ADOT

FUZZY VARIABLE SPEED LIMIT DEVICE MODIFICATION AND TESTING - PHASE II

Final Report 466(2)

Prepared by:
John Placer
Department of Computer Science and Engineering
Northern Arizona University – Box 15600
Flagstaff, Arizona 86011

July 2001

Prepared for:
Arizona Department of Transportation
206 S. 17th Avenue
Phoenix Arizona 85007
in cooperation with
The University of Arizona ATLAS Center
Systems & Industrial Engineering Department
Tucson, Arizona 85721

Technical Report Documentation Page

1. Report No. AZ-466(2)	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle FUZZY VARIABLE SPEED LIMIT DEVICE MODIFICATION AND TESTING PROJECT, PHASE II		5. Report Date: July 2001
		6. Performing Organization Code
7. Author: Dr. John Placer		8. Performing Organization Report No.
9. Performing Organization Name and Address Department of Computer Science and Engineering Northern Arizona University – Box 15600 Flagstaff, Arizona 86011		10. Work Unit No.
		11. Contract or Grant No.: ADOT JPA 98-156 Project No. H5170 10X
12. Sponsoring Agency Name and Address Arizona Department of Transportation - Flagstaff District, and, the Center for Excellence in Advanced Traffic and Logistics Algorithms and Software (ATLAS) at the University of Arizona Project Manager: Dr. Pitu Mirchandani		1. Type of Report & Period Covered: Final: November 1999 to July 2001
		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared in cooperation with the U.S. Department of Transportation, Federal Highway Administration. Performed with additional direct support from the Arizona Department of Transportation and Surface Systems Inc under ADOT JPA 99-66.

16. Abstract

In a previous project, Northern Arizona University (NAU) and the Arizona Department of Transportation (ADOT) designed and implemented the prototype of a variable speed limit (VSL) system for rural highways. The VSL system implements a real-time fuzzy control algorithm that utilizes information provided by Road Weather Information Stations (RWIS). This system continuously displays highway speeds appropriate to the atmospheric and road surface conditions at locations of interest along the I-40 corridor in rural northern Arizona. At the time of this initial project, none of the RWIS sites along I-40 were providing the complete data set needed for full utilization of the fuzzy control algorithm. A main objective of the current project described in this document was to fully upgrade an RWIS site on I-40 so that it could be used as a test site to monitor the complete data set of atmospheric and road surface conditions needed by the fuzzy control algorithm. A second objective was to enhance this upgraded site so that it would supply traffic flow data. The remaining objectives of the project were to collect atmospheric, road surface, and traffic data over a wide variety of weather conditions and to use this data to assess the reliability and appropriateness of the speed limits produced by the VSL system.

The first two objectives of implementing a full RWIS site upgrade and enhancement were achieved and are discussed in detail in this report. However, reconfiguring software and hardware for the project, installing power and telephone lines, and installing and calibrating sensor and traffic detection systems consumed most of the time allotted to the project. Collection of project data did not begin until July of 2001, just as this report was being written. Nonetheless, an interactive web site has been developed which employs software tools that will be used to analyze and compare the RWIS data and the traffic flow data when it is collected. The web site and its software tools are discussed in this report.

17. Key Words Variable speed limits, fuzzy logic, Road Weather Information Systems		18. Distribution Statement Document is available to the U.S. public through the National Technical Information Service, Springfield, Virginia 22161		23. Registrant's Seal
19. Security Classification Unclassified	20. Security Classification Unclassified	21. No. of Pages 23	22. Price	

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yards	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
	NOTE: Volumes greater than 1000L shall be shown in m^3.			
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000lb)	0.907	megagrams (or "metric ton")	mg (or "t")
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5(F-32)/9 or (F-32)/1.8	Celsius temperature	°C
		ILLUMINATION		
fc	foot candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE AND PRESSURE OR STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.315	cubic feet	ft^3
m^3	cubic meters	1.308	cubic yards	yd^3
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (or "metric ton")	1.102	short tons (2000lb)	T
		TEMPERATURE (exact)		
°C	Celsius temperature	1.8C + 32	Fahrenheit temperature	°F
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m^2	candela/m^2	0.2919	foot-Lamberts	fl
		FORCE AND PRESSURE OR STRESS		
N	newtons	0.225	poundforce	lbf
kPa	kilopascals	0.145	poundforce per square inch	lbf/in^2

SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380

Preceding Page Blank

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF ACRONYMS

ADOT	Arizona Department of Transportation
ATLAS	Advanced Traffic and Logistics Algorithms and Software
ATRC	Arizona Transportation Research Center
FVSLDMT	Fuzzy Variable Speed Limit Device Modification and Testing
GUI	Graphical User Interface
DPS	Department of Public Safety
JDBC	Java Database Connectivity
RPU	Remote Processing Unit
RWIS	Road Weather Information System
SSI	Surface Systems Inc.
TAC	Technical Advisory Committee
VSL	Variable Speed Limit
WWW	World Wide Web

1. INTRODUCTION

1.1 BACKGROUND

There are various management methods that can be employed to regulate traffic speeds. These include traffic calming techniques, road narrowing, the use of speed governors on heavy vehicles, various types of variable speed limit systems, and many others [1,2,3]. The particular speed management technique utilized must be matched to the specific transportation environment being served. Variable speed limit systems are now being used in rural locations where severe atmospheric and road surface conditions create a variety of transportation hazards [4,5]. These hazards can be acute on rural highways where static speed limit signs often post high speeds and emergency services may be distant. Normal posted speed limits are based on ideal conditions for the roadway geometry and surface. Variable speed limit systems can be used to alleviate the dangers of this type of environment by displaying to motorists' prudent maximum speed limits, which reflect the prevailing, atmospheric and road surface conditions.

In 1998, Northern Arizona University (NAU) and the Arizona Department of Transportation (ADOT) designed and implemented the prototype of a variable speed limit (VSL) system for rural highways that utilizes information provided by a typical Road Weather Information Station (RWIS).[6,7,8] This joint project produced a fuzzy logic control system that continuously displays highway speeds appropriate to the atmospheric and road surface conditions at locations of interest along the I-40 corridor in rural northern Arizona. Fuzzy logic [9,10] is a system of mathematics that allows the vagueness of linguistic concepts to be represented by sets with imprecise boundaries. In fuzzy logic, the membership of an element in a set is not all or nothing but can assume values between these two extremes. Working with degrees of membership allows the imprecision inherent in natural language to be represented and it supports a form of approximate reasoning that attempts to model the way human beings reason. Therefore, the fuzzy logic controller for the VSL system developed by NAU and ADOT uses a reasoning process similar to that of a human expert to determine a speed limit at a given location that is appropriate to the prevailing atmospheric and road surface conditions at that location.

1.2 PROJECT SCOPE

During the development of the fuzzy logic algorithm for the VSL system created by NAU and ADOT, none of the RWIS sites along I-40 in Arizona were providing the complete data set needed for full utilization of that algorithm. The primary objective of the current project described in this document was to fully upgrade an RWIS site on I-40 so that it could be used as a test site to monitor the complete data set of atmospheric and road surface conditions that can be utilized by the fuzzy control algorithm. A second objective was to enhance this upgraded site so that it would also supply traffic flow data. The remaining objectives of the project were to collect atmospheric, road surface, and traffic data over a wide variety of weather conditions and to use this data to assess the reliability and appropriateness of the speed limits produced by the VSL system.

This report first discusses the upgrades and enhancements completed for the selected RWIS test site on I-40. This includes a discussion of sensor upgrades and additions at the RWIS site, new power sources made available to the site, and computer hardware and software improvements that support the RWIS enhancements. Following this is a discussion of the project software that was created in order to prepare for the analysis of the RWIS and traffic flow data that is being collected. A final section of conclusions and recommendations complete this report.

1.3 PROJECT ADMINISTRATION AND OVERSIGHT

This project was funded and administered by the Center for Excellence in Advanced Traffic and Logistics Algorithms and Software (ATLAS) at the University of Arizona. A Technical Advisory Committee (TAC) composed of members from a number of interested agencies was responsible for oversight of the project. The membership of the TAC during the project is given below:

NAME	AGENCY
Pitu Mirchandani	ATLAS – University of Arizona
Manny Agah	ADOT - Transportation Technology Group
Jennifer Brown	Federal Highway Administration
John Harper	ADOT - Flagstaff District
Dan Wells (Lt.)	Arizona DPS District Two – Flagstaff
Mike Campbell	National Weather Service – Flagstaff
Mike Manthey	ADOT - Traffic Engineering Group
Robert Wilbanks	ADOT - Holbrook District
William Wang	ADOT - Kingman District
Steve Owen	ADOT – ATRC

1.4 ACKNOWLEDGEMENTS

I wish to express my thanks to the following persons at ADOT:

- John Harper, Flagstaff District, for always being a supportive partner in this project.
- Flagstaff District Engineer Don Dorman for the financial support he made available to the project.
- Russ Rowen, Information Technology Group, Flagstaff District, for supplying many of the details about the RWIS computer software and hardware upgrades.
- Steven Hill, Intermodal Transportation Division, Flagstaff District, for supplying much of the work and the details related to the installation of a power line at the test site.
- Steve Owen, project manager for the Arizona Transportation Research Center, for his vigilance and help in the project.

In addition, I wish to express my thanks to the following persons:

- John Hansen of Surface Systems, Inc. (SSI) for helping to ensure that enhancements, upgrades, and calibrations at the project test site were completed. Thank you also to SSI for equipment and software given to the project.

- My student assistants, Karim Nassar and Janice Wildrick, for their help in many different aspects of the project.

- Special thanks to all of the members of the project TAC for their ongoing assistance.

2. ENHANCEMENT OF THE RWIS TEST SITE

The RWIS site called Riordan, five miles west of Flagstaff, was selected as the project test site. (See Figure 1.) This site was modified so that it could supply traffic data as well as all of the atmospheric and road surface data required by the full VSL prototype system developed by NAU and ADOT in a previous project.[8] This included upgrading existing sensors at the site, installing new types of sensors, installing new computer software and hardware, installing power and telephone lines, and calibration of sensors. The details of these upgrades and additions are given in the following sections 2.1 through 2.3. Acquisition, installation, and integration of all this equipment encountered numerous delays and was not completed until the final weeks of the project. This meant that RWIS and traffic data collection did not begin until the allotted project time was nearly complete.

Figure 1. The Riordan RWIS Test Site

2.1 RECONSIDERATION OF COMPUTER SOFTWARE AND HARDWARE NEEDS

When the project first began one of the project partners, Surface Systems Inc. (SSI), advised its NAU and ADOT partners that significant improvements had been made in the computer software available for the RWIS test site. It was suggested that the list of computer software and hardware to be acquired as detailed in the original project proposal should be modified to include the latest software (and its associated hardware) available through SSI. This software, the ScanWeb package, provided a web-based monitoring system that could be expanded to integrate RWIS data collected by multiple vendors. The computer software and hardware to be acquired for the project was renegotiated because it was determined by ADOT that this new software package did represent a significant improvement over the software originally proposed. The money awarded for the project was already determined and fixed but the new software required additional funds. To accommodate for this, SSI increased its cost share to the project and provided the new software and licenses needed to bring ScanWeb into the project.

Although this process of renegotiation took several weeks to work out, the resulting software was clearly superior to what was originally planned for the project. Prior to the ScanWeb package, RWIS data could only be displayed to ADOT personnel on one PC in each district. These PCs used proprietary software and dial-up connections to access the RWIS information. The cost for the old system was high at about $3000 per client license. ScanWeb made the RWIS information available to everyone on the ADOT intranet and it made the information potentially available to Internet applications. With about sixteen maintenance personnel potentially needing to access the RWIS information, an equivalent upgrade of the old system would have run about $48,000. The ScanWeb package was supplied as part of the cost share contribution by SSI and is valued at $10,000.

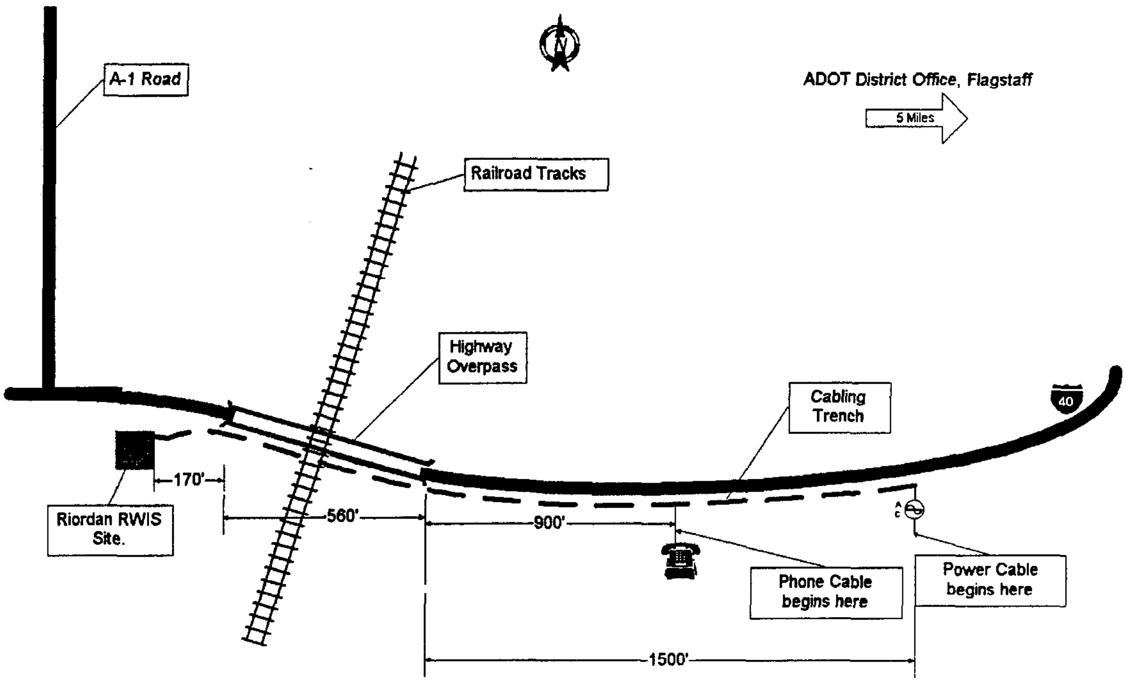

Figure 2. Diagram of Telephone and Power Lines Installed at the RWIS Test Site

2.2 POWER AND TELEPHONE LINE INSTALLATIONS

ADOT and SSI upgraded the battery capabilities of the Riordan test site for backup operations and in order to provide seven-day autonomy for data at the site. In the event of a power loss, battery backup will allow the site to continue in full operation for more than a day. If power is not restored beyond this time, all data at the RWIS site will be stored safely for seven days from the time RWIS operations failed due to the loss of battery backup.

ADOT brought a power line and a telephone line into the Riordan site. (See Figure 2.) This was a difficult and time consuming process, which involved a number of activities as outlined below:

1) Conduct meetings with Arizona Public Service (power company) and Qwest (telephone company).
2) Prepare an installation estimate.
3) Dig a trench accommodating 1500 feet of power line and 900 feet of telephone lines. This was a challenge because of the difficult terrain in which the trench had to be created.
4) Install 560 feet of rigid metal conduit over the Riordan Bridge in order to bring the power and telephone lines into the Riordan RWIS site. (See Figure 3.)
5) Splice electrical cables and install a 480-volt breaker from the lighting service power source.
6) Install a 480-volt breaker, a step-down transformer, a battery charger, a solar controller and a 12-volt, 210 AH battery at the RWIS site.

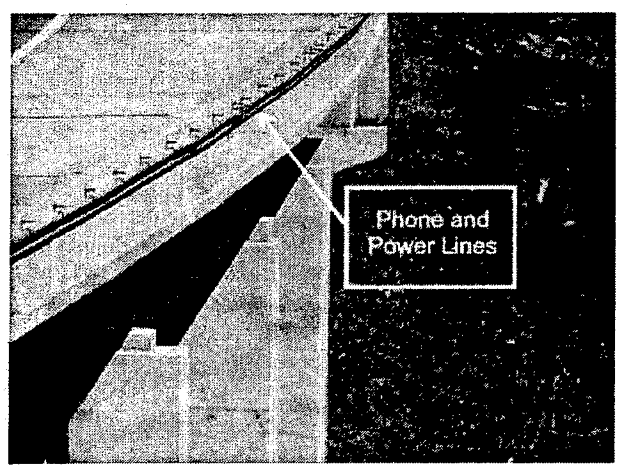

Figure 3: New Telephone and Power Lines Installed on Riordan Bridge

Incurring a number of unavoidable delays, the above activities took several months to complete. Contributing to these delays were the need to order equipment, the need to have custom equipment manufactured, re-scheduling road closures and work teams to avoid inclement weather, and difficulties encountered in digging the trench through rocky terrain.

All partners in the project (ADOT, SSI, and NAU) felt that the advantages offered by bringing power and telephone lines into the RWIS test site justified the potential delays in the project schedule. The existence of power and telephone lines at the test site assures greater reliability of the data communications system during severe weather conditions and it brings a significant increase in bandwidth to the communications system. The old communications system collected data at 9600 baud via a wireless system owned by the Department of Public Safety (DPS). The new communications system sends the RWIS and traffic data directly to the district office via telephone lines and modems. (See Figure 4.) The increase in bandwidth also allows real-time camera images of the site to be utilized.

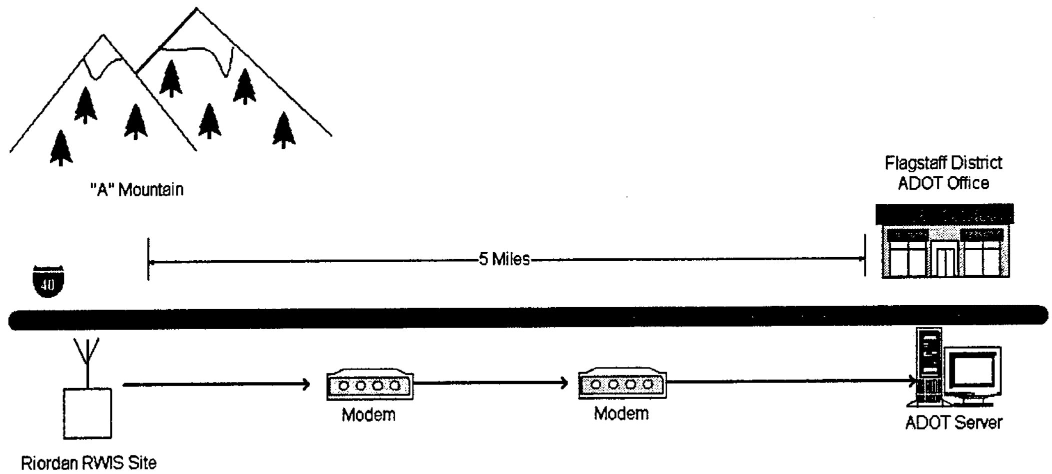

Figure 4. Communications at the RWIS Test Site

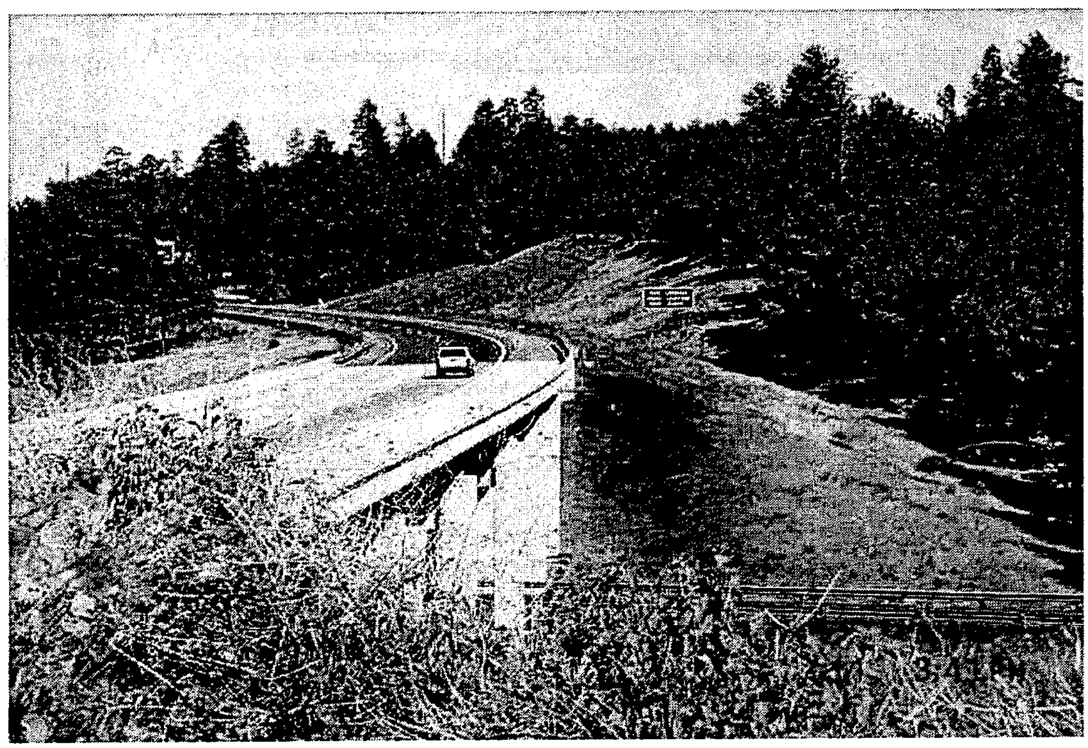

Figure 5. A View of Riordan Bridge Looking East from the RWIS site.

2.3 UPGRADES AND ADDITIONS OF SENSORS AND COMMUNICATIONS CAPABILITIES

Numerous sensor upgrades and additions were performed at the RWIS test site. In addition to this, improvements in communications capabilities were made at the RWIS site and at the district office. This included the following:

1) Software and hardware upgrades were implemented to improve the communications capabilities at the RWIS site.
2) Software and software licenses were acquired for the following:
    a. the surface sensors.
    b. the sub-surface sensors.
    c. the precipitation sensor.
    d. the wind speed and wind direction sensors.
    e. the relative humidity and air temperature sensors.
    f. the visibility sensor.
3) A Belfort Falcon visibility sensor was added to the site.
4) A Remote Traffic Microwave Sensor was added to the site.

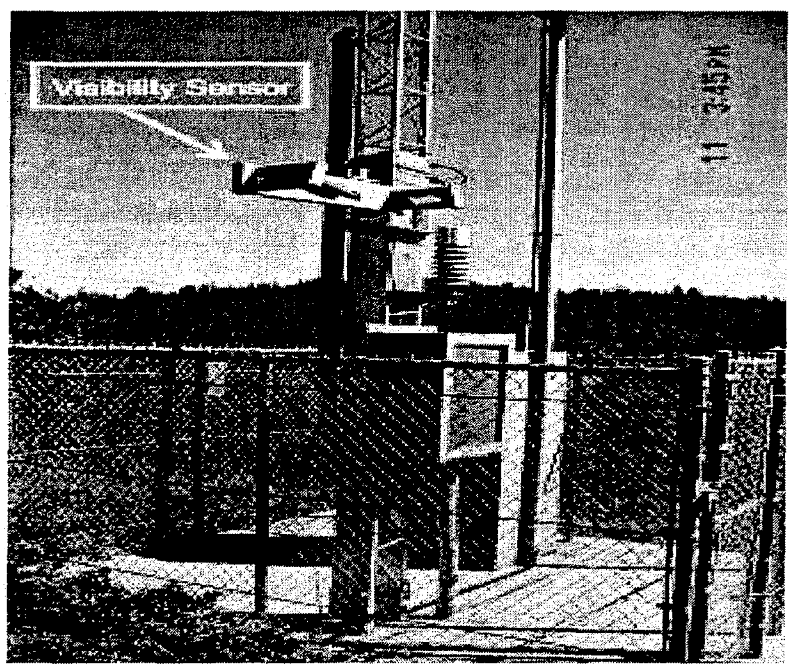

Figure 6. The Belfort Falcon Visibility Sensor at the RWIS Test Site

3. DEVELOPMENT OF DATA ANALYSIS TOOLS

Reconfiguring software and hardware for the project, installing power and telephone lines, and installing and calibrating the sensor and traffic detection systems were not completed until the last weeks of the project. Consequently, collection of atmospheric, road surface, and traffic data for the project did not begin until July of 2001. This means that data was not collected during the winter months when the most extreme weather conditions exist and, consequently, the desired data analysis could not be completed. Nonetheless, there was much that could be done in preparation for the required data analysis. An interactive addition to the variable speed limit project web site was constructed that will allow project participants to perform different types of analysis on the data as it is collected. The following sections 3.1 and 3.2 discuss this web site.

3.1 THE PROJECT WEB SITE

A project web site was constructed when the current project first began. This site is located at http://www.cse.nau/edu/~jpl/VSLProject. The web site includes links for reviewing the original project proposal, finding out when the next TAC meeting is scheduled, displaying presentations made at the project TAC meetings, viewing project progress reports, and reviewing the project milestones. In addition to this, the web site contains a link to a simulator that displays a prudent speed limit when the user inputs atmospheric and road surface information. Figure 7 gives one view of the project web site as the project simulator is being used.

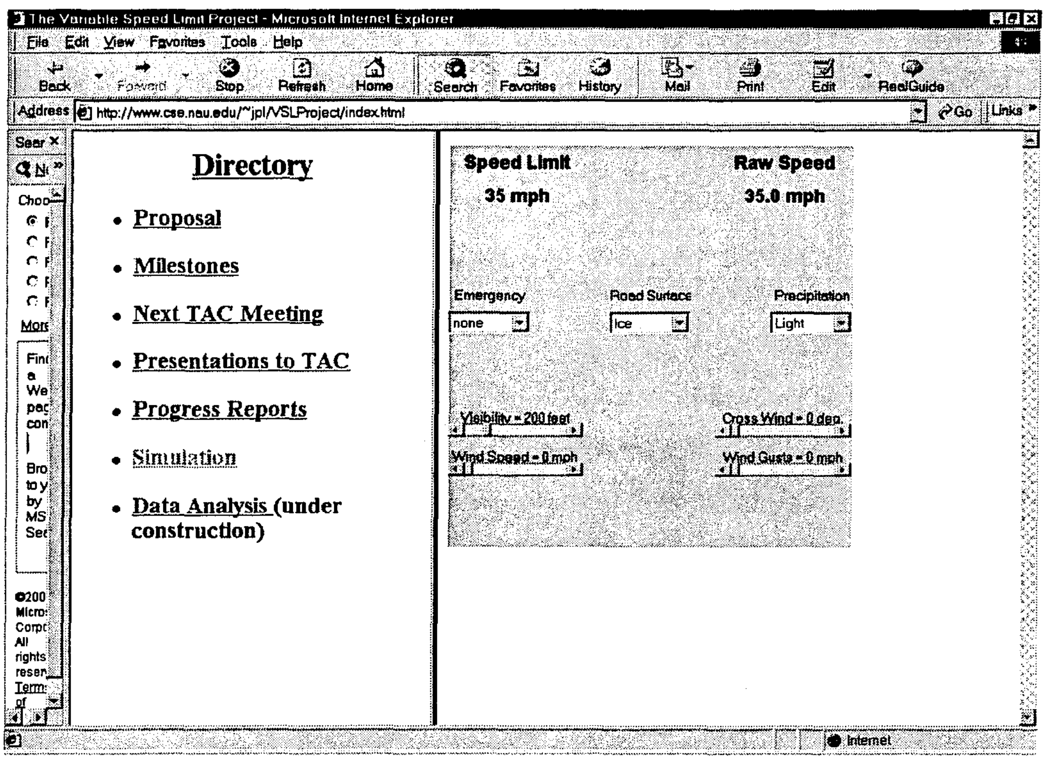

Figure 7. A View of the Project Web Site Simulator

In addition to the links described above, a new section was added that will allow different types of analysis to be performed on the project data as it is collected. This section is accessed through the link shown in Figure 7 in the left frame entitled *Data Analysis*. The data analysis section is implemented as a three-tier system that consists of a web portal front end that connects to Java servlets on one of the NAU College of Engineering web servers. The servlets handle all requests for analysis and connect to a database server via the Java Database Connectivity (JDBC) package. Although the system is currently using a MYSQL database, the JDBC is largely independent of the particular database that is being used. This would allow a number of other databases to be used in the future (e.g. Oracle or Access) if that becomes necessary.

3.2 INITIAL MODES OF ANALYSIS THAT ARE SUPPORTED

Currently there are two graphical user interfaces (GUIs) that have been developed to allow users to specify the analysis they want performed on the RWIS and traffic detection data. The first GUI is shown in Figure 8. This interface allows users to select a set of atmospheric and road surface conditions of interest and it allows for specification of the period of time over which the analysis is to be conducted. Once these conditions are submitted, a Java servlet will search the project database for all instances when the specified conditions were in effect. The servlet will then provide a distribution of speeds, which compares the speed computed by the fuzzy control algorithm for the specified conditions with the actual distribution of traffic speeds when the specified conditions were in effect.

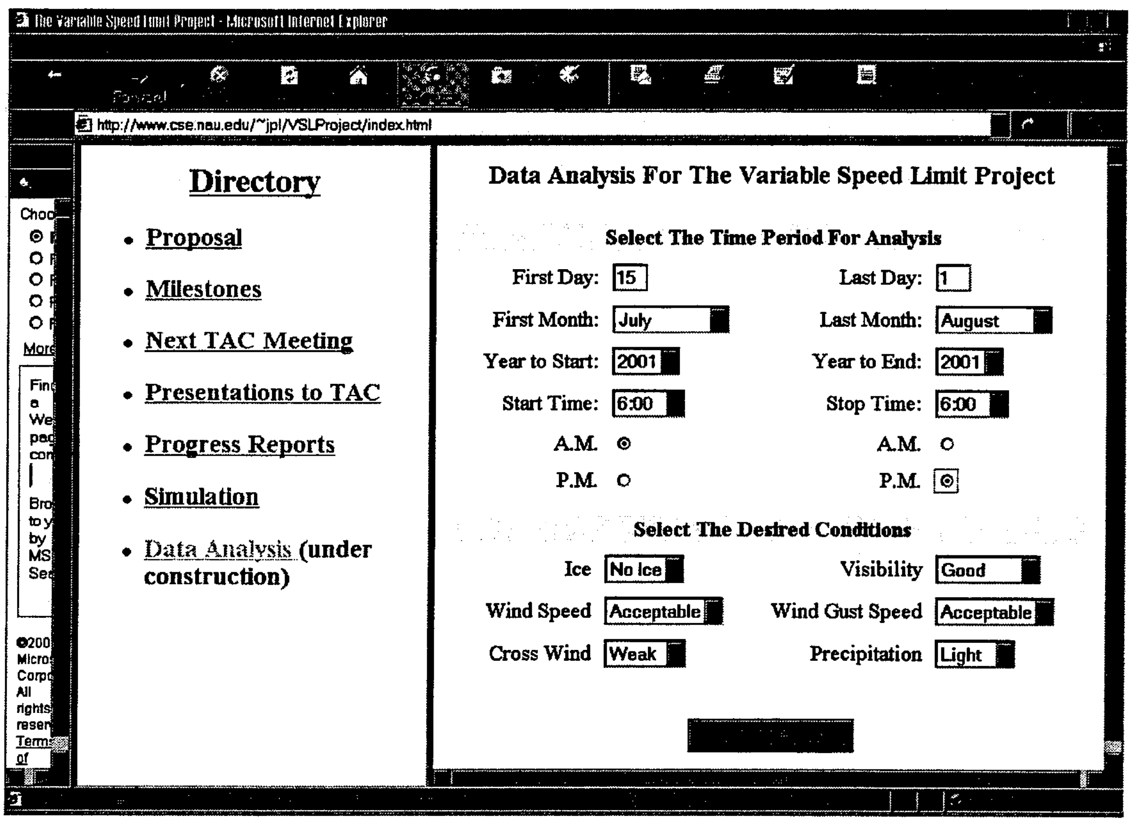

Figure 8. Selecting the Atmospheric and Road Surface Conditions for Analysis

The second GUI is shown in Figure 9. This interface allows users to select a speed limit that would be computed by the fuzzy algorithm and it allows for specification of the period of time over which the analysis is to be conducted. For example, if the speed 45 mph was selected, this would indicate an interest in all configurations of atmospheric and road surface conditions that resulted in the fuzzy algorithm computing a speed of 45 mph. Once a speed and time period are submitted, a Java servlet will search the project database for all configurations of conditions that resulted in the fuzzy control algorithm computing the specified speed. A servlet will provide a distribution of actual traffic flow data for the specific speed selected. The speed distribution provided would compare a speed computed by the fuzzy algorithm with the actual distribution of traffic speeds for all conditions over which the specified speed was in effect.

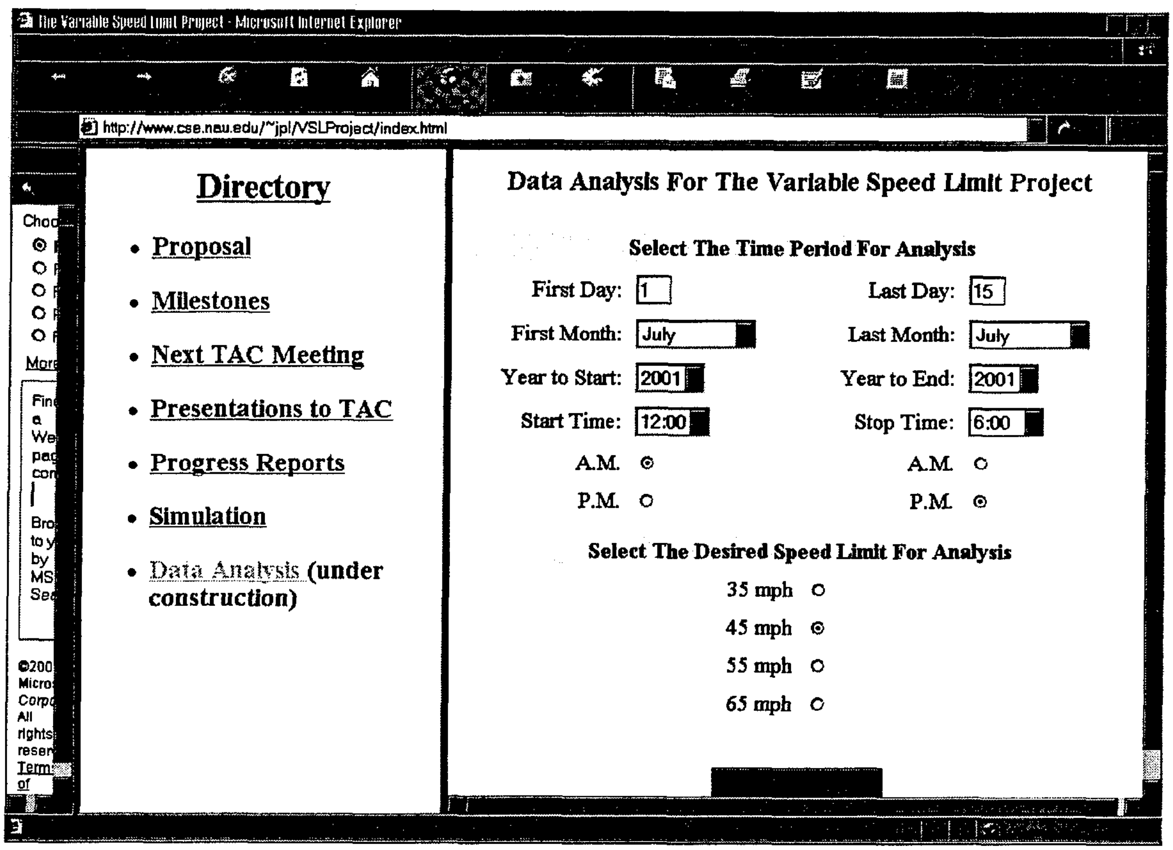

Figure 9. Selecting a Speed Limit For Analysis

4. CONCLUSIONS AND RECOMMENDATIONS

The three essential aspects of any speed management system are engineering, enforcement, and education. The engineering issues relate to the technical challenges that must be met in order to design and implement the system of interest. The educational issues relate to the efforts necessary to develop a common vision for all parties that might be affected by the new speed management system: the courts, law enforcement, department of transportation personnel, the motoring public, etc. The enforcement issues relate to the development of an effective and just law enforcement policy that can be used to help make the new speed management system a success.

4.1 RESULTS OF THE RESEARCH PROGRAM

We recommend that the work described in this report be considered in this tripartite context of engineering, education and enforcement. Furthermore, we recommend that the work just completed, the Fuzzy Variable Speed Limit Device Modification and Testing (FVSLDMT) Project, be thought of as Phase II of a larger four-phase project. The main objectives of the FVSLDMT Project were:

1.) To upgrade an RWIS test site on I-40 so that it generates all of the atmospheric and road surface data required by the fuzzy variable speed limit system created in Phase I of the project. [8]

2.) To add a traffic monitoring system to the RWIS test site so that the operation of the fuzzy variable speed limit system can be compared to the actual flow of traffic at the site.

3.) To collect the appropriate atmospheric, road surface, and traffic data over a wide variety of weather conditions.

4.) To use the collected data to analyze the operation of the fuzzy variable speed limit system across a wide variety of weather conditions.

- **Objective 1: To upgrade an RWIS test site on I-40 so that it generates all of the atmospheric and road surface data required by the fuzzy variable speed limit system created in Phase I of the project.**

  Objective 1 was completed. Telephone lines, a landline for power, and battery back-up equipment were successfully installed at the RWIS test site on I-40. In addition to this, all sensor upgrades and additions were successfully completed. This included installation of the following:

  1. Software and hardware upgrades were implemented to improve the communications capabilities at the site.

  2. Software and software licenses were acquired for the following:

     a. The surface sensors.

   b. The sub-surface sensors.

   c. The precipitation sensor.

   d. The wind speed and wind direction sensors.

   e. The relative humidity and air temperature sensors.

   f. The visibility sensor.

3. A Belfort Falcon visibility sensor was added to the site.

4. A Remote Traffic Microwave Sensor was added to the site.

- **Objective 2: To add a traffic monitoring system to the RWIS test site so that the operation of the fuzzy variable speed limit system could be compared to the actual flow of traffic at the site.**

  Objective 2 was completed. A Remote Traffic Microwave Sensor was installed and calibrated at the Riordan test site. This system is monitoring vehicle counts and average vehicle speeds on the Eastbound lanes at the RWIS site.

- **Objective 3: To collect the appropriate atmospheric, road surface, and traffic data over a wide variety of weather conditions.**

  Objective 3 was only partially completed. Reconfiguring software and hardware for the project, installing power and telephone lines, and installing and calibrating the sensor and traffic detection systems were not completed until the last weeks of the project. Consequently, collection of atmospheric, road surface, and traffic data for the project did not begin until July of 2001. This means that data was not collected during the winter months when the most extreme weather conditions exist.

- **Objective 4: To use the collected data to analyze the operation of the fuzzy variable speed limit system across a wide variety of weather conditions.**

  Objective 4 was only partially realized. Although the delay in data collection made it impossible to perform the desired data analysis, many of the software tools that will be used in that data analysis were developed. An interactive web site, which employs software tools that will be used to analyze and compare the RWIS data and the traffic flow data was developed.

Beyond the stated objectives of the project it should be mentioned that the ADOT district office in Flagstaff acquired, through this project, a significantly improved software system for monitoring their RWIS sites. This system allows the information provided by these RWIS sites to be displayed via the World Wide Web and it will allow the information at all sites, regardless of vendor, to be monitored in this way.

4.2 RECOMMENDATIONS FOR FUTURE RESEARCH

4.2.1 Phase III: Immediate Future Research

The engineering issues of a recommended Phase III of the VSL program would include long-term data collection during diverse weather conditions, and analysis of the fuzzy control system developed in Phase I. Comparing actual traffic flow data with the operation of the fuzzy algorithm would carry out this analysis. The RWIS site at Riordan is now fully functional and is sending the complete data set needed for analysis of the fuzzy algorithm to the ADOT district office in Flagstaff. The data is being archived and managed at the district office.

Another issue related to engineering would be to get potential vendors to consider new system designs for modular, low-cost variable speed limit systems and perhaps to work with one or more of these vendors in the development of these low-cost prototype VSL systems.

The educational issues to be engaged in Phase III would involve a formal analysis of the legal and liability issues related to the new speed management system. Essential to the future success of any variable speed limit system is for everyone concerned (courts, police, motoring public, etc.) to have a common understanding of the assumptions, expectations, and liabilities associated with that system. There are variable speed limit systems currently deployed in a number of locations both here in the United States and in other countries. The lessons learned and the procedures established in these other locations should be considered carefully. No public display of the variable speed limits would occur in Phase III because such a display must come only after the legal and liability analysis is complete.

Finally it would also be important in Phase III to begin a formal analysis of law enforcement techniques needed to support the new system. A number of enforcement issues must be addressed in order to know how best to make the design of a variable speed limit system compatible with a supportive law enforcement policy. Here again, studying the lessons learned and the successful procedures established in other states and countries, would be an important aspect of this effort to devise an effective and just set of law enforcement policies.

4.2.2 Phase IV: Long Term Future Research

In a recommended Phase IV of the VSL program, the engineering aspects would involve the implementation at limited sites of the new variable speed limit systems for general use. For some period of time, continuous monitoring of the systems would be needed in order to improve and refine them. Educational efforts would use the results of the legal and liability studies in Phase III to bring a common understanding of the relevant issues to the courts, the police, the Department of Transportation, the motoring public, and everyone else that might be affected by the new variable speed limit systems. Enforcement efforts in this fourth stage of the project would involve the continuous monitoring and evaluation of the appropriateness and effectiveness of the law enforcement policies that had been established in Phase III of the project.

APPENDIX

THE FUZZY VARIABLE SPEED LIMIT DEVICE PROJECT
(ATRC RESEARCH NOTES)
REPORT FHWA AZ98-466
AUGUST 1998

There are, of course, various management methods that can be employed to regulate traffic speeds. These include traffic calming techniques, road narrowing, the use of speed governors on heavy vehicles, various types of variable speed limit systems, and many others. The particular speed management technique utilized must be matched to the specific transportation environment being served. Variable speed limit systems are now beginning to be used in rural locations where severe atmospheric and road surface conditions create a variety of transportation hazards. These hazards can be acute on rural highways where static speed limit signs often post high speeds and emergency services may be distant. Variable speed limit systems can be used to alleviate the dangers of this type of environment by displaying to motorists prudent maximum speed limits which reflect the prevailing atmospheric and road surface conditions.

Background

The purpose of the Fuzzy Variable Speed Limit Device (FVSLD) Project was to demonstrate that fuzzy logic is well-suited to the design and implementation of a variable speed limit (VSL) system dedicated to speed management on rural highways. Fuzzy logic is a system of mathematics that allows the vagueness of linguistic concepts to be represented by sets with imprecise boundaries. In fuzzy logic, the membership of an element in a set is not always a matter of complete affirmation or total denial but can assume values between these two extremes. Working with degrees of membership allows the imprecision inherent in natural language to be represented and it supports a form of approximate reasoning that attempts to model the way human beings reason. Therefore, the purpose of a FVSLD would be to determine a speed limit at a given location that is appropriate to the prevailing atmospheric and road surface conditions using a reasoning process similar to that of a human expert.

The main objective of the project was to create a real-time fuzzy control system that could continuously display highway speeds that are appropriate to the atmospheric and road surface conditions that exist at any given time at locations of interest. The software that implements the control system was the main product of the project, although a micro-controller based hardware prototype of the final fuzzy control system was also to be created. The geographical area of concern for the project was the I-40 corridor in rural northern Arizona. This corridor passes through a variety of geographic locations that range from desert to mountainous terrain. As a final demonstration, the completed FVSLD Project software was to be used to remotely display, at the Arizona Department of Transportation (ADOT) district headquarters in Flagstaff, appropriate highway speeds for three target Road Weather Information System (RWIS) sites selected along the I-40 corridor. Information provided by each of these RWIS stations was to be monitored and an appropriate speed limit for each location was to be displayed. The sites selected were the RWIS stations located at Riordan, Pine Springs, and Ash Fork.

Methodology

Before a fuzzy algorithm can be developed it is necessary to determine the relevant input and output dimensions for the problem at hand. For the FVSLD Project, this was determined primarily through the acquisition of expert knowledge. Many of the Technical Advisory Committee (TAC) members of the FVSLD Project were experts in various aspects of road safety, atmospheric factors, or road surface conditions. TAC members from ADOT Flagstaff, the City of Flagstaff, the National Weather Service, and the Department of Public Safety were interviewed in order to determine which atmospheric and road surface conditions were essential to the determination of appropriate speed limits. Colleagues from the home institutions of TAC members who themselves were not officially members of the TAC often participated in the interviews that were conducted with official TAC members.

Through these interviews it was determined that the FVSLD system would have seven different types of inputs and two different types of outputs. The inputs that were selected are listed below:

- Road surface condition.
- Average wind speed.
- Wind gust speed.
- Visibility.
- Degree of cross wind.
- Precipitation intensity.
- Emergency.

The emergency input allowed an output speed limit to be set manually, overriding all RWIS data inputs.

The required system outputs are listed below:

- A prudent maximum speed limit.
- A display of the rules that are active for any given set of input values.

Displaying all active rules for a given input set supported the debugging and analysis of the fuzzy algorithm later in the design cycle. The intent was for the output display of active rules to be converted later into a simple message for a variable message board. This message would provide justifications for any reduction in speed that occurred.

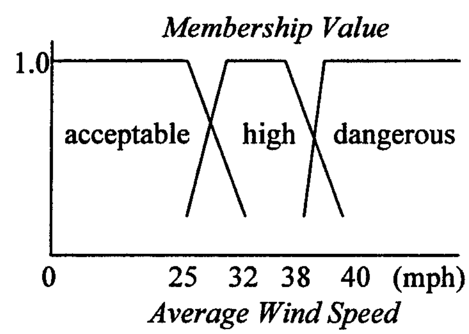

Figure 1. Average Wind Speed Partitions.

After the inputs and outputs of a fuzzy system are selected, they must be partitioned into appropriate conceptual categories. Each of these categories actually represents a fuzzy set on a given input or output domain. For the FVSLD Project, these categories were derived mostly from interviews with experts from the TAC. However, in some cases, the TAC experts recommended that reference materials be consulted in order to derive the bounds of various types of partitions. For example, reference materials were helpful in establishing conceptual categories for visibility and for wind speeds . An example of a set of partitions is given in Figure 1 which shows the conceptual partitions derived for the input dimension Average Wind Speed.

The conceptual partitions developed for the input and output dimensions are used to create a fuzzy rule set which determines the behavior of the fuzzy system being constructed. This fuzzy rule set is called the fuzzy algorithm for the system being developed. The fuzzy rule set codifies the relationships that exist among the various partitions of the input and output dimensions.

Project Software and Hardware

In order to support the testing and development of the fuzzy algorithm, a number of programs were created. These programs included the following:

- *An interactive simulator.* The simulator supported the development, refinement, and testing of the project's fuzzy rule set. It allowed the TAC members and the fuzzy engineering team to experiment with the fuzzy system as it was developed. Two versions of the simulator were created, both written in the programming language Java. The first version was written as an Applet that ran on a World Wide Web (WWW) site created for the FVSLD Project. The web version made the simulator accessible to TAC members who did not have their own computers at work but had some means of accessing the web. The second version of the simulator was written as a stand-alone application program and could be executed directly from a computer without access to the web.
- *A program for viewing the conceptual categories (fuzzy sets) associated with any input or output dimension of the FVSLD Project.* This program was especially useful when the partitions were being modified and refined.
- *A program for examining the latest fuzzy rule set.* This program allowed the current state of the fuzzy rule set to be viewed in a format that was easy to read.
- *A real-time program for displaying actual atmospheric and road surface condition inputs and their associated speed limit outputs at selected RWIS stations on the I-40 corridor.*

In addition to the software described above, a stand-alone hardware prototype was implemented using the MC68EC000 Integrated Development Platform (MC68EC000 IDP) from Motorola. The MC68EC000 IDP is a board set designed to provide a low-cost, yet flexible environment for developing hardware/software products based on the M68000 16/32 bits microprocessor.

Conclusions & Recommendations

The three essential aspects of any speed management system are engineering, enforcement, and education. The engineering issues relate to the technical challenges that must be met in order to design and implement the system of interest. The education issues relate to the efforts necessary to develop a common vision for all parties that might be affected by the new speed management system: the courts, law enforcement, Department of Transportation personnel, the motoring public, etc.. The enforcement issues relate to the development of an effective and just law enforcement policy that can be used to help make the new speed management system a success.

We recommend that the work described in this report be considered in this tripartite context of engineering, education and enforcement. Furthermore, we recommend that the work just completed, the FVSLD Project, be thought of as the first phase, a proof of concept stage, of a larger three-phase project. The main objective of the FVSLD Project, Phase I, was to meet the engineering challenge of demonstrating that fuzzy logic is well suited to the design and implementation of a variable speed limit system dedicated to speed management on rural highways. A fully functional fuzzy variable speed limit control system was designed and implemented in software and a prototype field unit was implemented in hardware. This system made use of several advantages offered by fuzzy logic. One of these advantages was the ability of fuzzy logic to accommodate complex systems of high dimensionality. This advantage significantly facilitated the design, development, and refinement of the FVSLD Project system.

Another important advantage of fuzzy logic was its ability to work advantageously with imprecision inherent in the problem domain. This advantage greatly simplified the modeling of complex transitions and interactions inherent in atmospheric and road surface information. Finally, a further advantage of fuzzy logic was its ability to facilitate two-way communication between experts in the problem domain and the fuzzy design engineers. This benefit made it possible to quickly produce a working prototype of the FVSLD Project fuzzy control system.

During the first phase of the FVSLD Project issues related to the essential aspects of education and enforcement began to appear. In developing the fuzzy algorithm of the FVSLD Project, TAC members had to deal with issues of interpretation. How was the posted speed of the new FVSLD to be understood? What were the liability issues involved? These and other related questions must be worked out in subsequent phases of the project.

The courts, law enforcement officers, and the motoring public must all share similar expectations and assumptions concerning a new variable speed limit system.

These common expectations and assumptions must be developed through an effective educational effort. Similarly, questions related to law enforcement issues began to appear which need to be addressed in any future stages of the overall project.

In brief, we recommend the execution of a Phase II that advances the engineering aspect of the project by deploying and monitoring micro-controller based field units at selected RWIS sites. The educational issues in Phase II would involve a formal analysis of the legal and liability issues related to the new speed management system. It would also be important in Phase II to begin a formal analysis of law enforcement techniques needed to support the new system. Until this analysis is complete, the field units deployed during Phase II should only send information to the involved agencies and their vehicles via transponders for verification. This would provide for validation of the accuracy and reliability of the information, before displaying it to the public.

In a recommended Phase III of the project, the engineering aspects would involve implementation and monitoring at limited sites of the new variable speed limit systems for public use. Educational efforts would use the results of the legal and liability studies in Phase II to bring a common understanding of the relevant issues to the courts, the police, the Department of Transportation, the motoring public, and everyone else that might be affected by the new variable speed limit systems. Enforcement efforts in this third stage of the project would involve the continuous monitoring of the appropriateness and effectiveness of the law enforcement policies that had been established in Phase II of the project.

REFERENCES

1. Van den Hoogen, E. and Smulders, S. "Control By Variable Speed Signs: Results of the Dutch Experiment," Seventh International Conference on Road Traffic Monitoring and Control, London, April 26-28, 1994. Road Traffic Monitoring and Control. Institution of Electrical Engineers, 1994. Conference Publication No. 391. pp.145-149

2. Kuhne, Reinhart. "Line Control on Urban Freeways Using Knowledge-Based Optimization Techniques," Proceedings of Seminar C held at the PTRC Transport, Highways and Planning Summer Annual Meeting, University of Manchester Institute of Science and Technology, England, September 13-17, 1993.

3. Kantonen, Jouko, and Toivonen, Kimmo, Road Weather and Road Conditions Services for Motorists. Finnish National Road Administration, 1996.

4. Yrjo, Pilli-Sihvola and Jukka, Lahesmaa. Weather Controlled Road and Investment Calculations. Finnish National Road Administration, 1995.

5. Senn, Larry. Variable Speed Limit And In-Vehicle Signing Operational Test. Washington State Department of Transportation, 1997.

6. Placer, John, Sagahyroon, Assim, and Harper, John. "Creating an Intelligent Variable Speed Limit System for Rural Highways," International Symposium on Automotive Technology and Automation, 32nd, 14th-18th June 1999, Vienna, Austria. Advances in Automotive and Transportation Technology and Practice for the 21st Century: Surface Transportation Advances and Intelligent Transportation Systems. ISATA, 1999. pp.51-58.

7. Placer, John, Sagahyroon, Assim, and Harper, John. "Design of a Fuzzy Variable Speed Limit System for Rural Highways," Rural Advanced Technolgy and Transportation Systems 1998 International Conference, August 31-September 2, 1998, University Park, Pennsylvania. Enhancing Safety and Mobility in Rural America. Pennsylvania State University, 1998. ptifiles/46.pdf

8. Placer, John and Sagahyroon, Assim, Fuzzy Variable Speed Limit Device Project. Report Number FHWA-AZ98-466. Arizona Department of Transportation, 1998

9. Zadeh, Lotfi. "Fuzzy Sets," Information and Control, vol. 8, no. 2, 1965 ,pp. 338-353.

10. Ross, Timothy. Fuzzy Logic With Engineering Applications. McGraw-Hill, 1995.