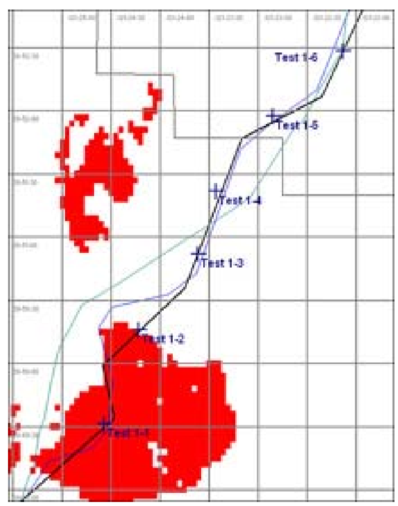
Test 1-2 VHF hi-gain



Test 1-2 VHF 3 dB

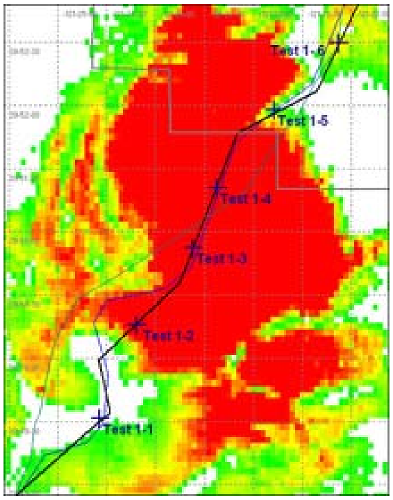


Test 1-2 UHF

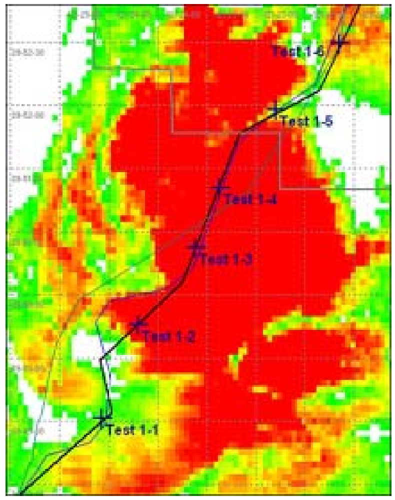


Test 1-2 900 MHz

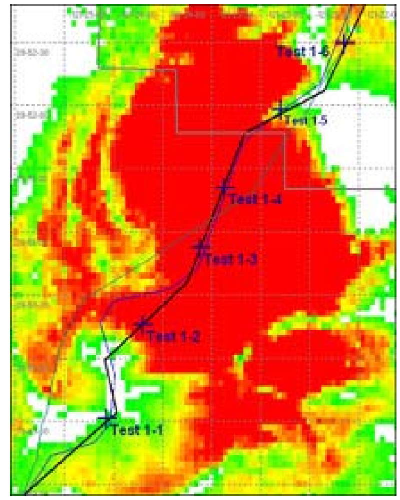
C.3.3 SR-70 Test 1-3



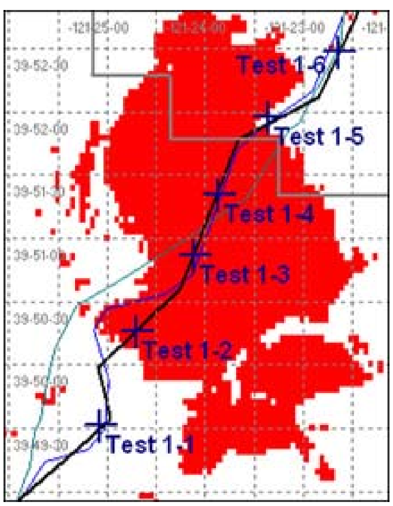
Test 1-3 VHF



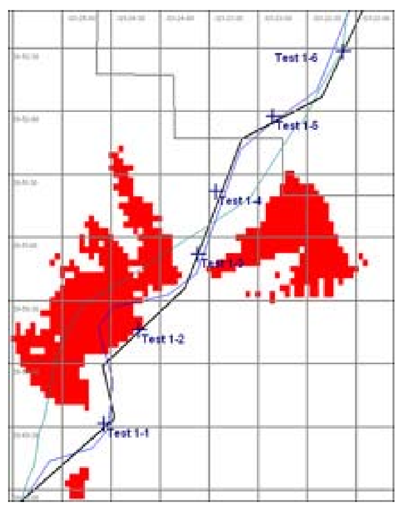
Test 1-3 VHF hi-gain



Test 1-3 VHF 3 dB

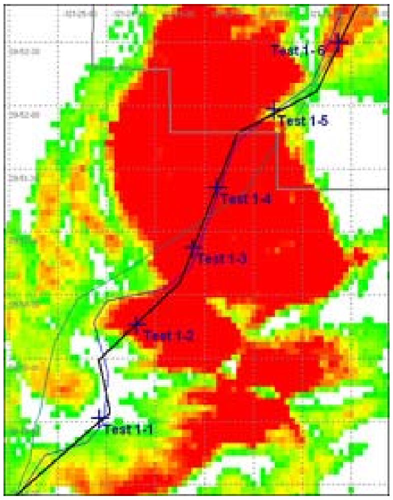


Test 1-3 UHF

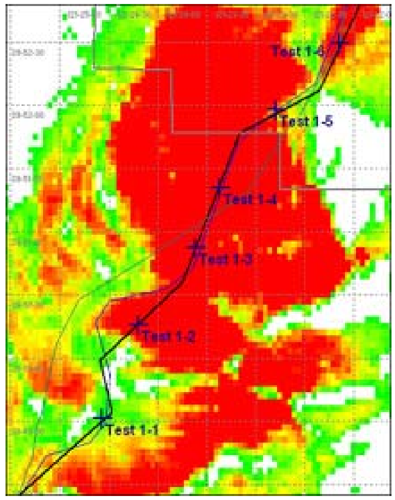


Test 1-3 900 MHz

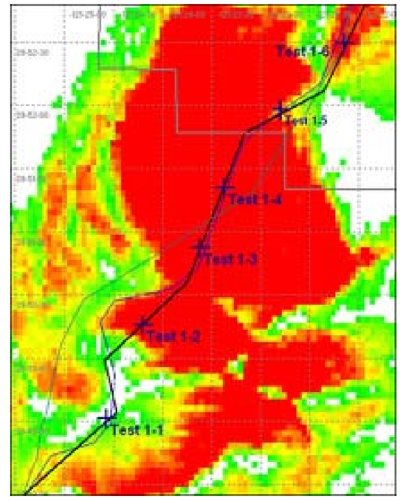
C.3.4 SR-70 Test 1-4



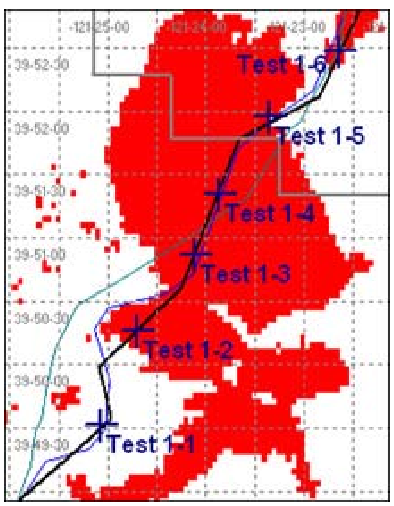
Test 1-4 VHF



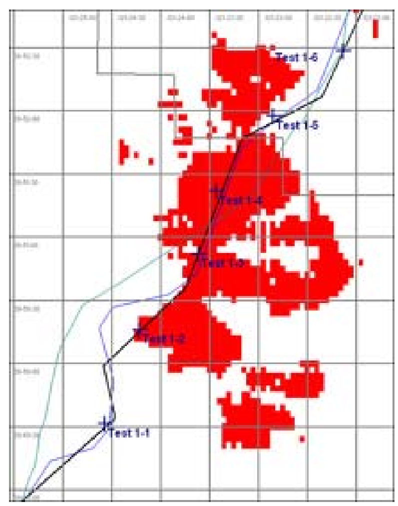
Test 1-4 VHF hi-gain



Test 1-4 VHF 3 dB

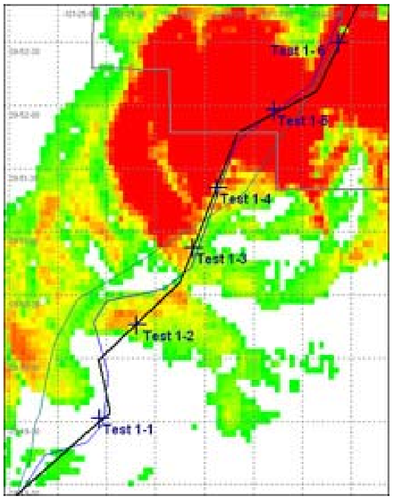


Test 1-4 UHF

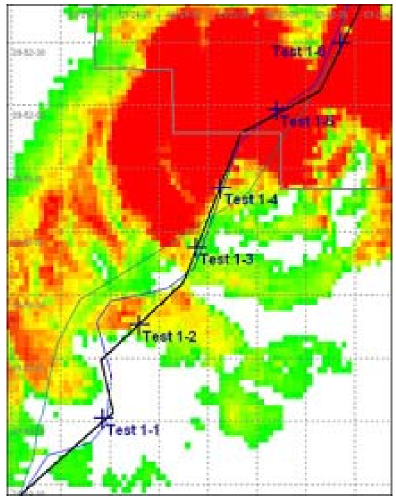


Test 1-4 900 MHz

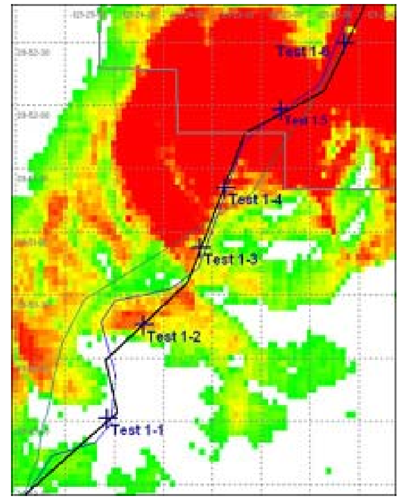
C.3.5 SR-70 Test 1-5



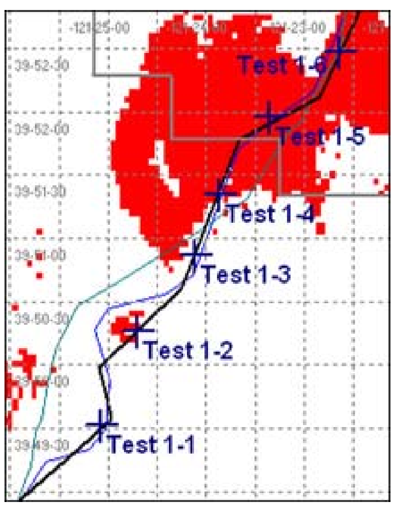
Test 1-5 VHF



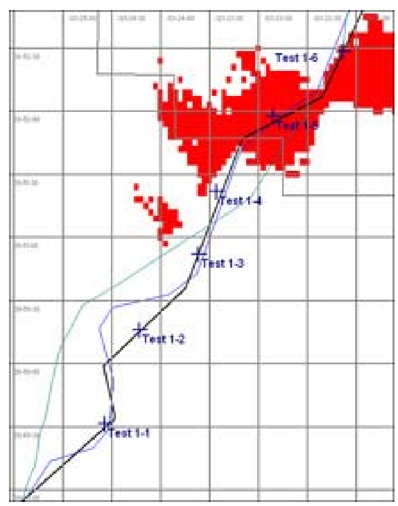
Test 1-5 VHF hi-gain



Test 1-5 VHF 3 dB

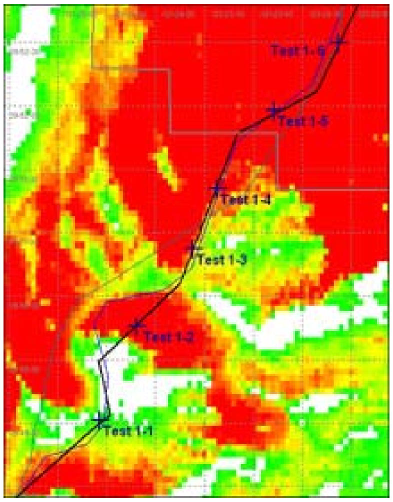


Test 1-5 UHF

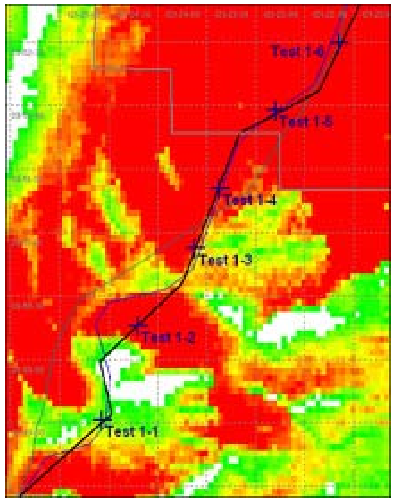


Test 1-5 900 MHz

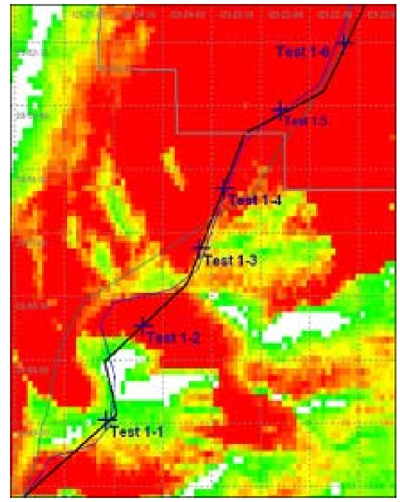
C.3.6 SR-70 Test 1-6



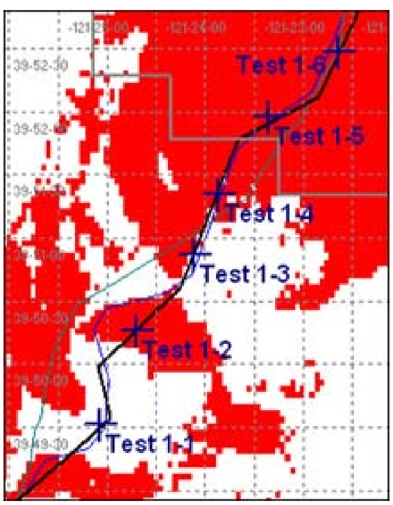
Test 1-6 VHF



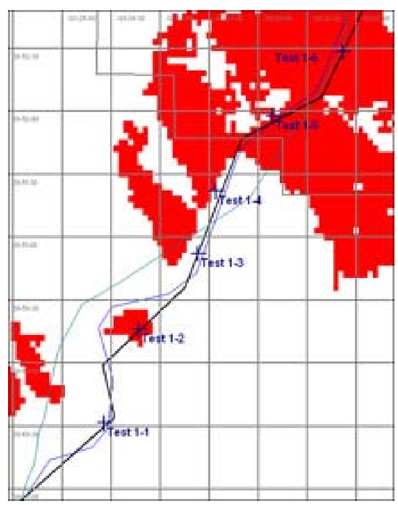
Test 1-6 VHF hi-gain



Test 1-6 VHF 3 dB



Test 1-6 UHF



Test 1-6 900 MHz

C.3.7 MDS 1710 Coverage Test Along US 191, Gallatin Canyon, South of Bozeman, MT

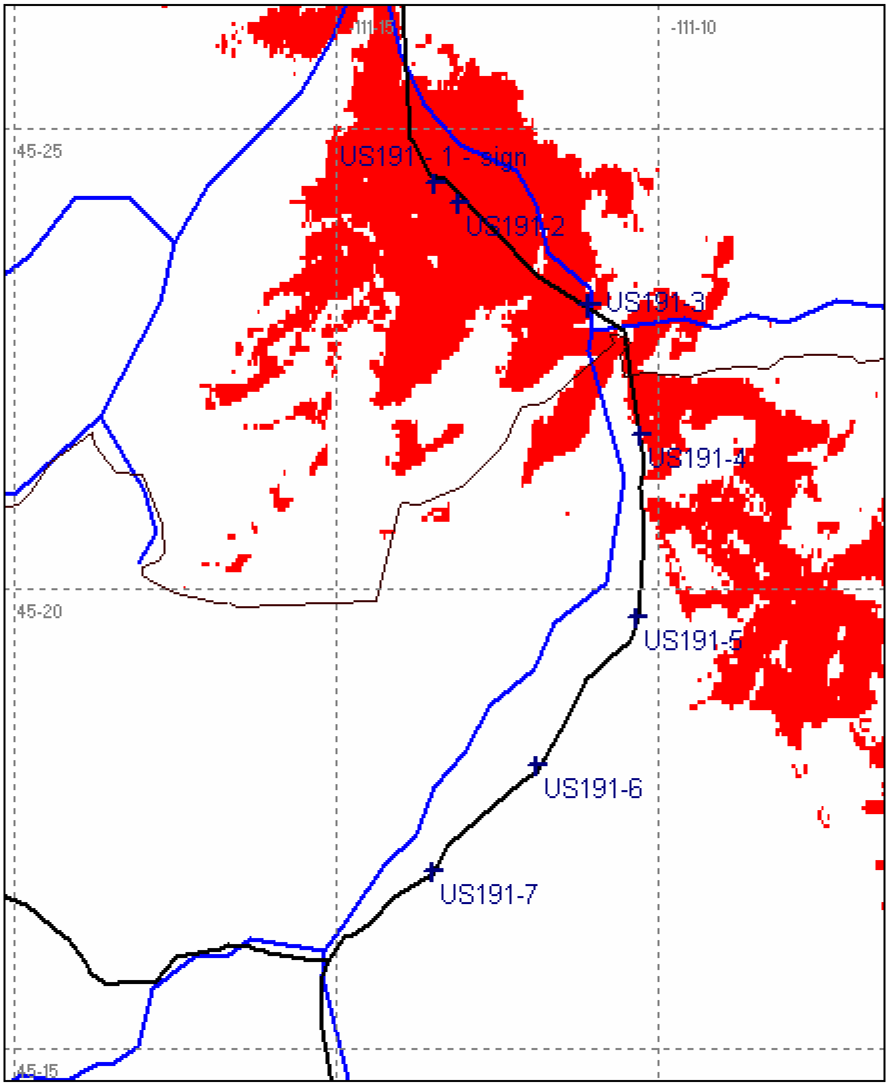
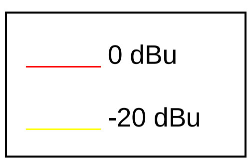


Figure C-3: MDS 1710 Test Area, US 191



Note that unity gain antennae were used in the US191 Test Run.

Table C-1: Field Strength Measurements at Specific Locations along Test Area

Site Location	Field Strength
Test Site US191-2	-16 dBu
Test Site US191-3	8 dBu
Test Site US191-4	-29 dBu
Test Site US191-5	-40 dBu
Test Site US191-6	-53 dBu
Test Site US191-7	-60 dBu

APPENDIX D: COMMUNICATIONS ALTERNATIVES ANALYSIS

by Kyoungwon Kim

D.1 Abstract

This appendix describes possible solutions for wireless communications between a pilot car and two traffic message signs at the ends of a highway maintenance construction zone. The pilot car should be able to communicate with both signs continuously as it travels through the work zone. Several alternative wireless technologies and topologies are examined to assess their ability to meet the requirements. Multi-hop and point-to-multipoint were regarded as possible solutions. We show that a multi-hop network provides the best results in terms of continuous coverage, but is also relatively expensive and potentially difficult to configure. Providing electrical power at the intermediate node locations poses a further problem to the multi-hop alternative. A point-to-multipoint solution is a low cost and less complex alternative, but may not provide continuous coverage under rough terrain conditions where the transmission path between the pilot car and the message signs is not line-of-sight.

D.2 Introduction

The major goal in this report is to propose solutions that will provide continuous communications between a pilot car and message signs as the car moves through the work zone. This system will be employed in rural area where rough terrain and large distances may result in non-line-of-sight paths.

We consider a scenario where the pilot car is equipped with a computer and a wireless interface, which can communicate with similarly equipped computers at the message sign locations. The pilot car computer will periodically transmit its location (determined by GPS) and an estimate of its time of arrival at the end of the work zone to the computers located at the signs. The required transmission rate is 100 kb/s. The following is a summary of the communications requirements considered in this portion of the study.

- Provide continuous connectivity between the pilot car and the message signs.
- Operate in areas with poor or no line of sight between end points.
- Operate in areas with poor or no cell phone coverage
- Use a type of communication that has low initial and recurring costs
- System should be able to overcome any communication hindrances from roadsides or other vehicles passing through the work zone
- Should be easy to deploy
- May use unlicensed radio spectrum
- Provide 100 kb/s throughput
- Digital and Ethernet compatible
- Operate while the pilot car is in motion
- Operate with a range of up to five miles
- Low power consumption

D.3 Solutions

The requirements of continuous communications and ease of use, combined with rugged terrain limit the solutions to a few alternatives. While low frequency radio systems can provide wide area coverage under non line-of-sight conditions, the available unlicensed spectrum where products that meet the throughput and Ethernet compatibility requirements necessitate use of radio bands at 900 MHz, 2400 MHz and 5800 MHz (ISM bands). At these frequencies, non line of sight communications is poor, requiring topologies that include multi-hop relays to assure continuous coverage.

As a test case, we consider a system that might be deployed in a rural area traversed by State Route 70 in northern California. As seen in Figure D-1, this section of State Route 70 is too curved to provide line-of-sight end-to-end communications. We consider several available radio technologies assess their ability to meet the requirements for this test case.

- Multi-hop using MeshDynamics system
- Multi-hop using ZigBee (802.15)
- Point-to-multipoint using Trangobroadband or Motorola Canopy systems

For each alternative we develop a plausible solution, identifying the system topology and a design that can best meet the requirements, and then estimate its cost and complexity as well as its ability to meet the requirements.

Figure D-4: Five-Mile Section along State Route 70 in California

D.3.1 Multi-hop using MeshDynamics

Multi-hop networks provide long-range connectivity by relaying packets from one mesh node to another, like a bucket brigade. The MeshDynamics approach employs a proprietary multi-hop routing protocol combined with 802.11 (Wi-Fi) radio technology. The nodes use a combination of 2.4 GHz and 5.8 GHz Wi-Fi radios to assure continuous, non self-interfering connectivity between fixed relays and mobile nodes. The MeshDynamics equipment can be configured in a topology where the pilot car is a mobile “root” node, the multi-hop network provides connectivity to stationary nodes located at the message signs. Figure D-5 shows a simple multi-hop network. The Ethernet connection would be used to connect the computer on the pilot car to the Root node.

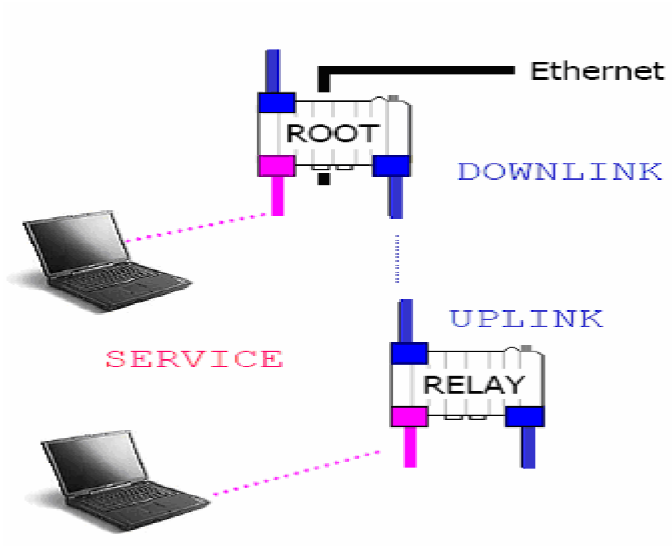


Figure D-5: Simple Multi-Hop Network

(Source: http://www.meshdynamics.com/DOWNLOADS/MD4000_HWMANUAL.pdf)

In this scenario, the mobile root node scans the available radio channels and connects to the closest stationary relay node. The relay nodes have uplink and downlink radios and form a wireless backbone for backhaul. The relay nodes have a second radio interface that serves as an access point for mobile or stationary clients. The mobile root node, mounted on the pilot car, operates at 2.4 GHz and the backhaul relay nodes operate at either 2.4 GHz or 5.8 GHz. Each relay node has two radio interfaces and a router function.

A solution can be implemented using the MeshDynamics MD 4000 Product Family. There are three models using 2.4 GHz backhaul and five models using 5.8 GHz backhaul radios. Two 2.4 GHz and one 5.8 GHz radios are recommended for this project by MeshDynamics.

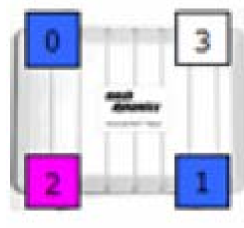


Figure D-6: MeshDynamics MD 4000 Product

(Source: www.meshdynamics.com/DOWNLOADS/MD4000_HWMANUAL.pdf)

The MD 4000 Modular MeshTM products support up to 4 radios in a single enclosure. Slots 0 and l house one uplink and one downlink radio operating on non-interfering channels but in the same frequency band. They are both 2.4 GHz or both 5.8 GHz radios. Slot 2 houses a 2.4 GHz radio for client connectivity. The 2.4 GHz radios can be set to 802.11b, 802.11 b/g or 802.11g only air interface protocols depending on throughput and compatibility requirements. Figure D-7 illustrates the recommended 2.4 GHz backhaul products and 5.8 GHz product in standard configurations.

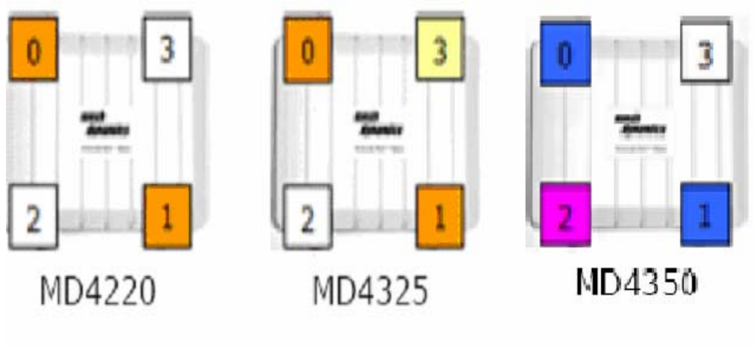


Figure D-7: MeshDynamics 2.4 GHz & 5.9GHz Backhaul Products

(Source: www.meshdynamics.com/DOWNLOADS/MD4000_HWMANUAL.pdf)

- MD4420-BBxx: 2-Radio module 2.4GHz uplink and downlink Backhaul (BH).
- MD4325-BBxB: 3-Radio module 2.4 GHz BH, Downlink also acts as AP. A 2.4 Mobility Scanner in slot 3.
- MD4350-AABx: 3-Radio module 5.8GHz BH and 2.4GHz AP radio in slot 2. AP modes may be b, g, or b&g.

MeshDynamics suggests that in rural areas or low client density situations, 2.4 GHz backhaul is preferred with panel antennas to reduce RF interference from other 2.4 GHz devices. In all other cases, they recommend using 5.8 GHz backhauls, starting with two 8 dBm omni-directional antennas and nodes 250 meters apart and then to increase node spacing until the throughput begins to decline.

There are two possible approaches to using the MeshDynamics multi-hop technology. The first is to have one of the nodes on the pilot car using the mobility option, where the node on the pilot car continuously scans the Wi-Fi channels and links to the strongest signal. As the pilot car moves along the highway, its connection to the backbone network, formed by the chain of relay nodes, will automatically switch as it leaves the neighborhood of one relay and approaches another relay node. Based on the map of State Route 70, nine stationary nodes and one mobile node would be needed for full and continuous coverage. A site survey would determine whether the number of nodes would need to be increased or decreased.

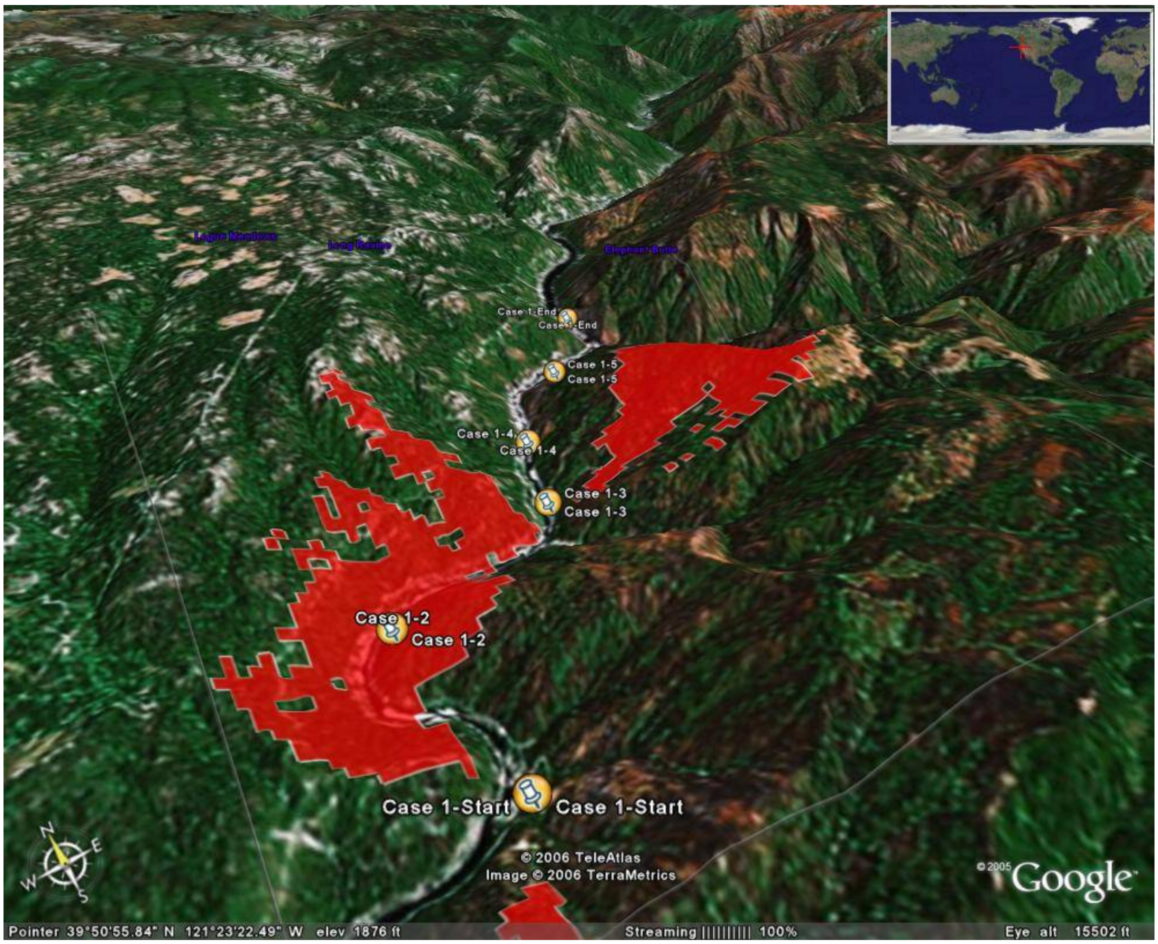


Figure D-8: Configuration of Mesh Network on State Route 70

(Source: Tom Dietz)

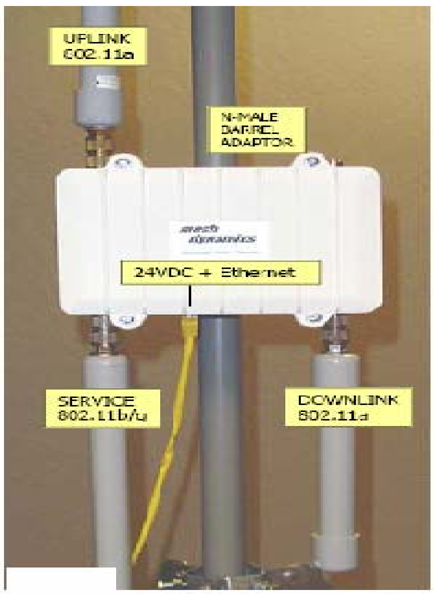
The other approach is to not have a MeshDynamics node in the pilot car, but to use a client 802.11 interface card attached directly to the computer in the pilot car. In this case, range becomes a limitation because the embedded wireless interface, without an external antenna, requires more relay nodes along the roadway to get continuous coverage. Furthermore, the pilot car speed would have to be less than 25 mph to enable the native 802.11 node association process to work properly as the car moves from the coverage of one relay node to another.

Multi-hop MeshDynamics Solution Cost

The first approach best meets the system requirements and will require the following MeshDynamics components:

- MD4220-IIxx-1100 – 9 stationary nodes.
- MD4325-IIIx-1100 – 1 mobile node.

Figure D-9 shows the connections on the product box and external features after mounting the antenna.



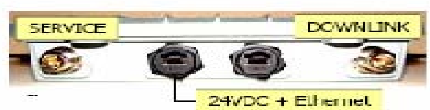


Figure D-9: External Features and Connections

(Source: www.meshdynamics.com/DOWNLOADS/MD4000_HWMANUAL.pdf)

Price estimate:

- MD4220-IIxx-1100 × 9 = $3,500 × 9 = $31,500
- MD4325-IIIx-1100 × 1 = $4,150 × 1 = $4,150
- Total = $35,650

MeshDynamics will extend a one-time evaluation unit discount of 40 percent. This would make the price $21,390. Antennas, power supplies and the other accessories were not included in the estimate. Existing power sources could provide power for the node on the pilot car and at the message signs. Powering the relay nodes is a significant issue. Note that each relay node consumes between 5 and 16 watts, depending on the number of radio interfaces in the configuration. The power consumption per relay node would be approximately 10 watts per node in the approach described here.

D.3.2 Multi-hop using ZigBee

The ZigBee Alliance (http://www.ZigBee.org) is developing a very low-cost, very low-power consumption, two-way, wireless communications architecture and protocols based on the IEEE 802.15.4 standard. Solutions adopting the ZigBee standard will target embedded processors in consumer electronics, home and building automation, industrial controls, PC peripherals, medical sensor applications, toys and games.

The IEEE 802.15.4 standard is a simple packet data protocol for lightweight networks and specifies the MAC and PHY layers. ZigBee technology takes full advantage of the IEEE 802.15.4 standard and adds the logical network, security and application software. ZigBee technology provides static and dynamic star, cluster tree and mesh networking structures that allow large area network coverage, scalable networks and single point-of-failure avoidance. Figure D-10 shows topologies enabled by the ZigBee network layer protcocol. ZigBee can provide a multi-hop network with 2.4GHz or 915MHz radio links.

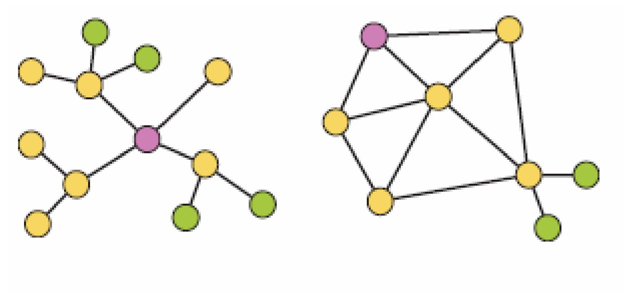


Figure D-10: Topologies for Multi-hop Communication Based on ZigBee

(Source: www.silabs.com/public/documents/marcom_doc/pbrief/Microcontrollers/en/ ZigBee_Brief_Web.pdf)

The ZigBee networking layer allows data from one device to be relayed to another device via intermediary devices. By relaying through these intermediary devices, the range of a given network can be significantly increased while at the same limiting the power consumption of each device. Thus a potentially large number of devices is necessary to form a five-mile relay chain. As with other multi-hop networks using 900 MHz or 2.4 GHz spectrum, the inter-node spacing is determined by terrain and the existence of line-of-sight conditions. The range of ZigBee is further constrained by its low transmission power, and is typically no more than 400 meters at 2.4 GHz, assuming use of omni-directional antennas.

Currently most of the ZigBee technology is available in chip sets for embedded applications (for example, see http://www.freescale.com/ZigBee) rather than packaged products. Helicomm (http://www.helicomm.com) offers seven 8051-based IP-Link embedded modules, providing the broadest selection of ZigBee and IP-layer wireless networking solutions. Figure D-11 shows IP-Link Modules that are available and compares their characteristics.

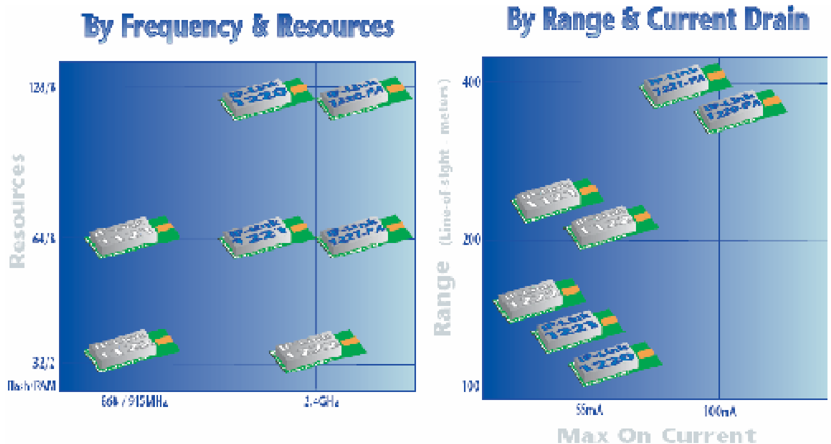


Figure D-11: Range, Frequency and Throughput Comparisons for IP-Link ZigBee Modules

These modules are designed for low data rate (up to 250 kb/s) applications. The line-of-sight range is maximum 400 meters. Part number 1221 PA has the largest coverage. If the 1221 PA is used for this project, at least 20 devices are needed to cover 5 miles in a multi-hop configuration. Table D-1 provides typical specifications for these products.

Table D-1: IP-Link 1221-2133 Specifications

Networking		ZigBee
RF	Frequency	2.4GHz
	Max. Data Rate	250kb/s
	Transmit Range	400m LOS
	RF Channels	16
	Power Consumption	55+45mA-Transmit
		16uA-Sleep
MCU	Type	F133
	RAM	8KB
	ROM	64KB
I/O	Physical Pins	48
	Serial	RS232, SMB, C2

Multi-hop Zigbee Solution Cost

Zigbee modules can be purchased along with a development kit to enable solution development. A 2.4 GHz ZigBee Development Kit (Silicon Laboratory <www.silab.com>) contains the following items:

- 2.4 GHz 802.15.4/ZigBee Target Boards (6)
- Antennas (6)
- 9 V batteries (6)
- 2.4 GHz ZigBee Development Kit User's Guide
- Silicon Laboratories Development Kit IDE and Product Information CD-ROM. CD content I

- Silicon Laboratories Integrated Development Environment
- Keil Software 8051 Development Tools (evaluation assembler, linker and C compiler)
- ZigBee Application Programming Interface (API) library
- Source code examples and register definition files
- 2.4 GHz ZigBee Demonstration Software Documentation
- AC to DC power adapter
- USB debug adapter (USB to debug interface)

Figure D-12 shows the components provided in the development kit. One development kit has six target boards, antennas and batteries. Thus, at least four development kits are needed to construct the number of IP devices required for the State Route 70 deployment.

Figure D-12: 2.4GHz ZigBee Development Kit

Figure D-13 shows how ZigBee modules interface to a laptop computer. The intermediate nodes will consist only of the IP devices (no laptop computer required) as the complete protocol stack (Phy, MAC and IP layers) runs on the embedded processor.

Figure D-13: ZigBee Device Interfaces to a Notebook Computer

Price estimate:

An IP-Module costs $39.03 from Digi-key and one development kit costs $950. The total price is:

- IP-Module × 20 = $780.60
- Development kit × 4 = $3,800
- Total: $4,580.60

This price includes the local power, which is provided by 9 V batteries, but not packaging and mounting hardware.

D.3.3 Point-to-Multipoint with 800 MHz

Trangobroadband (http://www.Trangobroadband.com) and Motorola Canopy (http://www.motorola.com/canopy) offer point-to-multipoint (PTM) digital radio systems designed for high-speed fixed wireless access. These systems operate in a range of frequency bands, and here we consider the 900 MHz unlicensed spectrum as it provides the best coverage in rough terrain. These systems offer highly versatile and cost effective outdoor solutions for wireless broadband service providers' enterprise connectivity. Communication occurs between one access point (AP) module to multiple subscriber modules (SMs). A typical deployment of a point-to-multipoint (PTM) wireless communications system is shown in Figure D-14.

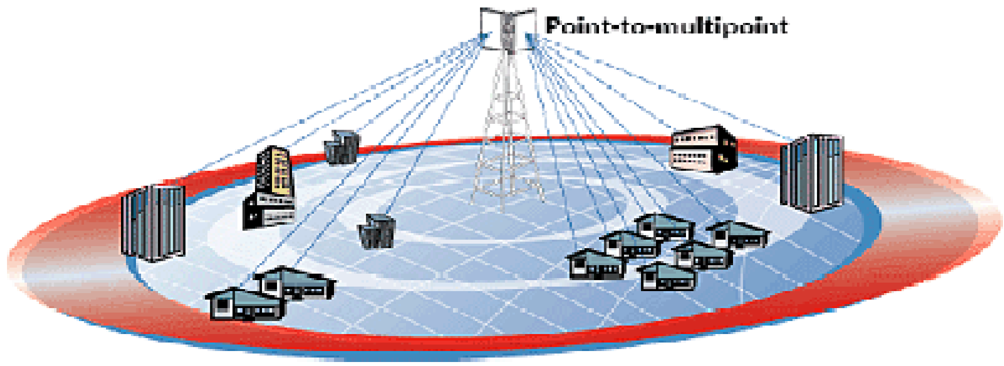


Figure D-14: Typical Point-to-Multipoint Deployment

(Source: www.trangobroadband.com/infobase/pdfs/M900S_UserManual.pdf)

For the work zone application, the pilot car serves as the AP and the message signs correspond to SMs. The computer in the pilot car connects to the AP through its Ethernet port, and the computers at the message signs use the Ethernet ports of the SMs. This approach will work well where there is line-of-sight available, as the range of these systems at 900 MHz is well in excess of five miles. However, performance under non-line-of-sight conditions is problematic and propagation modeling results for the State Route 70 route indicate that continuous communications between the pilot car and both message signs is not likely. Relay nodes would be needed to assure continuous coverage, but vendors are not making relays for these systems. Nevertheless, the turnkey nature of these systems, the ease in setting up a PTM network and the convenience of not having to deploy, power and maintain intermediate nodes makes PTM an attractive solution.

We consider here a PTM solution using Motorola/Canopy equipment. The Trangobroadband equipment is similar. Canopy will provide 3.3 Mb/s under non-line-of-sight conditions where the path is blocked by foliage, using a directional flat antenna. Throughput will be lower if the path is blocked by terrain. For the work zone application, the SMs (e.g., message signs) would be equipped with directional flat panel antennas oriented toward each other, and the pilot car would use an omni-directional antenna. The Trangobroadband M900 series equipment specifications are similar to Canopy, but Trangobroadband offers a certified omni-directional antenna option, whereas with Canopy a third party antenna supplier is needed.Figure D-15 shows the Canopy AP and SM modules and antennas.

Figure D-15: Canopy 900MHz AP and SM

(a) AP Connectorized (b) SM (c) 900-MHz radio (External Antenna) with flat panel antenna

<u>Price estimates (Canopy 900 MHz)</u>

Canopy provides a demo kit, part number TK10290C which has:

- 2 SMs
- 1 AP
- 3 AN900 Connectorized (External) antennas
- 1 300SS Surge Suppressor
- 1 SMMB1 SM Mounting Bracket
- 3 ACPS110-03 110-V AC Power Supplies2
- 3 CBL-0562 Straight-through Category 5 Cables
- 1 CBL-0565 Crossover Category 5 Cable
- 1 UGTK-0001 Trial Kit Quick Start Guide
- 1 CPT001-CD02EN Sales Overview on CD
- 1 CPT002-CD02EN Technical Overview on CD
- 1 CPT003-CD03EN Canopy System User Guide on CD

The cost per demo kit is $3,225, and is broken down in **Table D-**.2

Table D-2: Component Costs of Canopy 900 MHz Demonstration Kit

900 SM	$725
900 APC (External Antenna required)	$1,855
300 SS Surge Suppressor	$30
SMMB1 SM Mounting Bracket	$25
ACPS110-03 110-V AC Power Supplies	$10
CBL-0562	$150
AN900	$100
CPT001-CD02EN	$295
CPT002-CD02EN	$395
Total price	$3,225.00

Price Summary (Trangobroadband M900S Series)

Trangobroadband provides prices only for AP and SU (Subscriber Unit).modules:

- 1 M900S AP
- 2 M900s SU
- 1 BS915XL7 900-930MHz Omnidirectional BaseAntenna

The cost for these modules is $2,683, and is broken down in **Table D-**3.

Table D-3: Costs for Trangobroadband AP and SU Modules

Part Number	Price($)
M900S AP	1495
M900S SU	539
BS915XL7	110
Total price	2683

D.4 Comparisons

In this section, multi-hop network and point-to-multipoint network solutions will be compared. FTable shows the key features for MeshDynamics and ZigBee multi-hop and Trangobroadband and Canopy point-to-multipoint systems.

Table D-4: Comparison of Multi-Hop and Point-to-Multipoint Systems

Factor	MeshDynamics	ZigBee	Canopy 900MHz	Trangobroadband M900S Series
Frequency	2.4 GHz or 5.8 GHz	2.4 GHz	900MHz	900MHz
Range (LOS)	10 miles	400 meters	20 miles	20 miles
Range (NLOS)	It depends on environment	It depends on environment	It depends on environment	It depends on environment
Throughput	22 Mbps	250Kbps	3Mbps	3Mbps
Relay Capability	Yes	Yes	No	No
Cost of each component	Stationary Node-$3,500 Mobile Node-$4,150	IP-Module - $39.06, Development Kit- $980	AP-$1,855, SM-725	M900S AP-$1,495, M900S SU - $539
Total Cost	$35,650 ($21,390 discounted)	$4,580.60	$3,305	$2,575
Coverage Ability	Full	Full	Caps due to terrain	Gaps due to terrain
Temperature Range	-40 to 85° C	-20 to 70° C	-40 to 55° C	-40 to 60° C
DC voltage	24VDC	9VDC	24VDC	24VDC

Note that the cost is based primarily on the AP and SM modules or nodes. The other accessories prices were not included to enable a fair comparison.

Table D-5 shows the advantages and disadvantages of the solutions.

Table D-5: Advanatages and Disadvantages of Communications Alternatives

	Advantages	Disadvantages
MeshDynamics Multi-hop Network	▪ Full coverage	▪ Remote power for relays ▪ Long set-up time for locating relays ▪ High cost
ZigBee Multi-hop Network	▪ Full coverage ▪ Low cost ▪ Low power consumption	▪ Short range ▪ Longest set-up time due to locating relays ▪ Few commercial products
Canopy or Trangobroadband Point-to-Multipoint	▪ Simple to deploy ▪ Low cost ▪ Easy to supply power to SM	▪ Coverage gaps

Supplying power is a major concern. In the multi-hop case, each relay needs to be supplied remotely and separately and these costs have not been estimated for the MeshDynamics solution. For the other PTM case, each SM can be supplied power from the message sign and the AP can obtain power from the pilot car.

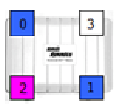
D.5 Conclusions

The most important requirement is continuous communication throughout the work zone, which can be met only by the multi-hop solution. However, this solution has several significant disadvantages including high cost, set-up time and power supply for the relay nodes. ZigBee is better than MeshDynamics in terms of cost and power consumption, but both solutions suffer from the disadvantage of the difficulty in proper placement of the relay nodes to assure continuous communication. The PTM approach is easy to implement but will not guarantee continuous communications where the terrain is rough.

D.6 Features Lists

MD4000 Series Features List	
Dimensions and weight.	8" (length) 6" (width) 2" (height), 3.0 lbs
Operating Temperature Range	- 40 to + 85 degrees Celsius.
Weather rating	NEMA 67 weather tight.
Power Supply Voltage	18-45 DC supplied by Power over Ethernet.
Power Consumption	5-16 W, depending on number of radios
Operating System	Embedded Linux 2.4.24
Ethernet Ports	Two on bottom. One with Power over Ethernet (PoE)
Serial Ports	One. May be exposed through second Ethernet Port.
Number of Radios per Box	Up to 4 mini-PCI Atheros a/b/g radio cards per box
Maximum Radio Supported.	An additional 4 more radios on slave module for a total of 8.
Frequency Bands Supported.	Support 2.4G, 5.8G and 4.9G Atheros based radios cards.
Backhaul Capacity	22 Mbps TCP/IP, 44 Mbps TCP/IP in Turbo mode.
Bandwidth Degradation	No degradation per hop. Validated by USAF Tests
Latency between hop	Less than 1 ms per hop. Validated by USAF Tests.
Security/Encryption?	Yes. Support both WEP and WPA/AES (e.g. with temporal keys).
Secure Backhaul Traffic?	Yes. 128 Bit WPA/AES encryption (e.g. with temporal keys).
Priority Traffic (QoS)?	Yes. Up to 4 IEEE 802.11e compliant categories supported.
Multiple VLANs Supported?	Yes.
Multiple SSIDs Supported?	Yes.
Hidden SSID possible?	Yes. SSID beaconing may be muted through the NMS.
Bandwidth control?	Yes. Selectable based on settings available for the radio card.
Transmit Power Control?	Yes. Slider scale user settable from the NMS.
Adjustable ACK timing for long range?	Yes. Range: 50 us - 500 us, for each radio.
Auto Channel Management?	Yes. Manual overrides/channel exclusions also possible.
Multi-country support?	Yes. Country and channel selection user-settable from NMS.
Module is FCC Compliant?	Yes.
Module is Field upgradeable?	Yes.

Modular Mesh™ Framework



The MD4000 Modular Mesh™ products supports up to 4 radios in a single enclosure. Slots 0, 1 are reserved for uplink and downlink radios operating on non-interfering channels but in the same frequency band. They are therefore either both 2.4G or both 5.8G radios. Slot 2 houses for an 2.4G AP radio for client connectivity. 2.4G radios can be set to b. b and g or g only modes. Slot 3 can house additional downlinks, AP radio or scanner for mobile mesh modules.

2.4 GHZ Backhaul Products	
MD4220-BBxx	2-Radio module with 2.4G uplink and downlink Structured Mesh Backhaul (BH). Downlink also acts as AP.
MD4320-BBBx	3-Radio module 2.4G sectored BH and 2.4G AP radio in 3rd slot. AP client connectivity settable to b, g, b and g.
MD4325-BBxB	3-Radio mobile mesh module 2.4G BH, Downlink provides AP service also. 2.4G Mobility Scanner in 4th slot

5.8 GHZ Backhaul Products	
MD4250-AAxx	2-Radio module with 5.8G uplink and downlink Structured Mesh Backhaul (BH), slots 0, 1.
MD4350-AABx	3-Radio module 5.8G BH and 2.4G AP radio in slot 2. AP client connectivity settable to b, g, b and g.
MD4455-AABA	4-Radio mobile mesh module 5.8G BH and 2.4G AP radio in slot 2. 5.8G Mobility Scanner in slot 3.
MD4452-AABA	4-Radio module 5.8G BH and 2.4G AP radio in slot 2. Second 5.8G Backhaul downlink in slot 3.
MD4458-AABB	4-Radio module 5.8G BH and two 2.4G AP radios in slot 2, 3. AP client connectivity settable to b, g, b and g.

Notes:
1. 2.4G downlink and AP radios may be set through the NMS to accept b, g or b and g clients.
2. 5.8G downlink radios may be set through the NMS to accept 11a clients
3. Radio characteristics e.g. ACK timing, power levels, throughput level etc are settable on a per radio basis

2953 Bunker Hill Lane, Santa Clara, CA 95054 Web: www.meshdynamics.com Phone: (408) 373 - 7700 Fax: (408) 516-8987

Figure D-16: Structured Mesh Product Family Features from MeshDynamics

SILICON LABORATORIES

ZigBee-2.4-DK

2.4 GHz ZigBee™ Development Kit User's Guide

1. Kit Contents

The 2.4 GHz ZigBee™ Development Kit contains the following items, shown in Figure 1.

- 2.4 GHz 802.15.4/ZigBee Target Boards (6)
- Antennas (6)
- 9 V batteries (6)
- 2.4 GHz ZigBee Development Kit User's Guide (this document)
- Silicon Laboratories Development Kit IDE and Product Information CD-ROM. CD content includes the following:
  - Silicon Laboratories Integrated Development Environment (IDE)
  - Keil Software 8051 Development Tools (evaluation assembler, linker and C compiler)
  - ZigBee Application Programming Interface (API) library
  - Source code examples and register definition files
  - 2.4 GHz ZigBee Demonstration Software
  - Documentation
- AC to DC power adapter
- USB debug adapter (USB to debug interface)
- USB cables (2)

Figure D-17: 2.4 GHz ZigBee Development Kit from Silabs

		IP-Link 1121-3033	IP-Link 1122-3033	IP-Link 1220-2033	IP-Link 1221-2033	IP-Link 1222-2033	IP-Link 1220-2133 INCL. PA	IP-Link 1221-2133 INCL. PA
NETWORKING	IP-Net	S	S	S	S	S	S	S
	ZigBee Library	O	N/A	S	O	N/A	O	O
	FFD	S	S	S	S	S	S	S
	RFD	S	S	S	S	S	S	S
	802.15.4	S	S	S	S	S	S	S
	Security ✢	S	S	S	S	S	S	S
MICROCONTROLLER	Version	F133	F410	F121	F133	F410	F121	F133
	FlashROM	64KB	32KB	128KB	64KB	32KB	128KB	64KB
	RAM	8KB	2KB	8KB	8KB	2KB	8KB	8KB
RF	Frequency	915MHz	915MHz	2.4GHz	2.4GHz	2.4GHz	2.4GHz	2.4GHz
	Max data rate	40Kbps	40Kbps	250Kbps	250Kbps	250Kbps	250Kbps	250Kbps
	Receive sensitivity	-97dBm	-97dBm	-94dBm	-94dBm	-94dBm	-94dBm	-94dBm
	Transmit range	200m LOS	200m LOS	150m LOS	150m LOS	150m LOS	400m LOS	400m LOS
	RF channels	10 (2MHz)	10 (2MHz)	16 (5MHz)	16 (5MHz)	16 (5MHz)	16 (5MHz)	16 (5MHz)
	Transmit power	-21 to 0dBm	-21 to 0dBm	-24 to 0dBm	-24 to 0dBm	-24 to 0dBm	-9 to15dBm	-9 to15dBm
	Data encryption ✢	128-bit AES	128-bit AES	128-bit AES	128-bit AES	128-bit AES	128-bit AES	128-bit AES
	Antenna	Chip	Chip	Chip	Chip	Chip	Chip	Chip
	Certification	FCC Part 15, CE	FCC Part 15, CE	FCC Part 15, CE	FCC Part 15, CE	FCC Part 15, CE	FCC Part 15, CE	FCC Part 15, CE
POWER CONSUMPTION	Transmit	55mA	55mA	55mA	55mA	55mA	100mA	100mA
	Receive	55mA	55mA	55mA	55mA	55mA	100mA	100mA
	Sleep	25uA	25uA	25uA	25uA	25uA	25uA	25uA
INPUT / OUTPUT	Physical pins	51	51	62	62	62	70	70
	Serial	2 RS232, JTAG	RS232, SMB, JTAG	2 RS232, JTAG	RS232, SMB, JTAG	RS232, JTAG, C2	2 RS232, JTAG,	RS232, JTAG
	A/D	5 (10-bit) & 1 Comparator	10-bit & 2 Comparators	3 (12-bit) & 2 Comparators	3 (12-bit) & 2 Comparators	10-bit & 2 Comparators	3 (12-bit)	3 (12-bit)
	D/A		2 (12-bit)	2 (12-bit)		2 (12-bit)	2 (12-bit)	
PHYSICAL	Size (W x H x D)							
	Inches	1.2 x 1.2 x 0.2	1.2 x 1.2 x 0.2	1.6 x 0.7 x 0.2	1.6 x 0.7 x 0.2	1.6 x 0.7 x 0.2	1.8 x 0.7 x 0.2	1.8 x 0.7 x 0.2
	Millimeters	30 x 30 x 4	30 x 30 x 4	41 x 19 x 4	41 x 19 x 4	41 x 19 x 4	46 x 19 x 4	46 x19 x 4
	Operating temp	-20°C to +70°C	-20°C to +70°C	-20°C to +70°C	-20°C to +70°C	-20°C to +70°C	-20°C to +70°C	-20°C to +70°C
	Humidity	10% - 90%	10% - 90%	10% - 90%	10% - 90%	10% - 90%	10% - 90%	10% - 90%

S: Standard O: Option N/A: Not Available
✢ Optional for US-based Customer Only

Figure D-18: ZigBee Family features from Helicomm

COMPATIBILITY / RANGE CHART

Part Number	Model Type	Antenna	Range / Fade Margin
M900S-AP	Access Point w/ internal & external antennas	Internal, 10 dBi, External	6 miles NLOS* / 10 dB
M900S-SU	Subscriber Unit w/ internal & external antennas	Internal, 10 dBi, External	Up to 20 miles / 18 dB
M900S-SU-EXT	Subscriber Unit Connectorized	External only	Up to 20 miles / 18 dB

* Non-line-of-sight performance with internal antenna - may vary due to leaf density, moisture content, and other environmental factors.

RADIO PARAMETERS	
Frequency of Operation	902 - 928 MHz
Channels	4 non-overlapping, user changeable
Channel Spacing	6 MHz, user changeable
RF Power Output	+26 dBm Max Setting -4 dBm Min Setting
Modulation Format	Direct Sequence Spread Spectrum (DSSS)
Certification / Compliance	FCC Part 15.247
Receiver Sensitivity (BER 10^{-6})	-90 dBm typical
DATA AND OPERATIONAL PARAMETERS	
Access Method	TDD with SmartPolling™
User Data Throughput	3 Mbps
Upstream/Downstream Throughput	Dynamic, automatically adjusts to suit demand
Bandwidth Control	CIR and MIR upstream/downstream control by AP
Maximum Number SUs per AP	126
Auto Repeat Request	Continuous ARQ with Selective Repeat
Security	Trango proprietary authentication method, based on MAC address and alphanumeric base ID; over-the-air data scrambling.
Configuration & Management	Telnet, SNMP, TFTP, HTTP
ANTENNA PARAMETERS	
Internal Antenna (AP and SU)	Integrated 10 dBi 60° X 60° patch dual polarized (HPOL/VPOL) (Not supplied in -EXT model)
*Omni Antenna** (Optional)*	8.5 dBi 360° X 10° (VPOL) - Comtelco Part # BS915XL7** (Requires N-SMA RP adapter)
*Yagi Antenna*** (Optional)*	15 dBi 30° X 30° (VPOL or HPOL) - Cushcraft part # PC9013N*** (Requires N-SMA RP adapter)
POWER PARAMETERS	
Power Method	Power over Ethernet (PoE Injector JBox included)
Voltage Input	24 VDC
Standard Power Supply	120VAC to 24VDC
PoE Cat-5 Max Cable Length	300 feet on 24 AWG STP Cat-5 cable
PHYSICAL AND ENVIRONMENTAL	
Ethernet Interface	RJ45, 10/100BaseT, auto sense, auto negotiate
Antenna Connector	SMA reverse polarity
Reset Button	Resets unit to factory default settings
Radio Enclosure	All-weather, powder coated, cast aluminum with polycarbonate radome
Temperature Range	-40° to 60° C (-40° to 140° F)
Radio Weight	4 lbs.
Radio Dimensions	12.5" x 8" x 2.75"
Standard Mounting Hardware	2 U-Brackets, all-thread, nuts and washers (for pole mount)
Shipping Weight	10 lbs. (without external antennas)
User Interfaces	RJ45 (shielded)

** Available from Comtelco (www.comtelcoantennas.com) and Comtelco distributors
*** Available from Cushcraft (www.cushcraft.com) and Cushcraft distributors

Features and specifications are typical and subject to change without notice.

Figure D-19: 900MS Specification from Trango Broadband

Specification	Canopy System Range
Frequency Band Ranges	902 to 928 MHz (ISM)
Access Method	TDD/TDMA
Signaling Rate	3.3 Mbps
Modulation Type	High-index 2-level FSK (Frequency Shift Keying) (Optimized for interference rejection)
Carrier to Interference (C/I)	Less than 3 dB nominal
Receiver Sensitivity	-90 dBm typical
Operating Range	Up to 40 miles (64 km) Line-of Sight Increased foliage penetration Non Line-of-Sight
Transmitter Power	Up to 0.63 W (28 dBm) (when the antenna gain is entered as 8 dBi in the user interface)
Effective Isotropic Radiated Power (EIRP)	Up to 4 W (36 dBm) (when the antenna gain is entered in the user interface consistent with the actual attached antenna, for example, set to 10 dBi for a 10 dBi antenna)
Subscriber Flat Panel Antenna	10 dBi gain. Vertically or horizontally polarized (changed by physical position), approximately 60° horizontal x 60° vertical 3 dB beam width. Horizontal polarization is recommended, since most cellular and paging systems (which use adjacent frequency bands) use vertically polarized antennas.
DC Power (measured at DC converter)	For both AP and SM: Typically 0.3 A @ 24 VDC (7.2 watts) For AP: May reach 0.35 A @ 24 VDC (8.4 watts) under heavy load (high transmit ratio (set by downlink percentage), high packet throughput)
Ethernet, GPS sync, and GPS coax cables	The use of cables that are rated for the operation temperature of the product and that conform to UV light protection specifications is mandatory. The use of shielded cables is strongly recommended, especially on infrastructure (APs).
Interface	10/100BaseT, half/full duplex. Rate auto-negotiated (802.3 compliant).
Protocols Used	IPv4, UDP, TCP, ICMP, Telnet, HTTP, FTP, SNMP, DES. Optionally, AES.
Protocols Supported	Switched Layer 2 Transport with support for all common Ethernet protocols, such as IPv6, NetBIOS, DHCP, IPX.
Software Upgrade Path	Remotely downloaded into flash memory

Figure D-20: Canopy 900MHz AP and SM Specifications

D.7 Sources

- MeshDynamics (http://www.meshdynamics.com)
- Helicomm (http://www.Helicomm.com)
- Trangobroadband (http://www.trangobroadband.com)
- Silicon Laboratory (http://www.silabs.com)
- Motorola Canopy (http://www.motorola.com/canopy)

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