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FUZZY VARIABLE SPEED LIMIT DEVICE PROJECT

Final Report

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16. Abstract

The main objective 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.

This objective was demonstrated through the creation of 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 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 used to remotely display, in real-time at the district headquarters of the Arizona Department of Transportation 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 monitored and an appropriate speed limit for each location was displayed. The sites selected were the RWIS stations located at Riordan, Pine Springs, and Ash Fork.

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METRIC (SI*) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	2.54	centimeters	cm
ft	feet	0.3048	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	6.452	centimeters squared	cm^2
ft^2	square feet	0.0929	meters squared	m^2
yd^2	square yards	0.836	meters squared	m^2
mi^2	square miles	2.59	kilometers squared	km^2
ac	acres	0.395	hectares	ha
		MASS (weight)		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams	Mg
		VOLUME		
fl oz	fluid ounces	29.57	millimeters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.0328	meters cubed	m^3
yd^3	cubic yards	0.765	meters cubed	m^3

Note: Volumes greater than 1000 L shall be shown in m^3.

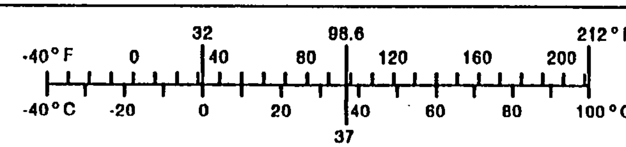
Symbol	When You Know	Multiply By	To Find	Symbol
		TEMPERATURE (exact)		
°F	Fahrenheit temperature	5/9 (after subtracting 32)	Celsius temperature	°C

These factors conform to the requirement of FHWA Order 5190.1A

*SI is the symbol for the International System of Measurements

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
yd	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	millimeters squared	0.0016	square inches	in^2
m^2	meters squared	10.764	square feet	ft^2
yd^2	kilometers squared	0.39	square miles	mi^2
ha	hectares (10,000 m^2)	2.53	acres	ac
		MASS (weight)		
g	grams	0.0353	ounces	oz
kg	kilograms	2.205	pounds	lb
Mg	megagrams (1000 kg)	1.103	short tons	T
		VOLUME		
mL	millimeters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	meters cubed	35.315	cubic feet	ft^3
m^3	meters cubed	1.308	cubic yards	yd^3
		TEMPERATURE (exact)		
°C	Celsius temperature	9/5 (then add 32)	Fahrenheit temperature	°F



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LIST OF ACRONYMS

ADOT	Arizona Department of Transportation
FVSLD	Fuzzy Variable Speed Limit Device
DPS	Department of Public Safety
IRD	International Road Dynamics
ITS	Intelligent Transportation System
RWIS	Road Weather Information System
TAC	Technical Advisory Committee
VSL	Variable Speed Limit
WWW	World Wide Web

1. INTRODUCTION

1.1 BACKGROUND

According to 1994 statistics, 31 percent of all fatal crashes in the United States involved speed as a contributing factor.[1] When one considers that tens of thousands of persons are killed in fatal crashes each year in the United States, the human tragedy of "speed too fast for conditions" becomes all too obvious. The financial impact of speeding is also staggering. Speed was cited as a contributing factor in 12 percent of all police-reported accidents in the United States.[1] With the annual economic impact of transportation mishaps reaching into the tens of billions of dollars, the financial impact of "speed too fast for conditions" also becomes obvious.

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. [2,3,4] 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.[5,6] 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.

1.2 PROJECT SCOPE

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 [7,8] 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 ADOT district headquarters in Flagstaff, appropriate highway speeds for three target 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.

This report first discusses the basic principles and advantages of fuzzy systems in the general context of the design of a VSL system. It then examines in depth the development of the fuzzy algorithm created for the FVSLD Project. Following this, a discussion of the project software that was created in order to both implement and facilitate development of the fuzzy algorithm is presented. This section is followed by a discussion of the hardware prototype that utilizes the fuzzy algorithm. A final section of conclusions and recommendations concludes this report.

1.3 PROJECT ADMINISTRATION AND OVERSIGHT

The FVSLD Project was administered by the Arizona Transportation Research Center of ADOT. 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
Steve Owen (Project Manager)	ADOT – ATRC
Manny Agah	ADOT-ENTERPRISE
Glenn Jonas	ADOT – FMS
Mike Young	ADOT – VISION
Don Dorman	ADOT – Flagstaff
John Harper	ADOT – Flagstaff
Debra Brisk	ADOT – Kingman
Dee Goodwin	ADOT – Kingman
Mike Tyler	ADOT – Holbrook
Jim Gerard (Lt.)	Arizona DPS District Two – Flagstaff
Mike Campbell	National Weather Service - Flagstaff
Jim Boles	City of Winslow – Mayor
Gerry Craig	City of Flagstaff – Traffic
Alan Hansen	FHWA

1.4 ACKNOWLEDGEMENTS

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2. THE BASIC PRINCIPLES OF FUZZY SYSTEMS

2.1 FUZZY LOGIC BASICS

Traditional or "crisp" logic only allows for elements of a given universe to belong to sets within that universe completely or not at all. An element x either belongs to set S completely and is said to have membership value 1 in that set, or it does not belong to set S at all and is said to have membership value 0 in that set. Unlike crisp logic, fuzzy logic allows for elements to possess partial membership in sets. One could think of such membership as being represented by a number in the range of values 0 to 1. At first this might seem strange, but in fact everyday logic is often more fuzzy than crisp. For example, consider the set of all possible wind speeds to be our universal set of interest. Now assume that one wanted to investigate a subset of this universal set that contained only dangerous wind speeds. In traditional logic, a single wind speed would have to be selected that would serve as a crisp boundary that divided dangerous wind speeds from wind speeds that are not dangerous. This situation is depicted in Figure 1 where all possible wind speeds have been divided into two disjoint sets: those that are greater than or equal to 40 mph and those that are less.

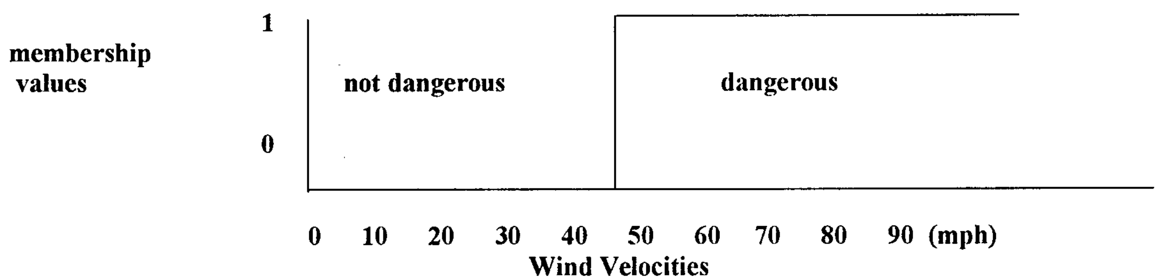

Figure 1. Sets according to traditional logic.

Unfortunately there is a conceptual flaw in Figure 1. The diagram tells us that a wind speed of 40 mph is dangerous but a wind speed of 39.999 mph is not dangerous. In general, this is a limitation of traditional logic. However, in fuzzy logic elements can have partial membership in sets. This allows sets to be represented as shown in Figure 2.

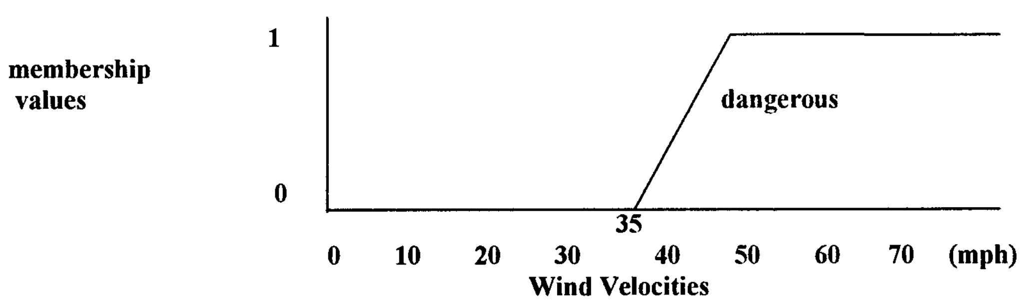

Figure 2. A fuzzy set.

Membership in the set of dangerous wind speeds now begins at 35 mph and increases gradually until 40 mph is reached. All wind speeds greater than or equal to 40 mph have full membership in the set of dangerous wind speeds. All speeds in the range 35 mph to less than 40 mph have partial membership in the set. All wind speeds less than 35 mph have no membership at all in the set of dangerous speeds. This example demonstrates that fuzzy sets are useful for characterizing the degree to which something possesses an attribute of interest.

A further advantage of fuzzy logic is that partial membership allows sets to overlap. The overlapping of sets allows transitions from one conceptual category to the next to be modeled easily and naturally. For example, consider the two sets shown in Figure 3. Two conceptual categories that blend into one another are shown. From this diagram we can see that a wind speed of approximately 39 mph has membership value 0.3 in the set of high wind speeds and membership 0.90 in the set of dangerous wind speeds. Thus one could say that a 39 mph wind possesses significantly more of the dangerous attribute than the high attribute.

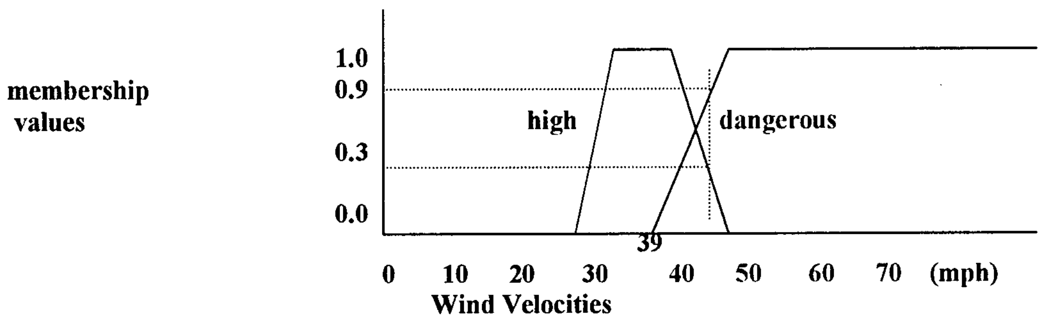

Figure 3. Overlapping fuzzy sets.

2.2 FUZZY SYSTEM BASICS

A simple two input, single output diagram of a fuzzy system is shown in Figure 4. One of the first things that must be done in the design of a fuzzy system is to identify the relevant input and output dimensions. In Figure 4 Surface Condition and Wind Speed are the two input dimensions and Speed Limit is the single output dimension. Once the inputs and outputs are selected, each dimension must be partitioned into conceptual categories. In Figure 4 Surface Condition is partitioned into three categories (error, no_ice, and ice), Wind Speed also is divided into three categories (low, mid, and high), and Speed Limit is partitioned into two sets (slow and fast). After the input and output partitions are selected, the fuzzy rule set is created. The rules are written in a simple form using the conceptual categories that were applied to the input and output dimensions. An example of a fuzzy rule is given in Figure 5. Once a fuzzy rule set is created, the resulting fuzzy system may be executed. In principle, during the operation of a fuzzy system, the fuzzy rules are all executed in parallel. A fuzzy rule is considered to be active if its computed antecedent is greater than zero. All active rules, for a given set of input values, are used to compute the resulting output values. The FVSLD Project system uses the weighted average equation developed by Kosco to compute an appropriate speed limit for the current input conditions. [9]

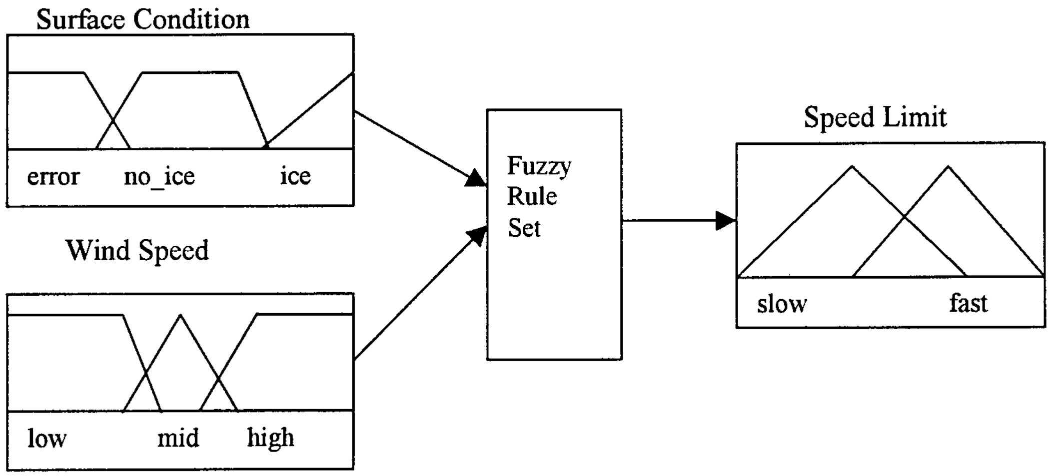

Figure 4. A simple fuzzy system.

Given the above discussion of fuzzy system basics, it can now be pointed out how fuzzy systems offer several advantages for designing a variable speed limit system that is based on road and weather information. First, fuzzy systems are well suited to complex non-linear problem domains with high dimensionality. In the case of a VSL system, a variety of atmospheric measurements combined with multiple types of road surface sensors create a large number of input parameters that must be monitored. System outputs include both a speed limit and, if necessary, information about conditions that required a speed reduction.

IF Surface Condition is ice AND Wind Speed is high THEN Speed Limit is slow

Figure 5. A simple fuzzy rule.

Fuzzy logic is also useful where imprecision is inherent to the problem domain. This is especially relevant in a VSL system where atmospheric and road conditions gradually transition from one set of circumstances to another. For example, there is no precise boundary at which wind speed moves from a classification of high to one of dangerous. Fuzzy logic allows these transitions to be represented naturally.

Finally, fuzzy logic supports two-way communication between the fuzzy design team and the experts in the problem domain. Fuzzy logic allows the conceptual categories of the experts in the problem domain to be translated directly into a set of rules that control the fuzzy system. Even the terminology used by the experts can be incorporated into the fuzzy rule set. In the case of a VSL system this allows experts in transportation and road safety issues to play an integral role in formulating the fuzzy rule set. It also allows these experts to understand and review the fuzzy rules as they are created.

3. DEVELOPMENT OF THE FUZZY ALGORITHM

This section discusses the various steps involved in the design of the fuzzy algorithm. In general terms the fuzzy algorithm design process can be divided into the following steps:

- Determination of the input and output parameters of the desired fuzzy system.
- Partitioning of the input and output parameters of the fuzzy system.
- Development of the fuzzy rule set.

Given below is a subsection devoted to each of these steps.

3.1 DETERMINATION OF THE INPUT AND OUTPUT PARAMETERS

As discussed in a previous section, 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 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 road surface condition parameter actually was based on two data values since each RWIS station was equipped with two road surface condition sensors. This will be discussed in more detail in the next section. 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.

3.2 PARTITIONING OF THE INPUT AND OUTPUT PARAMETERS

As mentioned in a previous section, the inputs and outputs of a fuzzy system 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 [10] and for wind speeds [11]. An example of a set of partitions is given in Figure 6 which shows the conceptual partitions derived for the input dimension Average Wind Speed.

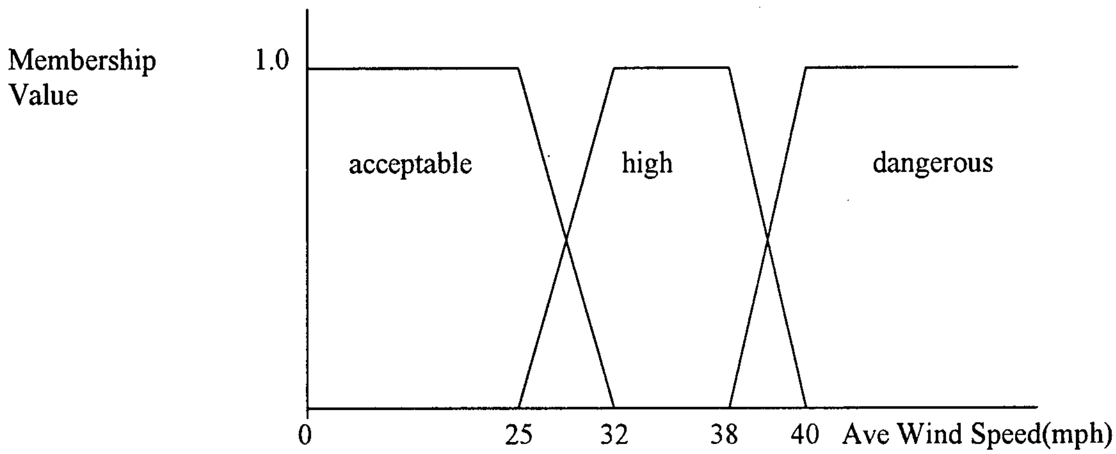

Figure 6. Average Wind Speed partitions.

In Figure 6, the input dimension of Average Wind Speed is divided into three conceptual partitions: *acceptable*, *high*, and *dangerous*. Each of these partitions actually represents a fuzzy set. In order to gain a better understanding of partitions like those shown in Figure 6, consider that the first fuzzy set (*acceptable*) has a trapezoidal shape and is distinguished by four parameters: 0, 0, 25, and 32 mph. The meaning of these values is as follows. There is no range of speeds that have steadily increasing membership values in the conceptual category *acceptable*; this is indicated by the first two numbers: 0,0. All speeds in the range of 0 to 25 mph have full membership in the conceptual category *acceptable*. Speeds in the range 25 to 32 have steadily declining membership in this category. Furthermore, the fuzzy set *high* also has a trapezoidal shape and is represented by four parameters: 25, 32, 38, and 40. Unlike the fuzzy set *acceptable*, fuzzy set *high* does have a range of speeds (25 through 32 mph) for which the membership values in set *high* are steadily increasing.

Although fuzzy sets can assume any shape, the partitions developed for the FVSLD Project are composed only of triangles and trapezoids. A complete set of the names, shapes, and parameters associated with the partitions (fuzzy sets) applied to each of the input and output dimensions for the FVSLD Project is given in Table 1. Columns P1 through P4 represent parameters 1 through 4.

Table 1 A complete summary of partition parameters.

IO Dimension	Partition Name	Shape	P1	P2	P3	P4	Units
Emergency	crawl	Triangle	5	15	30		mph
Emergency	slow	Triangle	30	35	40		mph
Emergency	medium	Triangle	40	45	50		mph
Emergency	submax	Triangle	50	55	60		mph
Emergency	maximum	Triangle	60	65	70		mph
Road Surface Condition	error	Triangle	.5	1	1.5		
Road Surface Condition	no_ice	Triangle	1.5	2	2.5		
Road Surface Condition	ice	Triangle	2.5	3	3.5		
Visibility	poor	Trapezoid	0	0	200	250	ft
Visibility	moderate	Trapezoid	200	250	400	475	ft
Visibility	good	Trapezoid	400	475	1000	1000	ft
Wind Speed	acceptable	Trapezoid	0	0	25	32	mph
Wind Speed	high	Trapezoid	25	32	38	40	mph
Wind Speed	dangerous	Trapezoid	38	40	70	70	mph
Wind Gust	acceptable	Trapezoid	0	0	25	32	mph
Wind Gust	high	Trapezoid	25	32	38	40	mph
Wind Gust	dangerous	Trapezoid	38	40	70	70	mph
Cross Wind	near_zero1	Triangle	0	0	90		deg
Cross Wind	strong	Triangle	0	90	180		deg
Cross Wind	near_zero2	Triangle	90	180	180		deg
Speed Limit	err	Triangle	–15	–5	5		mph
Speed Limit	crawl	Triangle	5	15	30		mph
Speed Limit	slow	Triangle	30	35	40		mph
Speed Limit	medium	Triangle	40	45	50		mph
Speed Limit	submax	Triangle	50	55	60		mph
Speed Limit	maximum	Triangle	60	65	70		mph
Precipitation Intensity	light	Trapezoid	0	0	3	4	
Precipitation Intensity	heavy	Triangle	3	4	4		

Note that the input dimensions of Road Surface Condition and Precipitation Intensity are actually partitioned into fuzzy sets with dimensionless parameters. The RWIS station actually outputs simple integer codes for these dimensions that represent specific conditions. In the case of Road Surface Condition, the RWIS stations may output any of 14 different codes (values 0 through 13). These 14 codes were divided into three sets of codes representing the following conceptual categories:

- Error.
- Ice.
- No Ice.

A similar type of reduction was performed on the input dimension Precipitation Intensity. In this case, four different integer codes were reduced to the two conceptual categories *light* and *heavy*.

Each RWIS data station used in the project had two road surface condition sensors which slightly complicated the Road Surface Condition input. If either of these sensors indicated icy conditions, then the overall road surface condition input was considered to be icy. If none of the sensors indicated an icy condition but either of the sensors indicated an error condition, then the overall road surface condition input was considered to be an error condition. Only when both sensors indicated a no ice condition was the overall road surface condition considered to be free of ice.

3.3 DEVELOPMENT OF THE FUZZY RULE SET

As mentioned earlier, 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.

In collaboration with the fuzzy engineers, the domain experts for the FVSLD project devised a set of guidelines that were used to guide the development of the project's fuzzy rule set. First, the conceptual categories that partitioned the input dimensions were divided into three general groups: *safe*, *uncertain*, and *dangerous*. These groups are indicated below:

Dangerous conditions.

- Road Surface Condition = *ice*.
- Visibility = *poor*.
- Average Wind Speed = *dangerous* OR
- Average Wind Speed = *high* and Cross Wind = *strong* OR
- Wind Gust Speed = *dangerous* OR
- Wind Gust Speed = *high* and Cross Wind = *strong*.
  (Notice that wind can only account for a single dangerous condition.)

Uncertain conditions.

- Visibility = *moderate*.
- Average Wind Speed = *high* and Cross Wind = not *strong*.
- Wind Gust Speed = *high* and Cross Wind = not *strong*.
- Precipitation Intensity = *heavy*.

Safe conditions

- Road Surface Condition = *no_ice*.
- Visibility = *good*.
- Average Wind Speed = *acceptable*.
- Wind Gust = *acceptable*.
- Precipitation Intensity = *light*.

Based on the classifications given above, the following guidelines were established:

- If all input conditions are safe (i.e no uncertain or dangerous conditions exist), then the maximum speed limit (65 or 75 depending on the location) should be in effect.
- If one or more uncertain conditions exist but no dangerous conditions exist, then a single speed reduction to 55 mph should be posted.
- If a single dangerous condition exists (without regard to uncertain conditions), then two speed reductions to 45 mph should be posted.
- If two or more dangerous conditions exist (without regard to uncertain conditions), then three speed reductions to 35 mph should be displayed.

The emergency input can be used to set the output speed of the FVSLD to any of the speed zones mentioned above (35,45,55,65 or 75 mph). It can also be used to set the speed at 15 mph in case of accident or other extreme conditions. Notice that according to the guidelines given above, the FVSLD would never post a speed limit below 35 mph during its normal automatic operations. The emergency input (manual override) must be used to post a speed of 15 mph.

Table 2. The FVSLD Project fuzzy rule set.

#	Emerg	RSC	Visib	Wind Speed	Wind Gust	Cross	P	Speed
1	none	error	0	0	0	0	0	err
2	crawl	0	0	0	0	0	0	crawl
3	slow	0	0	0	0	0	0	slow
4	medium	0	0	0	0	0	0	medium
5	submax	0	0	0	0	0	0	submax
6	max.	0	0	0	0	0	0	max.
7	none	ice	poor	0	0	0	0	slow
8	none	ice	-poor	dangerous	0	0	0	slow
9	none	ice	-poor	high	0	strong	0	slow
10	none	ice	-poor	acceptable	high	strong	0	slow
11	none	ice	-poor	high	dangerous	-strong	0	slow
12	none	ice	-poor	acceptable	dangerous	0	0	slow
13	none	no ice	poor	dangerous	0	0	0	slow
14	none	no_ice	poor	high	0	strong	0	slow
15	none	no_ice	poor	acceptable	high	strong	0	slow
16	none	no_ice	poor	acceptable	dangerous	0	0	slow
17	none	no_ice	poor	high	dangerous	-strong	0	slow
18	none	ice	-poor	-dangerous	-dangerous	-strong	0	medium
19	none	ice	-poor	acceptable	acceptable	strong	0	medium
20	none	no_ice	poor	-dangerous	-dangerous	-strong	0	medium
21	none	no_ice	poor	acceptable	acceptable	strong	0	medium
22	none	no_ice	-poor	dangerous	0	0	0	medium
23	none	no_ice	-poor	high	0	strong	0	medium
24	none	no_ice	-poor	high	dangerous	-strong	0	medium
25	none	no_ice	-poor	acceptable	dangerous	0	0	medium
26	none	no_ice	-poor	acceptable	high	strong	0	medium
27	none	no_ice	-poor	high	-dangerous	-strong	0	submax
28	none	no_ice	-poor	acceptable	high	-strong	0	submax
29	none	no_ice	moderat	acceptable	acceptable	0	0	submax
30	none	no_ice	good	acceptable	acceptable	0	heavy	submax
31	none	no_ice	good	acceptable	acceptable	0	light	max.

A listing of the complete fuzzy rule set created for the FVSLD Project is given in Table 2. The full names of the abbreviated column headings in Table 2 are given below:

- **Emerg** = Emergency (manual override) input.
- **RSC** = Road Surface Condition input.
- **Visib** = Visibility input.
- **Wind Speed** = Average Wind Speed input.
- **Wind Gust** = Wind Gust Speed input.
- **Cross** = Degree of Cross Wind input.
- **P** = Precipitation Intensity input.
- **Speed** = Speed Limit output.

The first column in Table 2 simply assigns a number to each rule so that any given rule can be referred to later in this document. Each remaining column represents the particular input dimension or output dimension indicated by that column's label. Table entries in a specific column give the names of conceptual categories (fuzzy sets) associated with the input or output dimension represented by that column.

The one exception to this is an entry of 0. When a 0 is encountered, it should be interpreted as a wild card value that represents all possible conceptual categories associated with the column in which it is found. Finally, note that some fuzzy set names in the table are preceded by a minus sign. This is simply a short hand way of representing the logical NOT operation. Thus an entry of –poor in the Visibility column is used to represent any partition on the Visibility domain except the partition labeled poor.

As an example, consider rule number 22 in Table 2. The entries for this rule are reproduced below:

#	Emerg	RSC	Visib	Wind Speed	Wind Gust	Cross	P	Speed
22	none	no_ice	-poor	dangerous	0	0	0	medium

Rule 22 should be read as follows:

If the Emergency input is *none* AND
the Road Surface Condition input is *no_ice* AND
the Visibility input is *good* or *moderate* but not *poor* AND
the Average Wind Speed input is *dangerous* THEN
the Speed Limit displayed should be *medium* (45 mph) no matter what the values of Wind Gust Speed, Degree of Cross Wind, and Precipitation Intensity may be.

The rules represented in Table 2 can be grouped into several classes that reflect the guidelines for development of the fuzzy rule set discussed earlier. The outline given in Figure 7 shows these natural groupings within the fuzzy rule set.

Rule 1 contains an error in the Road Surface Condition and an Emergency input of *none*. This is the unique set of inputs that give an error status for the output speed limit.

Rules 2 - 6 contain an Emergency input other than *none*. Therefore, all other input values are ignored.

Rules 7 - 17 determine all *slow* (35 mph) output speeds.

> **Rules 7 - 12** contain the dangerous Road Surface Condition input of *ice* plus one other dangerous condition.
>
> **Rules 13 - 17** contain the dangerous Visibility input of *poor* plus some type of dangerous condition related to wind.

Rules 18 - 26 determine all *medium* (45 mph) output speeds. This set of rules encodes a single dangerous condition only.

> **Rules 18 - 19** have a Road Surface Condition input of *ice* as the only dangerous condition.
>
> **Rules 20 - 21** have a Visibility input of *poor* as the only dangerous condition.
>
> **Rules 22 - 26** have a single dangerous wind condition only. Note that Average Wind Speed and Wind Gust Speed cannot combine as two dangerous conditions.

Rules 27 - 30 determine all *submax* (55 mph) output speeds. These rules encode any combination of uncertain but not dangerous conditions.

Rule 31 determines the combination of inputs that yield a *maximum* output speed. This would be 65 or 75 mph depending on the location.

Figure 7. Natural groupings of the FVSLD Project fuzzy rule set.

4. THE PROJECT SOFTWARE

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.
- A program for viewing the conceptual categories (fuzzy sets) associated with any input or output dimension of the FVSLD Project.
- A program for examining the latest fuzzy rule set. (The rule set evolved in stages.)
- A real-time program for displaying actual inputs and their associated speed limit outputs at selected RWIS stations on the I-40 corridor.

Given below is a subsection devoted to each of these programs.

4.1 THE INTERACTIVE SIMULATOR

A FVSLD Project interactive simulator was developed that supported the development, refinement, and testing of the project's fuzzy rule set. The simulator 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.

The simulator allowed a value for each input dimension to be entered on the computer screen. For each set of inputs given, a corresponding speed limit is computed by the fuzzy system and displayed on the screen. In addition to the speed limit, all active rules for a given set of input values are displayed on the screen. Thus, the screen display can be used to examine both the projected speed limit and the justification for that speed. The simulator proved to be an invaluable aid in the development and refinement of the project's fuzzy algorithm.

A snap shot of a screen display of the interactive simulator is shown in Figure 8. Notice that above the projected speed limit of 55 mph there is a smaller text field with the value 50.7. This is the raw continuous speed limit computed by the fuzzy algorithm. Raw continuous speed limits are rounded off to the nearest speed zone of 35, 45, 55, or 65 mph. (Depending on the site of deployment, the upper speed limit may be 75 mph rather than 65 mph.) Notice also how the Wind Speed parameter (actually average wind speed) has two conceptual categories displayed: acceptable and high. Recall that fuzzy sets (conceptual categories) may overlap. The Wind Speed dimension has an input value of 30 mph (shown in the lowest text field) which belongs to the Wind Speed category of *acceptable* to degree 0.29 and it also belongs to the Wind Speed category of *high* to degree 0.71.

Finally notice the large scroll box in the upper left corner of the screen. This area allows one to scroll through and view all of the rules that are active given the current input values. Only part of one rule is visible in the scroll box in Figure 8. The parenthesized value of 0.29 just preceding the rule indicates the degree to which the rule is active. A fully active rule would be preceded by the value 1.0. Completely inactive rules would be active to degree 0.0. However, completely inactive rules are not displayed.

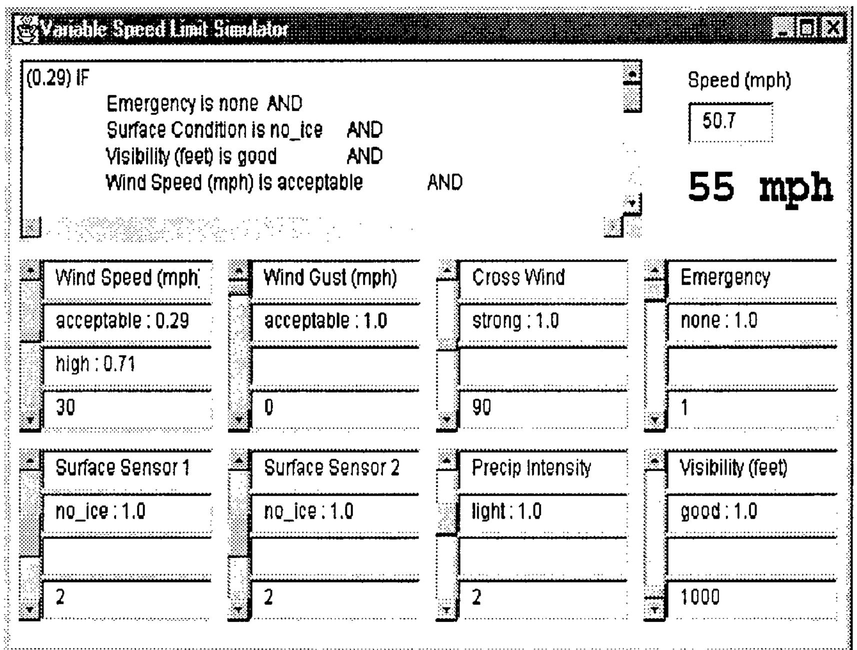

Figure 8. The FVSLD Project simulator.

4.2 THE PARTITION (FUZZY SET) VIEWER

A graphing program was developed that allowed examination of the partitions of all input and output dimensions of the FVSLD. This program was especially useful when these partitions were being modified and refined. A snap shot of a screen display of the partition viewer is shown in Figure 9. To understand the concept of fuzzy set a little more precisely, consider that given some universal set U, a fuzzy set is defined to be a set of ordered pairs as indicated below.

Fuzzy set $A = \{ (x , \mu_A(x)) \mid x \in U \}$

The entity $\mu_A(\ldots)$ above is called the membership function of fuzzy set A and $\mu_A(x)$ is the degree of membership of input value x in fuzzy set A. Thus, the fuzzy sets displayed in Figure 9 are actually the graphs of three different membership functions. Each function accepts as input a measurement from the universe of possible visibility readings. In turn each function yields as output the degree to which its input is a member in the fuzzy set associated with that function.

This is why the title Membership Function Graphs is found in the upper left section of the graphic in Figure 9.

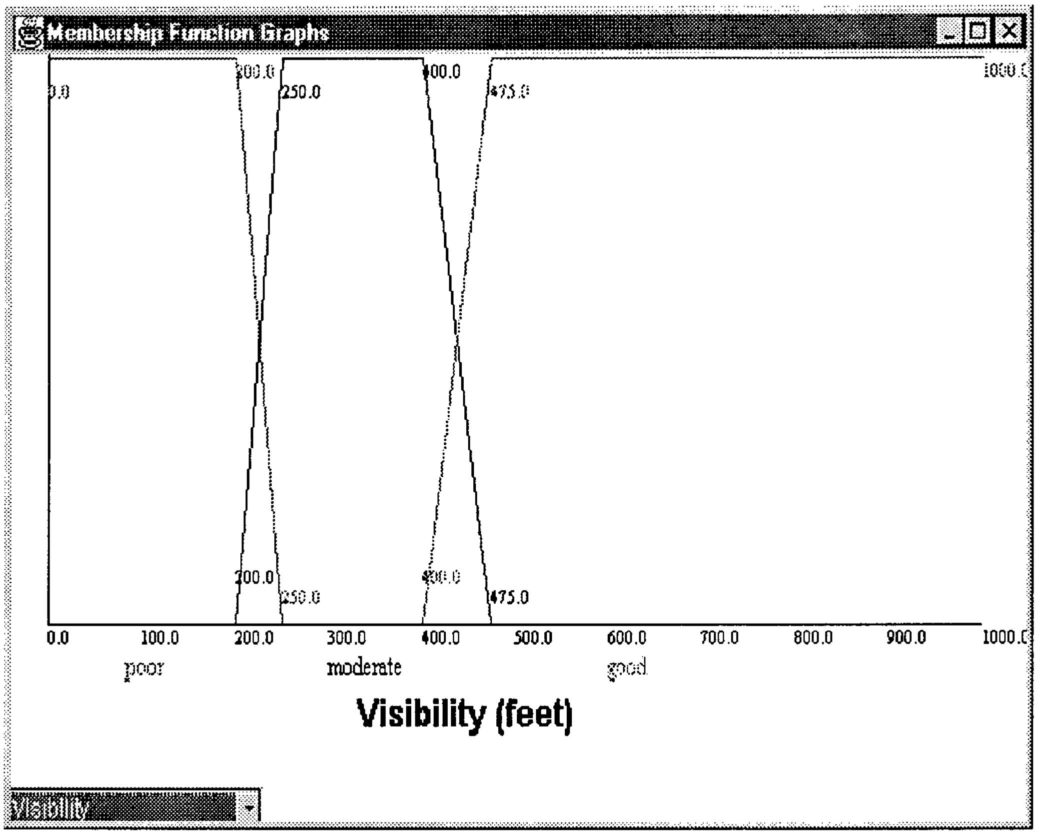

Figure 9. The FVSLD Project fuzzy set viewer.

The selection box in the lower left corner of Figure 9 allows any of the seven input dimensions or the output dimension to be selected. Once a particular dimension is selected its associated fuzzy sets (partitions) are displayed on the computer screen. A second example of a screen display of the partition viewer is given in Figure 10.

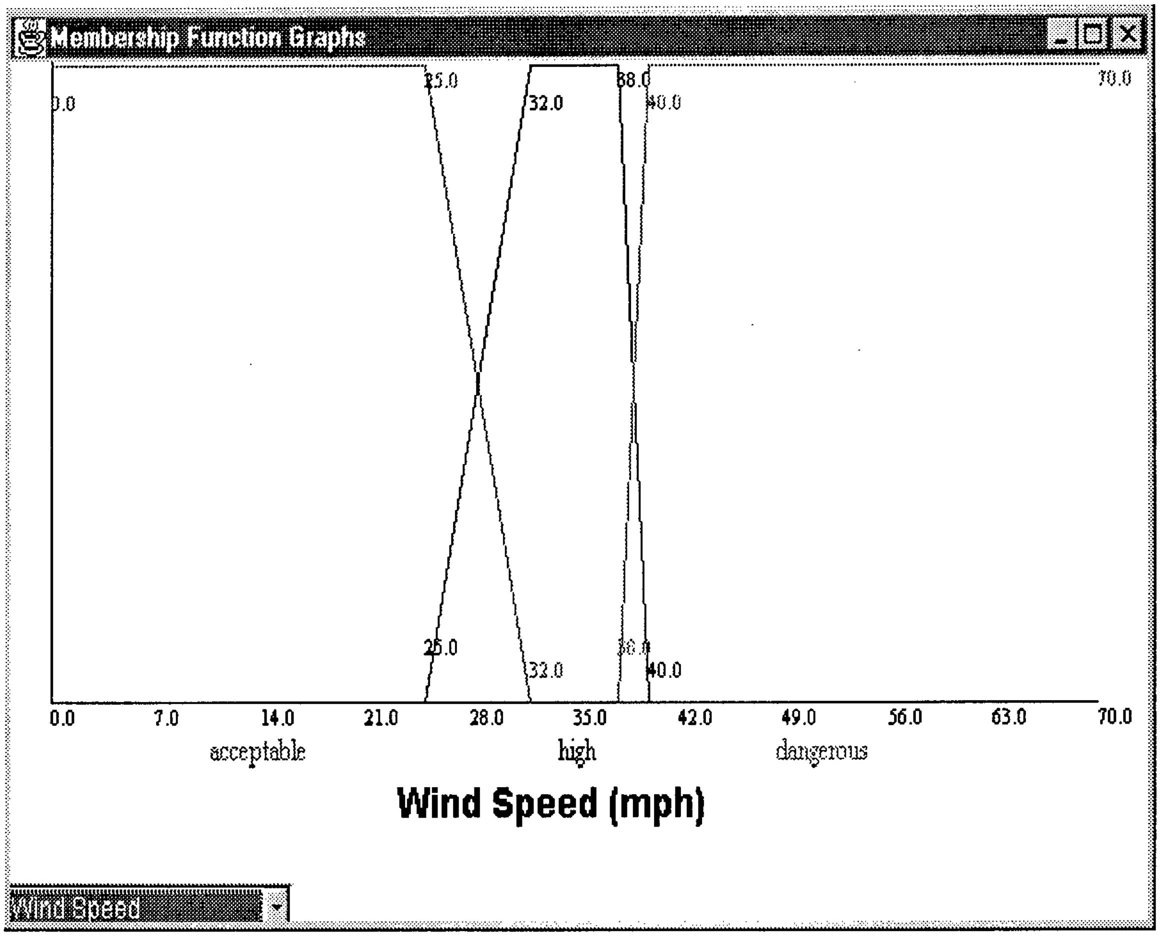

Figure 10. Fuzzy sets associated with *Average Wind Speed.*

Notice that the values displayed in Figure 10 are the same as the partition parameters given for Average Wind Speed in Table 1.

4.3 THE FUZZY RULE SET VIEWER

A program for viewing the project's fuzzy rule set was also created. This program allowed the current state of the fuzzy rule set to be viewed in a format that was easy to read. A snap shot of a screen display of the fuzzy rule set viewer is shown in Figure 11.

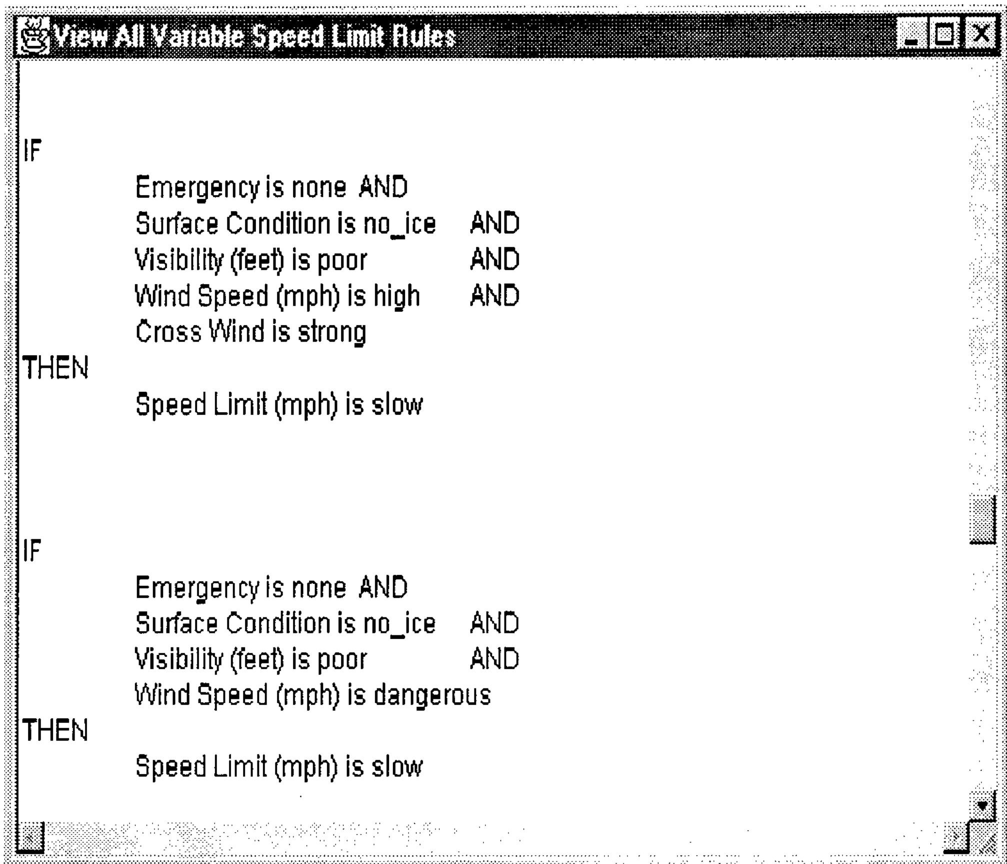

Figure 11. The FVSLD Project's fuzzy rule set viewer.

Two rules are visible in the large scroll box displayed in Figure 11. By scrolling up or down all rules in the fuzzy rule set can be reviewed.

4.4 THE REAL-TIME PROGRAM

A real-time version of the FVSLD system was run continuously on a stand-alone PC at the ADOT district office in Flagstaff. This program displayed atmospheric and road surface input information and associated output speed information for three different RWIS locations along the I-40 corridor. Rather than display actual input data measurements, the conceptual categories associated with the values of the input parameters were displayed along with the computed output speeds. A snap shot of a screen display of the real-time program is shown in Figure 12.

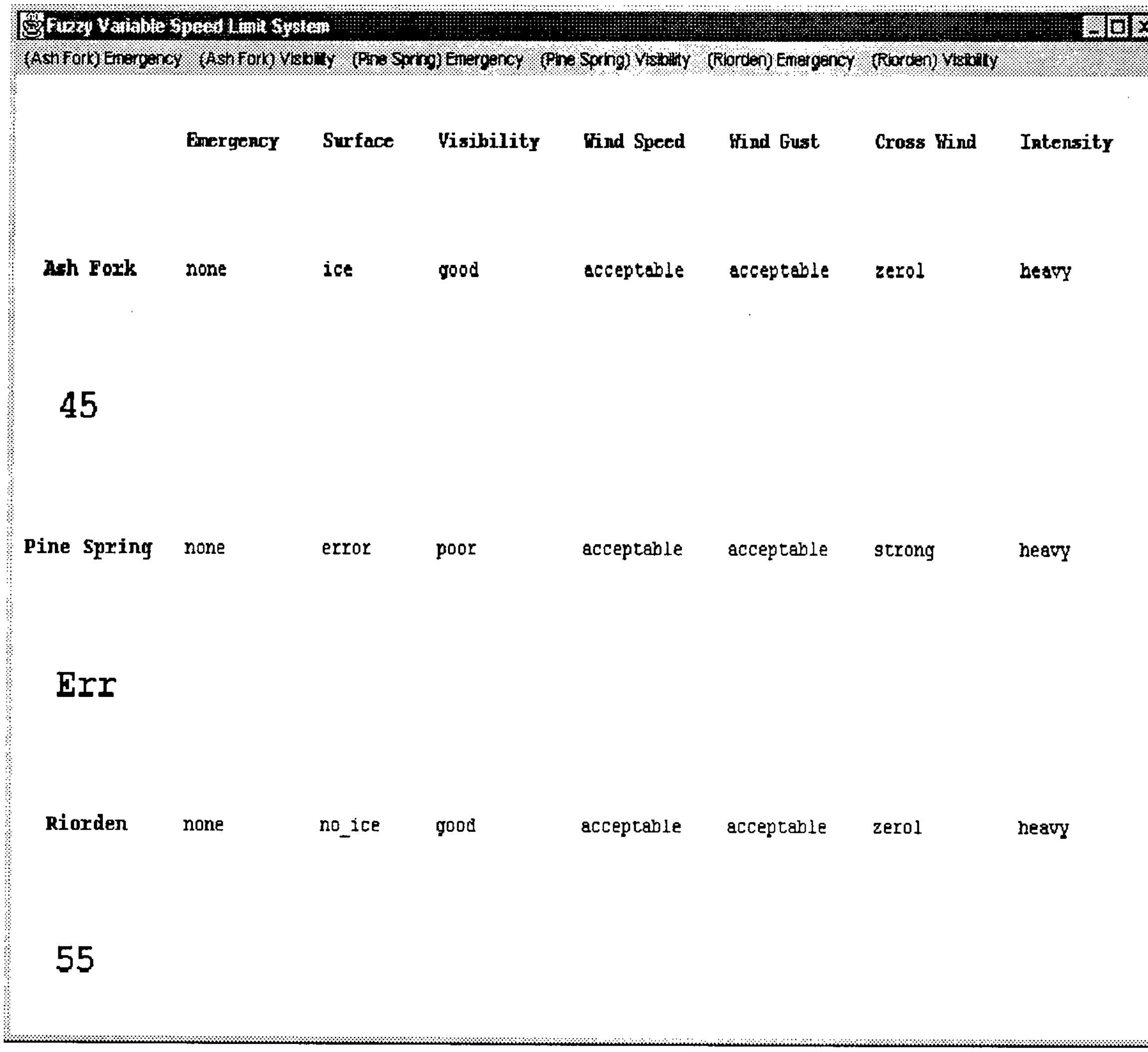

Figure 12. Input and variable speed information at three RWIS locations.

The menu bar shown in Figure 12 allows the emergency and visibility settings for the three target RWIS locations to be manually entered. The other input values are read from a data file provided by the RWIS stations. The visibility inputs were provided manually because the ADOT RWIS stations did not yet have visibility detection systems at the time the FVSLD Project was conducted. The display of the real-time software is updated periodically.

Notice that the road surface condition sensors at the Pine Springs RWIS station are transmitting an error condition. This causes the speed display to read "ERR" rather than an actual speed value. In actual use on a highway, the variable speed limit display could be programmed to go blank. In addition to an error in the road surface condition sensors, the real-time software can detect another type of error. When an RWIS station is malfunctioning, no data is transmitted for that station. If the FVSLD project software detects the absence of information for a target RWIS site, the message "ERR" also is shown on the display associated with that site.

5. THE HARDWARE PROTOTYPE

In its final stage the fuzzy variable speed limit device being proposed would contain multiple inputs and at least two outputs. The inputs would include the various types of sensor data and the emergency information already discussed. Other inputs might include traffic information such as traffic flow density data and traffic speed data. The output of the proposed fuzzy system would include a variable speed limit value, a signal to be provided as input to a preprogrammed traffic message board, information broadcast to an Advanced Traveler Information System, and information sent to ADOT and Department of Public Safety (DPS) response groups. A simple block diagram of the proposed system is given below.

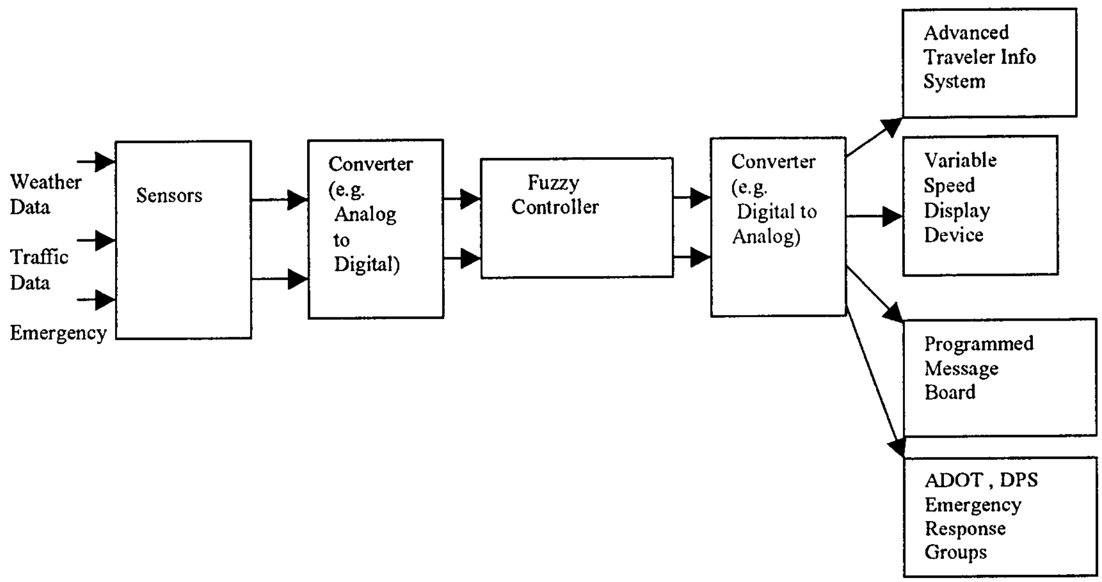

Figure 13. The Fuzzy Variable Speed Limit System.

In Phase I of the project, a subset of the system depicted in Figure. 13 was constructed and tested in a simulation environment. This stand-alone hardware prototype was implemented using the MC68EC000 Integrated Development Platform (MC68EC000 IDP) from Motorola and an IBM PC. 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.

When a conventional embedded processor such as the M68000 is used with a program that implements a fuzzy logic algorithm, the rules that constitute the base of the algorithm are evaluated in sequence, one after the other. Once all the rules are evaluated, their outputs are combined to provide a single value that will be defuzzified. In this work, this value represents the recommended speed limit. If the conventional controller has fast internal peripherals for data acquisition, the sequential rule-processing scheme becomes transparent to the user and the process appears to have been performed in parallel. This alleviates the need for dedicated but expensive fuzzy-controllers.

In this project, the fuzzy algorithm was re-coded using the C language, cross-compiled and downloaded to the target processor using the RS-232 link between the PC and the MC68000 IDP. The equivalent C code of the fuzzy algorithm occupied approximately 30 Kbytes of memory. This implies that the overall memory requirement of the final system will be quite manageable.

In this implementation, the user was provided with a very simple and user friendly software interface. The interface queried the user who then input values corresponding to the various atmospheric and road conditions. The fuzzy rules were then evaluated by the target processor and the recommended speed was displayed on a 3" X 1.5" seven segment display unit.

For verification purposes, the same test data used for the simulation environment described in section 4 was used to test the hardware prototype. The two systems produced identical results (speed limits) in all cases.

6. 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 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.

6.1 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 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. 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.

This first phase of effort, the FVSLD Project, also needed to address issues related to the essential aspects of education and enforcement. In developing the fuzzy algorithm of the FVSLD Project, TAC members frequently had to wrestle with issues of interpretation. How was the posted speed of the new FVSLD to be understood? What were the liability issues involved if a motorist was adhering to the posted speed reduction and yet still had an accident? These and many other related questions are educational issues that must be worked out. The courts, law enforcement officers, and the motoring public must all share similar expectations and assumptions concerning a new variable speed system. These common expectations and assumptions must be developed through an effective educational effort. Similarly, questions related to law enforcement issues began to surface early in the FVSLD Project. In short, although engineering issues were the main emphasis of Phase I, relevant education and enforcement issues began to surface that needed to be addressed in any future stages of the overall project.

6.2 RECOMMENDATIONS FOR FUTURE RESEARCH

6.2.1 Phase II: Immediate Future Research

The engineering issues of a recommended Phase II of the project would involve field testing and debugging of the fuzzy control system developed in Phase I. This would involve deployment of field units at selected RWIS sites and subsequent careful monitoring of those sites. Micro-controller based field units must be developed and deployed at the RWIS sites selected for the field testing phase. A prototype of a micro-controller system has already been developed in Phase I. However, the system must be packaged in a weather-resistant container suitable for deployment in the field and then integrated into the selected RWIS sites. It would also be useful to compare the data collected from the FVSLD field units to 85th percentile data in order to compare the fuzzy algorithm to the actual perceptions and driving habits of the motoring public. Another engineering aspect of Phase II would involve analysis of how to integrate the new variable speed limit system into the current and anticipated intelligent transportation system (ITS) infrastructure in Arizona.

The educational issues to be engaged in Phase II 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 I because such a display must come after the legal and liability analysis is complete. The variable speed limit information would be made available via transponder so that only ADOT, DPS, and NAU participants in the research program would be able to receive the information. Another activity related to education would involve engaging potential vendors, encouraging them to consider new system designs for low-cost variable speed limit systems. The community of potential vendors must also be included in the educational effort if variable speed limit systems are to be fully successful. These educational issues would become equal in importance to the engineering challenges of the project.

Finally it would also be important in Phase II 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.

6.2.2 Phase III: Longer Term Future Research

In a recommended Phase III of the project, the engineering aspects would involve 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 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.

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