□ 論 文 □

영상검지기를 이용한 실시간 교통신호 감응제어

A Development of a Real-time, Traffic Adaptive Control Scheme Through VIDs.

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목 차

ABSTRACT

The development and implementation of a real-time, traffic adaptive control scheme based on fuzzy logic through Video Image Detector systems (VIDs) is presented. Through VIDs based image processing, fuzzy logic can be used for a real-time traffic adaptive signal control scheme. Fuzzy control logic allows linguistic and inexact traffic data to be manipulated as a useful tool in designing signal timing plans. The fuzzy logic has the ability to comprehend linguistic instructions and to generate control strategy based on a priori verbal communication. The implementation of fuzzy logic controller for a traffic network is introduced. Comparisons are made between implementations of the fuzzy logic controller and the actuated controller in an isolated intersection. The results obtained from the application of the fuzzy logic controller are also compared with those corresponding to a pretimed controller for the coordinated intersections. Simulation results from the comparisons indicate the performance of the system is better under the fuzzy logic controller. Integration of the aforementioned schemes into an ATMS framework will lead to real-time adjustment of the traffic control signals, resulting in significant reduction in traffic congestion.

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1. Introduction

Several metropolitan areas nowadays experience severe traffic congestion on street networks in central districts and other high-activity centers of urban areas. As the problem of traffic congestion spreads, there is a pressing need to introduce and apply advanced technological concepts to alleviate the congestion problem.

Video Image Detector systems (VIDs) [Ini89,MWB90] can monitor and. control the traffic in the most reliable manner.VIDs based on Video Image Processing can access traffic parameters such asspeed, volume, and queue length in real time, thus enabling real-time signal timing control schemes to adjust their parameters. In our simulation purpose, the number of vehicles observed within 200 ft. distance behind the stop lines in every directions of an intersection are enough for the input data1).

Fuzzy logic control [Zad73,BR79] allows linguistic and inexact traffic data to be manipulated as a useful tool in designing signal timing plans. This logic provides a mean of converting a linguistic control strategy, which is expressed by "if...then...else" statements, into a control algorithm. Fuzzy logic has the ability to comprehend linguistic instructions and to generate control strategies based on a priori verbal communication.

The motivation for designing a fuzzy controller is that there is a fairly direct relationship between the loose linguistic expressions of a traffic control strategy and its manual implementation. It is important that the fuzzy algorithms have the distinct advantage of not relying on a mathematical transfer function for formulating a control strategy.

Instead, the design of a fuzzy controller for this system requires the expert knowledge and experience of traffic control in formulating the linguistic protocol which generates the control input to be applied to the traffic control system. The fuzzy statement protocol is a fruitful technique for modeling the knowledge and experience of a human operator.

This paper is organized in the following manner. The next Section contains the historical development of the underlying fuzzy set theory and the fundamentals of fuzzy control from fuzzification, to rule based control, to defuzzification techniques. Section II is devoted to the development of fuzzy algorithms, while the subsequent Section presents the implementation of fuzzy logic controller for an isolated traffic junction where all turning movements are allowed. The use of the theory of fuzzy sets in constructing a controller is presented and comparisons are made between implementations of the fuzzy logic controller and the actuated controller in terms of delays. Next, the fuzzy controller implementation for coordinated signalized is presented.

The results obtained from the implementation of the fuzzy controller are compared with those corresponding to a pretimed controller. Concluding remarks are offered in the final Section.

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1) As if taking a snap shot for this area, it collects rough input data for fuzzy control.

2. Development of fuzzy control theory

Fuzzy set theory was initiated by Zadeh in the early 1960s[Zad65]. However, the term ensemble flou (French for fuzzy set) was invented by Menger in 1951[DP80]. Menger uses a "max-product" transitive fuzzy relation with a probabilistic interpretation. In the mid-1970's, the pioneering research of Mamdani [Mam76] and Tong [Ton77] on fuzzy control was motivated by Zadeh's work on fuzzy set. The work focused on control of systems that were difficult to model for ordinary controllers. The first referred application of fuzzy control was related to the control of a steam engine by Mamdani and Assilian [MA75]. The controller implementation required using 24 linguistic rules in the form of "if-then-fuzzy rules", and provided a better performance compared with the one of a classical control algorithm. Mamdani also developed a self-organizing controller using the same steam engine model [Mam77,PM79]. A research survey during this period is provided in [Ton77,Mamd77]. After these pioneering steps towards instituting fuzzy logic control theory, other researchers have published various interesting articles. Detailed description of several applications can be found in [PM79,BG80,TS85,End87,TM87,LL89].

2.1 Fuzzy logic controller

The basic diagram of a fuzzy logic controller is shown in Figure 2.1. It has four main components: 1) the fuzzification interface, 2) the knowledge base, 3) the decision making logic unit, and 4) the defuzzification interface. The following paragraphs describe these four main components.

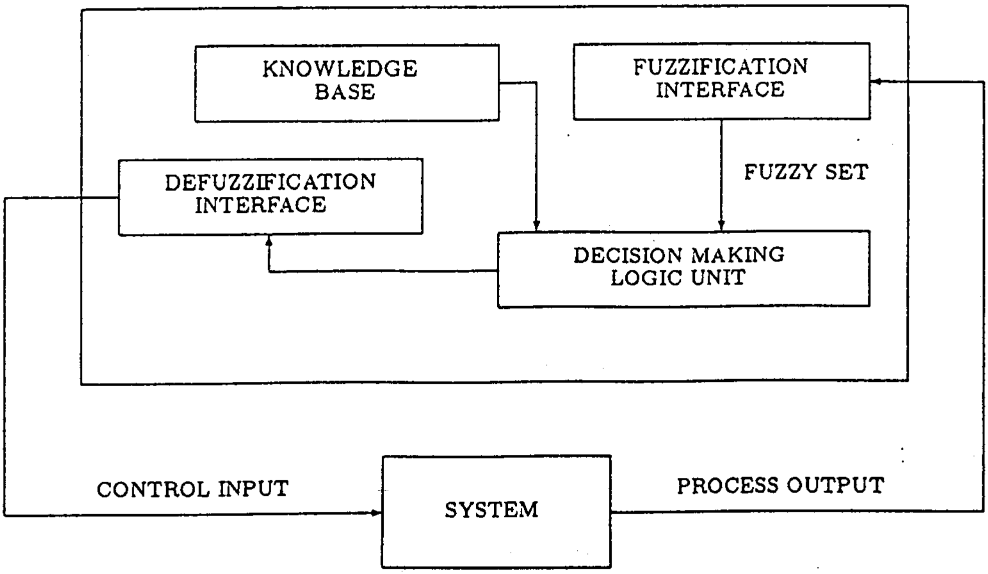

Figure 2.1: Diagram of a fuzzy logic controller

Fuzzification interface

The fuzzification process involves the scale mapping of the measured input variables into the corresponding universes of discourse. This process includes an evaluation of the membership value of the crisp input x_0 with respect to each fuzzy set x of the input universe. Symbolically,

$$x = \text{fuzzifier}(x_0)$$

where "fuzzifier" represents a fuzzification operator. The operator converts the crisp values into suitable linguistic labels of fuzzy sets.

Knowledge (Rule) base

The foundation of a fuzzy controller is a set of linguistic rules which are expressed by "if-then" rules. These typically have the following form:

If (a set of conditions are satisfied) then (a set of consequences are inferred)

The controller receives the fuzzy input from the fuzzifier (antecedent) and evaluates the set of rules on it, thus producing the fuzzy output (consequents). The antecedents and consequents are associated with fuzzy linguistic terms or sets. The above conditional statement that relates the process state in the antecedent with the control action in the consequent is defined as a fuzzy control rule. The proper choice of process state and control variables is essential in the implementation of the controller. Engineering knowledge and experience play important roles in the selection of this linguistic variables, which has substantial effect on the performance of the fuzzy controller. Furthermore, the fuzzy control rules can be derived from expert experience and control engineering knowledge. Therefore, this rule base characterizes the control policy of the domain experts by a set of fuzzy control rules.

For a well-constructed rule-base, the fuzzy controller must always be able to produce a proper control action for every state of the process (completeness).

Decision making mechanism

The inference mechanisms simulate the human decision-making process based on fuzzy concepts. These mechanisms employed in a fuzzy logic controller are relatively simple since the control actions are closely related to the forward data-driven inference.

For a multi-input multi-output system with n fuzzy rules derived by using the sentence connective "and", the consequent

y_k can be obtained by composing the antecedent x_k and the rules R_i as follows:

$$\begin{aligned} y_k &= (x_k \circ R_1) \text{ and } (x_k \circ R_2) \text{ and} \\ &\quad \ldots (x_k \circ R_n) \\ &= x_k \circ (R_1 \cap R_2 \cap \ldots R_n) \\ &= x_k \circ \widetilde{R} \end{aligned}$$

where $\widetilde{R}$ is called the system transfer relation. $\widetilde{R}$ is used to calculate the fuzzy output y_k from the fuzzy input x as follows

$$\begin{aligned} Y &= X \circ \widetilde{R} \Rightarrow \mu_V(Y) \\ &= \max \{\min \{ \mu_U(X), \mu_{\widetilde{R}} (X,Y)\} \end{aligned}$$

where X and Y are the input and output vectors in fuzzy sets U and V, respectively. Note that $\tilde{R}$ was obtained through the conjunction of the individual rules, but in general any operators such as product, bounded-product or drastic-product can be used. The output of this inference is still a membership junction, hence a defuzzification strategy is required in order to obtain a non-fuzzy(crisp) control action. The defuzzification stage will be presented in the next section, together with an example of different defuzzification methods.

Defuzzification interface

The defuzzification process involves a mapping from a space of fuzzy control actions into a space of nonfuzzy control actions. This procedure is inverse to that of the fuzzifier. The initial data value, y, consists of the membership values of the current output with respect to all the output fuzzy subsets of the output space. Symbolically,

$$y_0 = \text{defuzzifier}(y)$$

where y_0 is the nonfuzzy control output and defuzzifier is the defuzzification operator. This process is necessary since a crisp control action is required in many practical applications.

3. Application of fuzzy logic control to traffic load management

The application of fuzzy logic control to the traffic load management problem for isolated intersections and coordinated signalized intersections is considered in the remaining of this section.

The average delay of vehicles resulting from the implementation of the fuzzy logic controller is compared to the delay obtained from the actuated controller in isolated intersections. For the coordinated signalized intersections in over-saturated conditions[2], the performance of the fuzzy logic controller is compared to that of the pretimed controller, in terms of prevention of spillback, maximum output, and queue extent.

Traf-Netsim(Network Simulation Model) [KLD92] software package has been interfaced with the fuzzy logic controller to simulate the effects of the fuzzy logic based traffic control. These modifications include recording the number of vehicles present within 200ft away behind the stop lines in every direction and distinguishing the "through-vehicles" from the "turning ones".

Based on this information and the fuzzy algorithm, the length of the extension of the green time for the phase having the right of way is decided at each intervention. Depending on the extension of the green time, either the state of the system will immediately change to the competing phase or remain the same at the end of the extension period. Further details will be described later in this chapter.

In the next section this control policy will be applied to isolated and coordinated intersections.

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2) Conditions that take place when queues fill entire blocks and interfere with the performance of adjacent upstream intersections.

3.1 Fuzzy Logic Traffic Control for an Isolated Intersection

The signal timing control problem of an isolated intersection is considered in this section. An intersection is defined to be isolated, if it is "sufficiently far" away from all other intersections so that platoons can not be formed. Figure 3.1 shows the basic phase plans for a four-phase signalization with the associated geometry for an isolated intersection. Exclusive left-turn phases require that exclusive left turn lanes be provided with protected phasing. Isolated intersections are tested primarily to acquire basic understanding of the policy, which would then be useful in applying this control approach to a coordinated system of signals.

The system parameters (with their associated values) are presented in Table 3.1.

3.1.1 Fuzzy Control Algorithm

In this application, the control tuning scheme is intended to fully utilize the entire possible green time generated by the fuzzy control algorithms. The fuzzy algorithm based on the accumulated expert knowledge, can be regarded as a set of heuristic decision rules.

The fuzzy algorithm adjusts the duration of the green traffic light by evaluating the traffic conditions at the end of the each phase. The green time for each phase is divided into a number of periods called, "interventions". Each intervention can last

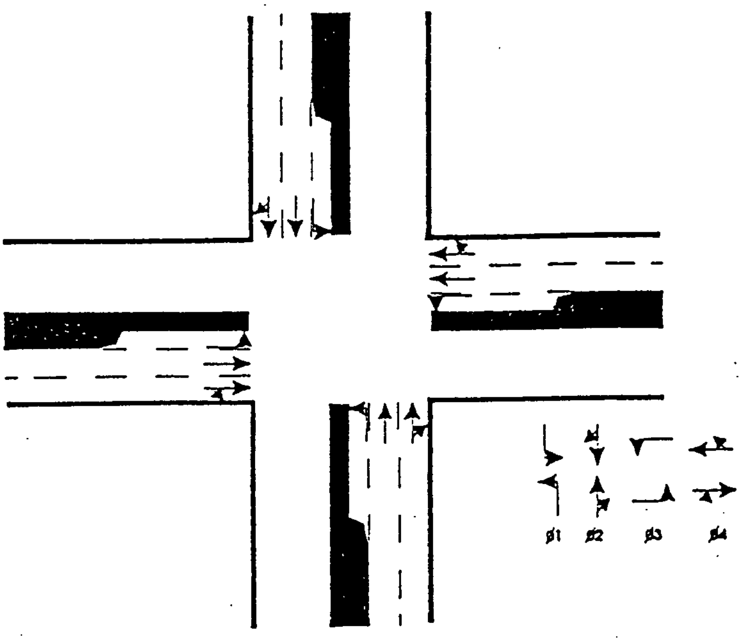

Figure 3.1 : Four-phase operation, protected turns on two streets

Link Length	500 ft.
Length of Left-Turn Pocket, if exists	200 ft.
Number of Full Lanes	2 lanes
Number of Lanes in Left-Turn Pocket, if exists	1 lane
Mean Value of the Start-up Lost Time	2.6 sec.
Mean Queue Discharge Headway	2.1 sec.
Free-Flow Speed	35 mph.

TABLE 3.1: Isolated Traffic Intersection System Parameters

from 0 up to a maximum of 10 seconds. A maximum of 5 independent interventions can be applied to the total green duration for a single phase in this application. The fuzzy controller determines the duration of the extension of the green time at the end of each intervention.

The control policy determines the length of the extension of the green time based upon the number of vehicles present within a certain area at each intervention. Thus, the duration of the green time that one approach can receive during a given time interval depends on the link length and the number of lanes, as well as on the flow rates of all approaches. The control responds to the present number of vehicles in a similar manner as the traffic-actuated control responds to demand. When one approach has a relatively low flow rate, drivers on that approach could suffer long delays because the number of vehicles present on the competing phases of that approach need a longer time to be discharged. Given the flow rates, the effective cycle length is only a function of the number of vehicles. To avoid long or extremely short cycle lengths, maximum and minimum values of green time are imposed, which determine the upper and lower bounds of the cycle length and the green time.

Every fuzzy control rule is parameterized by the process state variables in conjunction with the linguistic values devoted to these variables. The output variable corresponds to the "extension" of the green cycle and each fuzzy control rule is of the

following typical form

IF **S.LEFT** = LARGE AND
S.THRU = LT(MEDIUM) AND
C.LEFT = MT(SMALL) AND
C.THRU = ANY
THEN **EXTENSION** = LONG
ALSO
IF …
etc,

where

S.LEFT represents the fuzzy set related to the number of left-turning vehicles present within 200 ft. distance behind the stop line at the phase having the right of way.

S.THRU represents the fuzzy set related to the number of through vehicles present within 200 ft. distance behind the stop line at the same (or compatible) phase as the variable S.LEFT.

C.LEFT represents the fuzzy set describing the number of left-turning vehicles present within 200 ft. distance behind the stop line at the phase having the halted traffic.

C.THRU represents the fuzzy set related to the number of through vehicles present within 200 ft. distance behind the stop line at the same (or compatible) phase as the variable C.LEFT.

EXTENSION represents the fuzzy singleton of the length of the extension of the green time.

Note that among the compatible phases, the phase that has the largest number of vehicles present within 200 ft. is selected. Every rule is a fuzzy relation between the inputs S.LEFT, **S.THRU, C.LEFT** and **C.THRU.** The connectives "**AND**"and "**ALSO**"are interpreted as the operators "min" and "max" respectively. Therefore, each rule can be described in terms of the grade of the corresponding membership function. For example, the aforementioned fuzzy control rule described above can be described as

$$\mu_{R1}(S.LEFT, S.THRU, C.LEFT, C.THRU) = \min(\mu_{large}(s.left), \mu_{lt(medium)}(s.thru), \mu_{mt(small)}(c.left), any(c.thru)) = \min(\mu_{large}(s.left), \mu_{lt(medium)}(s.thru), \mu_{mt(small)}(c.left), 1)).$$

Finally two or more rules R1,R2,..., connected by the "ALSO" connective are defined on S.LEFT × S.THRU × C.LEFT × C.THRU with the appropriate grades of their membership function as

$$\mu(s.left, s.thru, c.left, c.thru) = \max(\mu_{R1}(s.left, s.thru, c.left, c.thru), \mu_{R2}(s.left, s.thru, c.left, c.thru), \ldots).$$

The terms "large", "more than medium(=MT(medium))", "less than or equal to small(=LE(SMALL))", "ANY", etc. are labels of fuzzy sets defined on the relevant universes of discourse S.LEFT, S.THRU, C.LEFT, C.THRU. Figures 3.2, 3.3 and 3.4 indicate the fuzzy sets used throughout this application study.The labels of the fuzzy sets for left-turn movements at the link having both the right of way and the halted traffic are shown in Figure 3.2. The labels of the fuzzy sets for the through movements at the link having the right of way and the halted traffic are shown in Figures 3.3 and 3.4, respectively.

The singletons for the extension of the green time are:

LABEL		DURATION(SECONDS)
"short"	→	3
"short plus"	→	5
"medium"	→	7
"long"	→	10

The operator "ANY" is defined throughout the universe of discourse with a grade of membership equal to one. The operators "MT()" and "LE()", standing for "more than" and "less than or equal to" respectively, are defined as follows:

$$\begin{aligned}
\mu_{LE()}(x_i) &= 0 && \text{for } x_i > x_o \\
&= 1-\mu_{()}(x_i) && \text{for } x_i \leq x_o, \\
\mu_{MT()}(x_i) &= 0 && \text{for } x_i \leq x_o, \\
&= 1-\mu_{()}(x_i) && \text{for } x_i > x_o
\end{aligned}$$

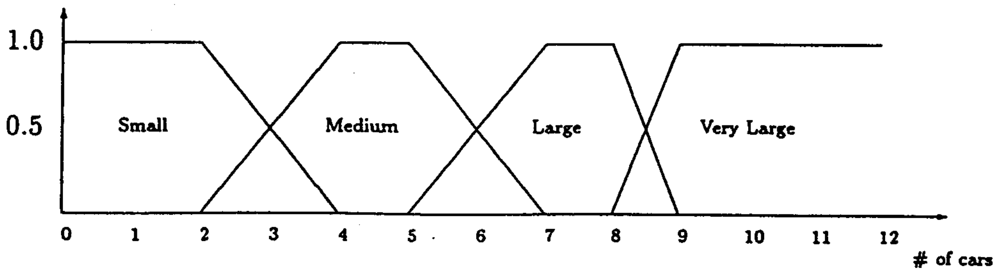

Figure 3.2 Fuzzy set labels applied to left-turn movements.

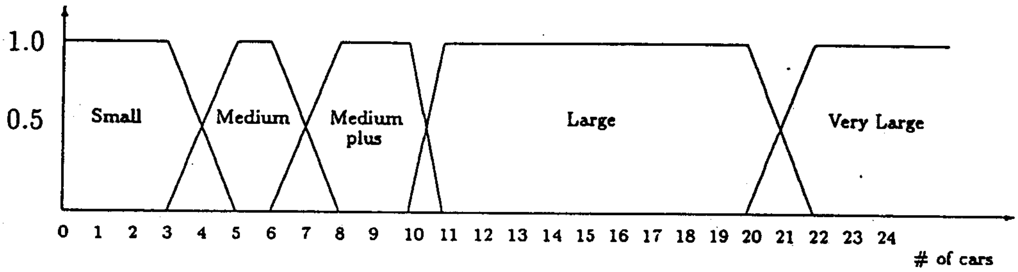

Figure 3.3 Fuzzy set labels applied to through movements for the link having the right of way.

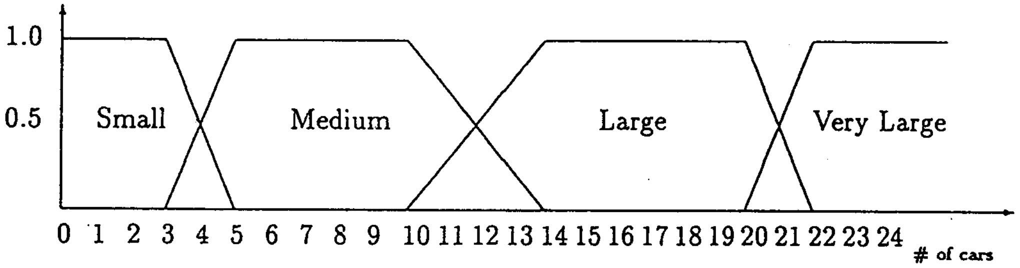

Figure 3.4 Fuzzy set labels applied to through movements for the link with halted traffic.

where () is a fuzzy set defined on the real line R= x_i and x_o is the element of the real line x_i for which $\mu_0(x_i)$ is maximum. A sample of the rulebase employed throughout this study appears in Appendix.

3.1.2 Decision Making Procedure

The fuzzy-logic algorithm, represented by the collection of the fuzzy control rules, is employed at each intervention to decide the control action. The number of vehicles present within 200 ft. distance behind the stop lines in every direction is available at the beginning of each intervention. The rules at each intervention are invoked in a sequential manner.

To exemplify this discussion consider the case where the fuzzy algorithm parameters used at the first intervention of the controller in the first set were: S.THRU = 5 vehicles and C.THRU = 2 vehicles present within 200 ft.distance from the stop lines.

The first fuzzy control rule R1 for the first intervention of the controller in the first set described in the Appendix is

if S.THRU = SMALL AND
C.THRU = SMALL
then EXTENSION = SHORT

According to the membership functions presented in Figure 3.3 and 3.4,

$\mu_{\mathrm{small}}(5) = 0$, $\mu_{\mathrm{small}}(2) = 1$ and EXTENSION = SHORT = 3.

Thus

$\mu_{R1}(5,2) = \min(\mu_{\mathrm{small}}(5), \mu_{\mathrm{small}}(2)) = \min(0,1) = 0$ and EXTENSION = 1

Similarly we find

$\mu_{R2}(5,2) = \min(\mu_{\mathrm{small}}(5), \mu_{\mathrm{nt(small)}}(2)) = \min(0,0) = 0$ and EXTENSION = 7

$\mu_{R3}(5,2) = \min(\mu_{\mathrm{nt(small)}}(5), \mathrm{ANY}) = \min(1,1) = 1$ and EXTENSION = 10

Thus, using the center-of-gravity method,

$$\text{EXTENSION} = (0 \times 1 + 0 \times 7 + 1 \times 10) = 10 \text{ (sec)}.$$

Therefore, the output of the control action which represents the extension of green time at the first intervention of the controller in the first fuzzy rule set is 10 seconds. Depending on the output of control action, there are two cases to consider for the next intervention.

The extension is greater than zero: The state of the system (i.e. the phase) will remain the same at the end of the extension period. At the end of the extension period, another control action from the algorithm at the next intervention of the current one will be determined in the manner described above. This process will be repeated by updating the algorithm at the next intervention, until either no extension would be given or the maximum intervention is reached.

No extension is given(or the maximum intervention is reached in the current phase): The state of the system would be immediately changed to the competing phase, and a control action from the algorithm at the first intervention for the new phase will be determined.

3.1.3 Simulation Studies

A wide range of flow rates were applied to obtain comparative traffic delay results between the actuated and the fuzzy logic controller. Simulation results for two cases of "Through movements only" and "Permissible left turns" are presented. In the following plots, the horizontal axis represents the ratio of the East-West(E-W) traffic to the North-South(N-S) traffic. The vertical axis indicates the ratio of delays caused by the actuated controller to those caused by the fuzzy logic controller. The actual simulation time corresponds to one hour of traffic. For the left turn case, the volume of left-turn traffic is 20% of the through traffic volume in each lane. Throughout the simulation, the E-W traffic volume was kept fixed, while the N-S traffic volume was varied in a certain range. Table 3.2 gives the E-W and N-S traffic volumes for which the simulations are carried out. The graphs in Figures 3.5 and 3.6 correspond to the "Through movements only" cases, while those in Figures 3.7 and 3.8 to the "Permissible left-turns movements".

From the plots of Figures 3.5 and 3.6, the ratio of delays caused by the actuated controller to those caused by the fuzzy logic controller is greater than one for various combinations of flow rates. Furthermore, the plot of Figure 3.5(Figure 3.6) shows up to 19%(16%) efficiency, in terms of the ratio of delays, due to the fuzzy logic control for low traffic(heavy traffic). In Figure 3.5, we observe that the ratio of delays between two controllers increases as the ratio of E-W to N-S traffic increases.

Figure	E-W traffic($\frac{\text{vehicles}}{\text{hour} \cdot \text{lane}}$)	Range of N-S traffic($\frac{\text{vehicles}}{\text{hour} \cdot \text{lane}}$)
3.5	350	350-750
3.6	500	500-750
3.7	240	240-570
3.8	330	330-570

Table 3.2: Simulation traffic flow rates

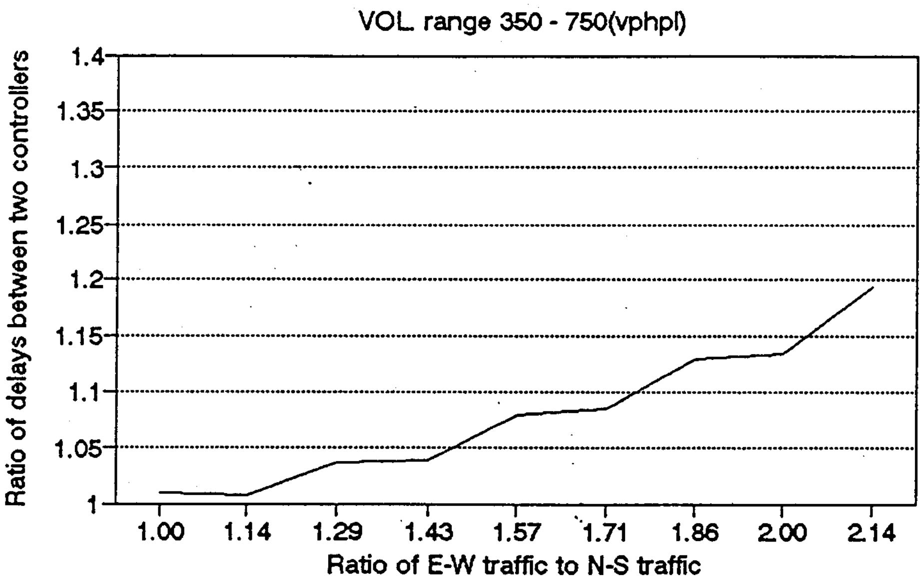

Figure 3.5 Ratio of delays caused by the actuated controller to those caused by the fuzzy logic controller in the "Through movements only" case, with low traffic.

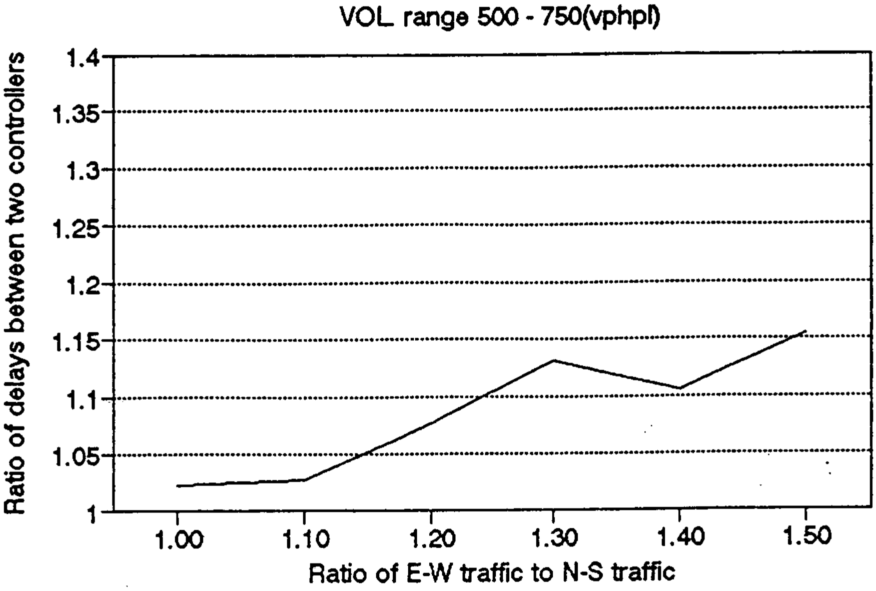

Figure 3.6 Ratio of delays caused by the actuated controller to those caused by the fuzzy logic controller in the "Through movements only" case, with heavy traffic.

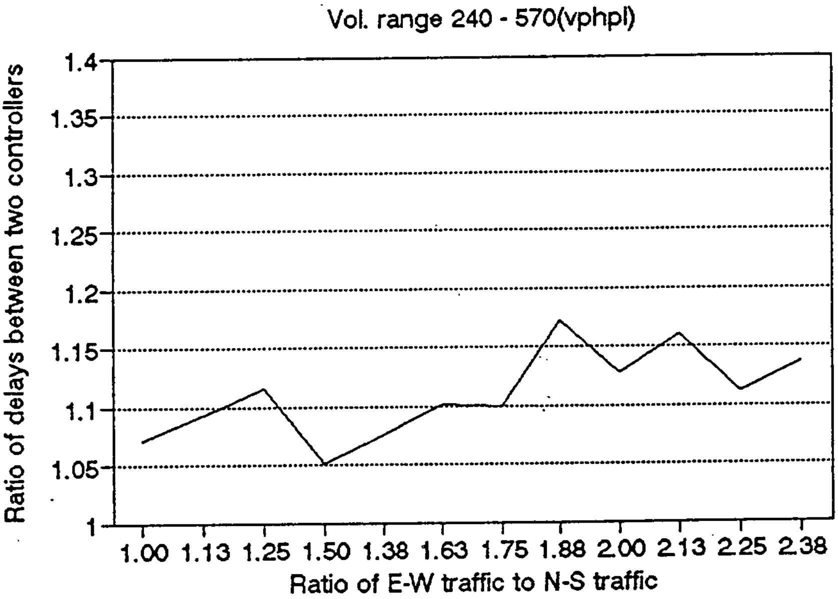

Figure 3.7: Ratio of delays caused by the actuated controller to those caused by the fuzzy logic controller in the "Permissible left-turns" case, with low traffic.

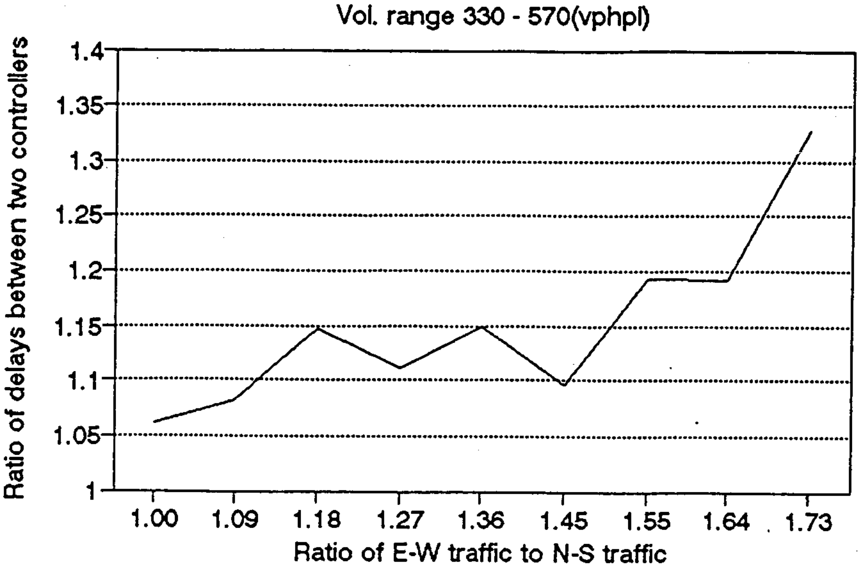

Figure 3.8: Ratio of delays caused by the actuated controller to those caused by the fuzzy logic controller in the "Permissible left-turns" case, with heavy traffic.

In the plots of Figures 3.7 and 3.8, the ratio of delays between the actuated and fuzzy logic control is also greater than one for various combinations of flow rates. Moreover, the plot of Figure 3.7(Figure 3.8) indicates up to 17%(33%) efficiency of fuzzy logic traffic control for low traffic(heavy traffic). In particular, the difference in efficiency between the low traffic and the heavy traffic case indicates that the efficiency of the actuated controller deteriorates significantly when the left-turn vehicle volume increases in heavy traffic.

From the plots of Figures 3.5 through 3.8, it is evident that the ratio of delays between the actuated and the fuzzy logic controller is greater than one for all possible combinations of flow rates, thus validating the fact that the performance of the fuzzy logic controller is better than that of the actuated controller. Furthermore, the comparison ratio (the efficiency of fuzzy control) increases for larger E-W and N-S traffic ratio.

Performance variation with respect to traffic parameters detection distance

The robustness of the fuzzy logic controller to the detection distance for the traffic parameters is investigated in the following simulation study.

In the previous section, the fuzzy sets **S.LEFT** and **S.THRU** were defined based on a 200ft detection distance. To accommodate various detection distances, the fuzzy variables have been modified by introducing the notion of the "normalized traffic volume." This is defined with respect to the volumes that were used in the previous simulation cases (Figures 3.2 thru 3.4.)

The main difference is that the horizontal axis is proportional to the detection distance. The number of automobiles considered in the fuzzy rules, which maintain their structures, have been modified to

$$\text{VEHICLES} \times \frac{200}{\text{DISTANCE}}$$

where **VEHICLES** the number of vehicles present within the detection distance behind the stop line.

DISTANCE detection distance.

A combination of three discrete detection distances (500 - □, 300 - × and 150 - +feet) were used in this study. The performance of the fuzzy logic controller was evaluated using the same traffic scenario as in the previous section. Figures 3.9, 3.10, 3.11, and 3.12 are related to Figures 3.5, 3.6, 3.7 and 3.8, respectively, from the previous section.

In spite of the large distance detection variation, the fuzzy logic controller overall exhibited a better performance compared to the classical control scheme. The only case where the performance deteriorated was for the largest (500ft) detection distance and the equal traffic bound volume. This is mainly attributed to the uncertainty of distinguishing automobiles which are standing from those which are still moving (due to this large distance).

3.2 Fuzzy Logic Traffic Control for a System of Coordinated Intersections

Networks with coordinated traffic signal sys-

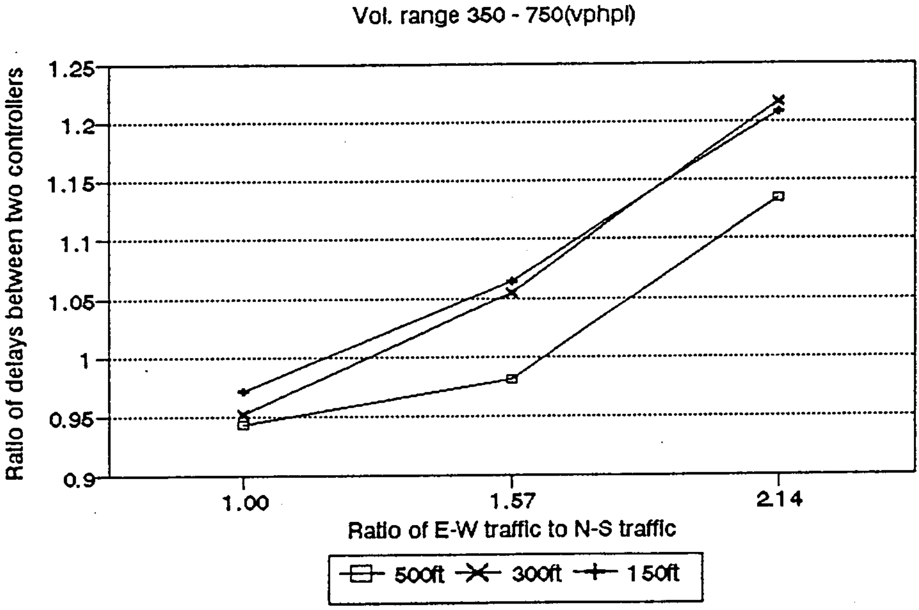

Figure 3.9: Ratio of delays caused by the actuated controller to those caused by the fuzzy logic controller in the "Through movements only" case, with low traffic and various detection distances

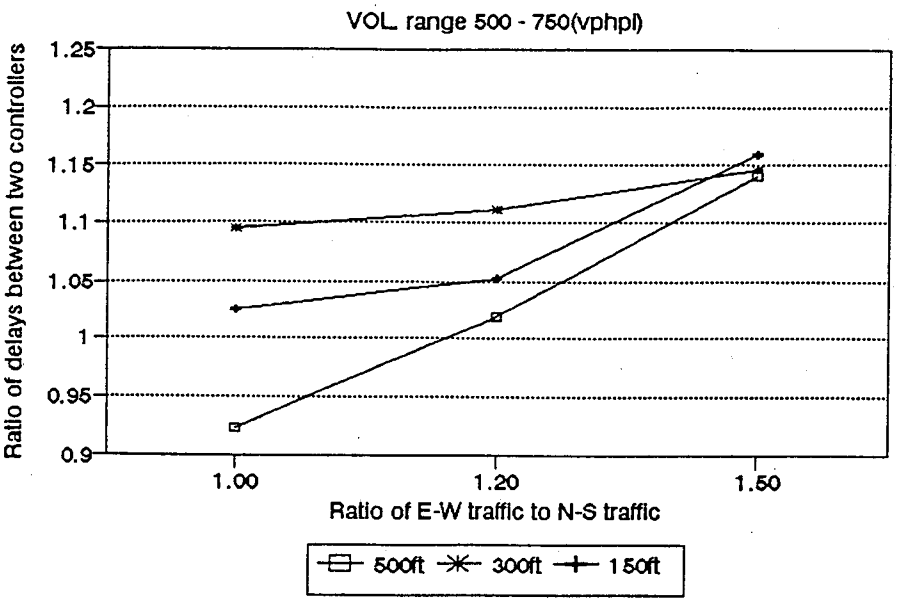

Figure 3.10: Ratio of delays caused by the actuated controller to those caused by the fuzzy logic controller in the "Through movements only" case, with heavy traffic and various detection distances.

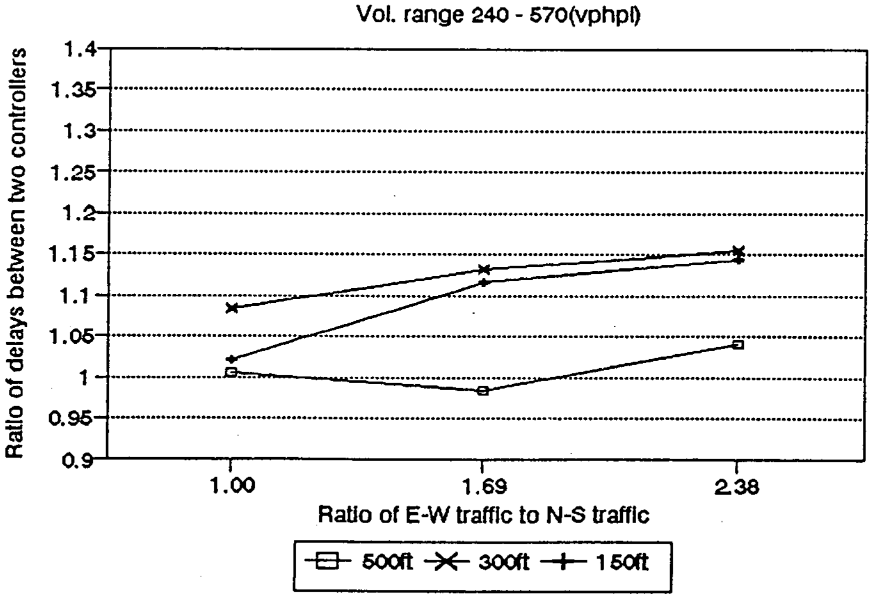

Figure 3.11: Ratio of delays caused by the actuated controller to those caused by the fuzzy logic controller in the "Permissible left-turns" case, with low traffic and various detection distances.

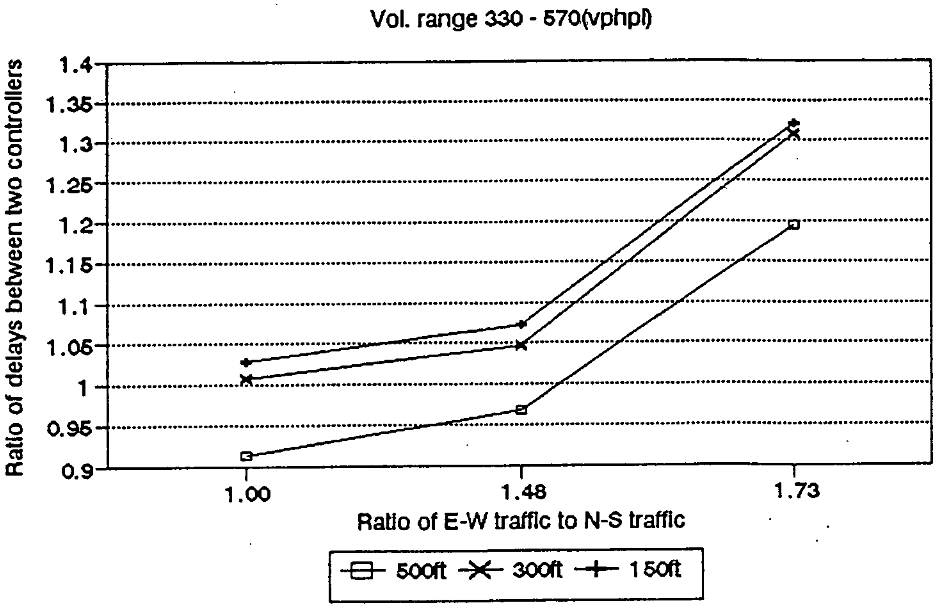

Figure 3.12: Ratio of delays caused by the actuated controller to those caused by the fuzzy logic controller in the "Permissible left-turns" case, with heavy traffic and various detection distances.

tems require the underlying philosophy to establish a synchronized signal timing strategy to facilitate the uninterrupted movement of through vehicles along the roadway.

Transportation networks with high traffic volumes require continuous tuning of the relative signal timing offsets since the classical offset plans appear to be ineffective.

For example, simultaneous offset plans are effective in eliminating oversaturation at critical intersections: however they tend to degrade the performance of adjacent intersections in the system[Gaz64,Pig78]. Smooth flow theory and reverse progression[Pet47,HCM85] generally reduce excessive queues at the critical intersection to prevent oversaturation and therefore reduce the productivity of a critical intersection. The modification of the cycle length and the split ratio does not act positively to prevent the blockage of intersections, which is the prime concern during the oversaturation period.

A new control concept is desired, which not only ensures the prevention of intersection blockage as much as possible, but also minimizes the performance degradation at other intersections in the system. In saturated or oversaturated operations all vehicles must join the queues and stop at least once somewhere upstream of the critical intersections, since the critical intersection can not handle the volumes delivered to it at any cycle length. In practical terms, there is no "through" traffic without haulting at the critical intersection. The new control concept should be capable of maintaining high productivity of the maximum "through" traffic at a critical intersection. The intersection productivity is more important than the quality of operation (signal progression) during a period of oversaturation.

3.2.1 The fuzzy logic traffic control policy.

The adopted control strategy relies upon an overlapping framework in which an "isolated" fuzzy control algorithm is applied at each intersection. The fuzzy control algorithm used at each intersection is mostly identical to the utilized control scheme under the assumption of a completely isolated intersection as described in the previous section.

Figure 3.13 shows a typical example network of five coordinated intersections with their geometries, phasing, and respective volumes expressed in $\frac{vehicles}{hour \cdot lane}$. In this Figure, the intersections N1 through N4 lead into the critical intersection (CI). By definition, a CI is one which can not handle the volumes delivered to it at any cycle length. For the link names which have the general form of "xxy" in the Figure, the first two letters in the link name describe the intersection name and the last letter corresponds to the main bound direction; i.e., "CIE" refers to the east bound direction

of the

"CI" intersection.

The introduction of the "fuzzy logic control policy", in the midst of a coordinated system of signals, is functionally similar to the introduction of a more conventional traffic-responsive control strategy, such as the full-actuated, in the sense that it places an essentially cycle-free traffic controller in the midst of a set of fixed-time signals.

The coordinated intersection can be subdivided into four symmetric regions (sections), separated by the dashed arcs as shown in Figure 3.13. It is sufficient to analyze the control behavior for any one of these sections. As an example, consider the upper dashed arc section for intersection N1 and CI. The traffic flow from the immediate upstream intersection (N1) of CI into CI decides the timings of the signal at the critical intersection (CI). In this case, two extreme conditions may occur.

1. The through movement traffic from the upstream of the intersection (N1) of the critical intersection into CI provides all the traffic flow.
2. The turn-in (left or right turn) traffic from the upstream of the intersection (N1) of the critical intersection into CI feeds the queue at the critical intersection.

The fuzzy control policy handles the first case by initiating the green as soon as sufficient additional through vehicles arrive at CI. Thus, the relative offset between these two intersections looks like a forward progression, since vehicles from the upstream intersection(N1) will arrive at the downstream intersection(CI) just as the signal at that intersection(CI) is initiated to green.

In the second case, the maximum number of allowable vehicles will be reached before the initiation of green at the upstream intersection (N1). Thus the relative offset will imitate a reverse progression scheme.

For some combination of through and turn-in traffic, the relative offset will imitate a simultaneous progression scheme, since the green time initiations between these two intersections will occur at the same time.

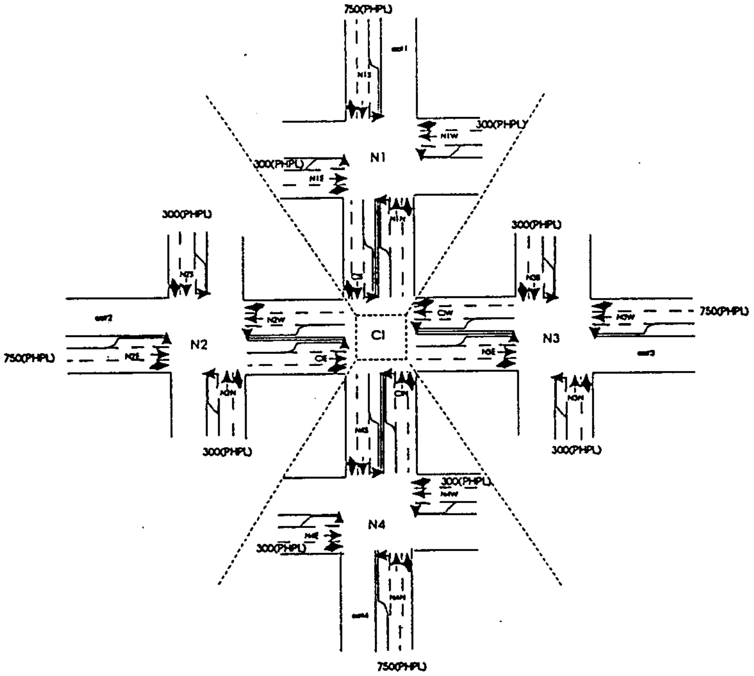

Figure 3.13: Coordinated intersections with their geometries, phasing and respective volumes.

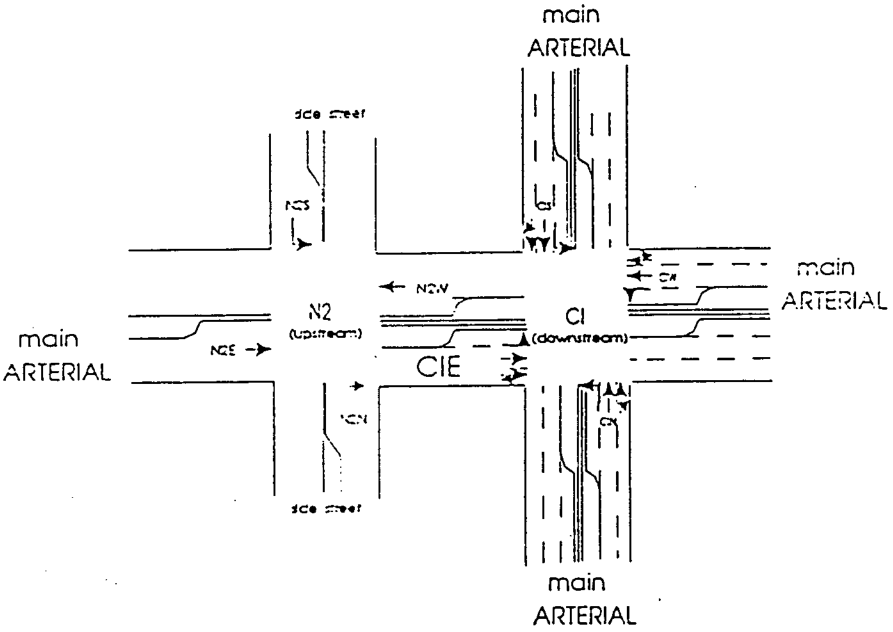

Figure 3.14: General form of any interconnected section of the coordinated intersections.

The fuzzy rulebase needs to take into account the possible blockage at the intersection due to potential heavy traffic conditions. To prevent intersection blockage, the following modifications can be made in the "isolated intersection" fuzzy control policy (as applicable to Figure 3.14):

IF the link CIE is saturated[3] and the signal for that approach at CI is red
THEN
Do not allow any traffic into the link CIE from the upstream intersection (N2) of CI, but allow traffic only out of the link N2W if it has the right of way.

IF the link is saturated and the signal for that approach at CI is green
THEN
Allow only the turn-in traffic from links N2S and N2N into the link CIE if they have the right of way.

IF the link CIE occupied[4] is described as "NOT saturated" and the signal for that approach at CI is green
THEN
Allow either the turn-in traffic from N2S and N2N links into CIS, if it has the right of way.
OR
Allow the through traffic from the link N2E into link CIE, if they have the right of way.

To implement these modifications within the "isolated" fuzzy control algorithm is through the use of fuzzy singletons. The modified fuzzy algorithm has the general form of:

IF "BLOCKAGE-CONDITIONS" are about to occur
THEN
Implement the corresponding aforementioned action for each condition for the prevention of blockage.
ELSE
Apply the same fuzzy algorithm used in the isolated case to the system.

where "BLOCKAGE-CONDITIONS" represent one of the three conditions mentioned above for the prevention of blockage.

The prevention of intersection blockage becomes significant with arterials or networks where the traffic flow is heavy in all incoming directions. In this case, the intersection blockage not only increases the delay through the system, but also affects other neighboring segments of that system. This control policy confronts the intersection blockage problem by predicting the spillback conditions that may generate these blockage.

3.2.2 Simulation Study

The fuzzy controller performance was assessed in simulation studies by comparing to that of a pretimed controller. Both controllers were tested in saturated traffic network conditions. For these heavy traffic conditions the performance index of these controller needs to focus primarily in the spillback avoidance factor. Table 3.3 indicates the

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[3] Defined as the number of vehicles observed in a link reached 90% of the capacities delivered to it in NETSIM-described as "Very Large" in Page 8.

[4] Defined as the number of vehicles observed in a link.

most common objectives that should be considered by the control designer during saturated/oversaturated traffic periods[Pig78].

The spillback prevention, the total number of vehicles traveling out of the exit links, and the queue extent in all entry links were considered in the controller performance comparison study.

Several traffic flow levels were considered with the main arterial link set at a higher volume (750 veh/hour/lane, Figure 3.13) compared to the neighboring intersection side-link (300 veh/hour/lane, Figure 3.13). The presented results correspond to a 30 minute simulation period (Case 1).

Figure 3.15 shows the total duration of spillback in seconds for the pretimed controller, while on the other hand the fuzzy logic controlled system did not indicate any spillback occurrence.

In Figure 3.16, the horizontal axis represents the total number of vehicles that traveled through the exit links of the system during the simulation time, while the vertical axis refers to the corresponding link exits. In this case, 2544 vehicles traveled through the exit links for the fuzzy controlled system, compared to the 2504 vehicles for the pretimed-controlled system.

Figure 3.17 shows the plot of the mean content(or queue extent) for each entry link during the simulation period. For the pretimed controller, the mean contents were almost the same as the link capacity (near saturation); for the fuzzy logic controller the mean content 90% of the entry link capacity. It indicates that additional 10% vehicles of the entry link capacity can enter to the system for the fuzzy logic control.

The robustness of the fuzzy logic controller with respect to incoming traffic volume variations was tested in a series of simulation test cases. Table 3.4 provides the main arterial link and the neighboring intersection side-link traffic volumes for which the additional simulations were carried out for this comparison study.

By comparing Figures 3.18 through 3.25, it can be seen that the traffic flow levels, i.e., the total number of vehicles traveling out of the system and the queue extent in all entry links,

Table 3.3: Controller objectives in saturated/oversaturated networks.

Desired objective	Avoid spillback Provide equitable service
Objective impact	Reduced rate of spread congestion Reduced potential occurrence of wide area congestion
Performance index	· Queue extent Maximum output

Table 3.4: Simulation traffic flow rates (Cases 2 through 5).

Case	Figure index	Arterial traffic($\frac{vehicles\ over}{hour \cdot lane}$)	Side traffic($\frac{vehicles\ over}{hour \cdot lane}$)
2	3.18 and 3.19	675	225
3	3.20 and 3.21	700	250
4	3.22 and 3.23	725	275
5	3.24 and 3.25	775	325

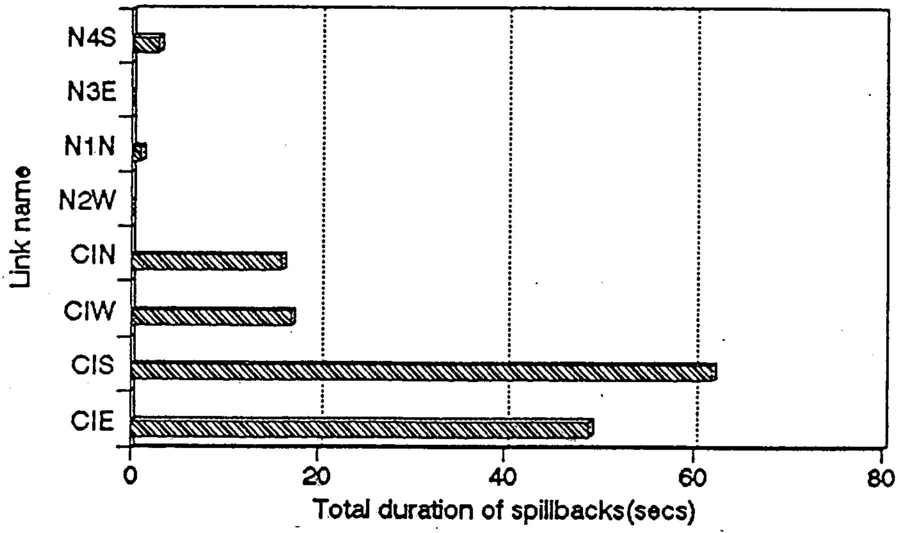

Figure 3.15 : Total Duration of spillback for pretimed controller(Case1).

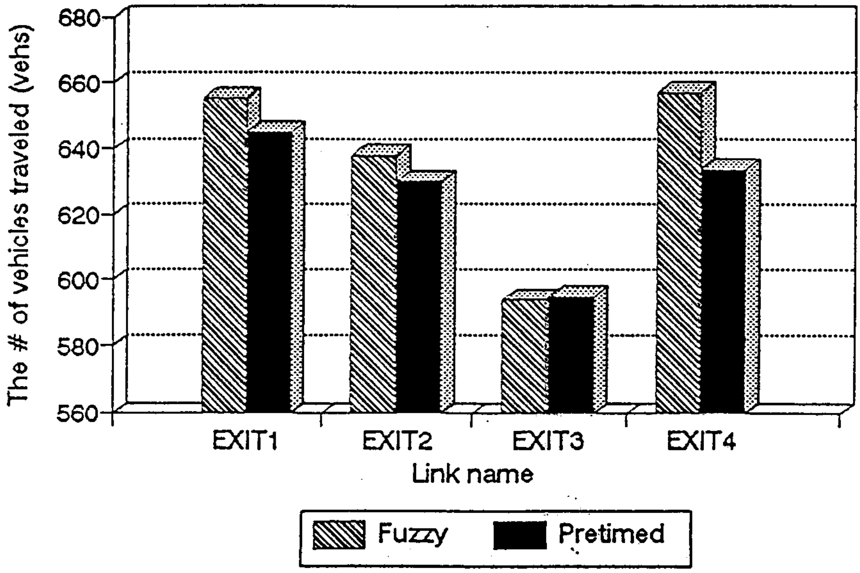

Figure 3.16: Total number of vehicles traveling out of link exits(Case1)

the fuzzy logic controller results in a better overall performance.

4. Summary and Conclusion

In this chapter, a general overview of fuzzy sets and the underlying theory of fuzzy logic control was introduced. The development a real-time traffic adaptive control based on fuzzy logic for isolated and coordinated intersections was presented. For the isolated intersection case, a wide range of flow rates were applied to compare the system's performance in terms of delays experienced by the actuated and the fuzzy logic controller. Simulation results for the case of "Through movements only" and "Permissible left-turns" indicated the performance of the system was better under the fuzzy logic controller.

The results obtained from the application of the fuzzy logic controller were compared with those corresponding to a pretimed controller for the coordinated intersections. With the performance criterion being the prevention of spillback, occupancy and queue extent, it was shown that the use of a fuzzy logic controller resulted in a better performance.

It is important to note that the fuzzy algorithms have the distinct advantage of being amenable to a real-time application since they do not rely on a complicated mathematical transfer function for formulating their control rules. Instead, the fuzzy algorithms rely mainly on the expert knowledge of the designer which easily can be converted into a linguistic control strategy. Furthermore, by using different sets of control rules, the fuzzy controller can operate over a large range of inputs.

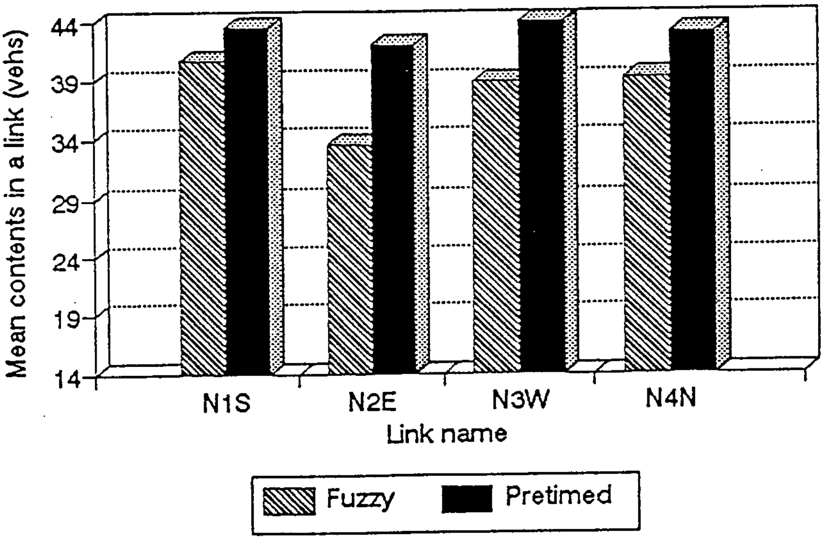

Figure 3.17: Mean contents in all entry links (Case 1).

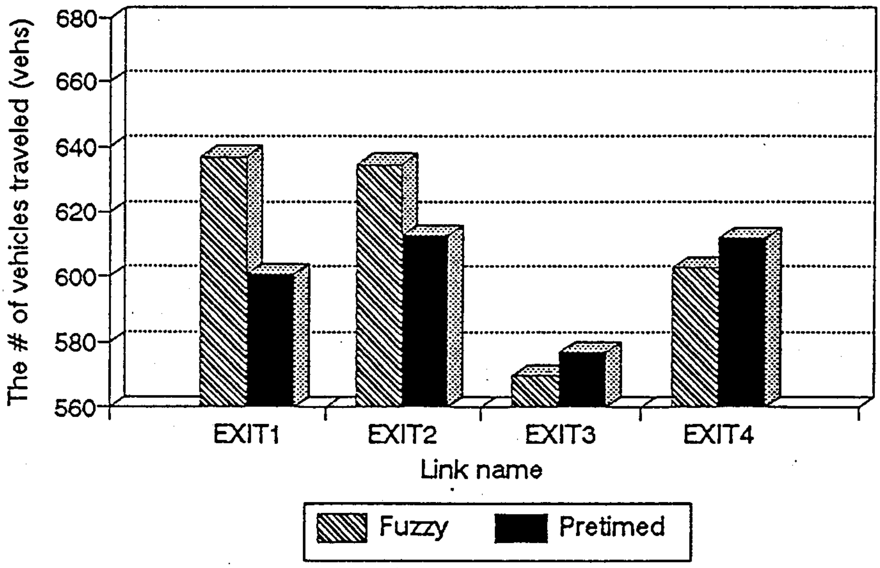

Figure 3.18: Total number of vehicles traveling out of link exits (Case 2).

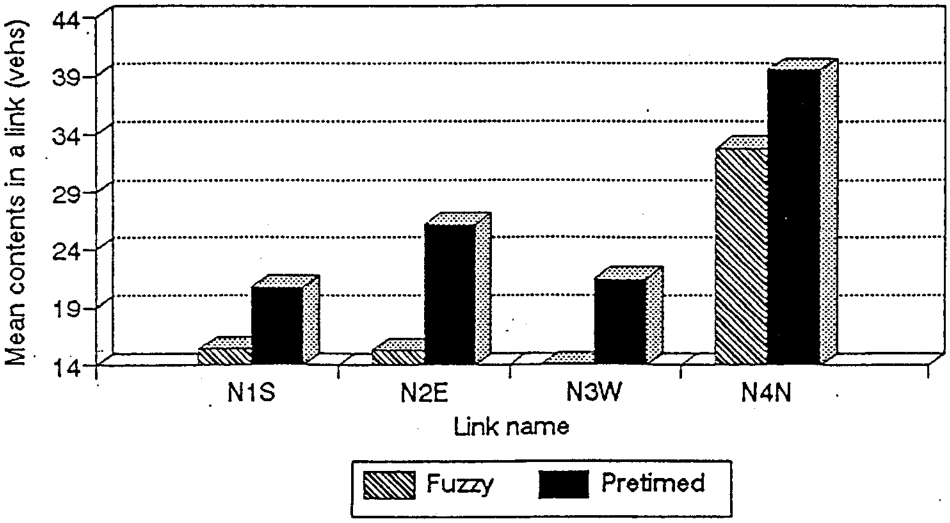

Figure 3.19: Mean contents in all entry links (Case 2).

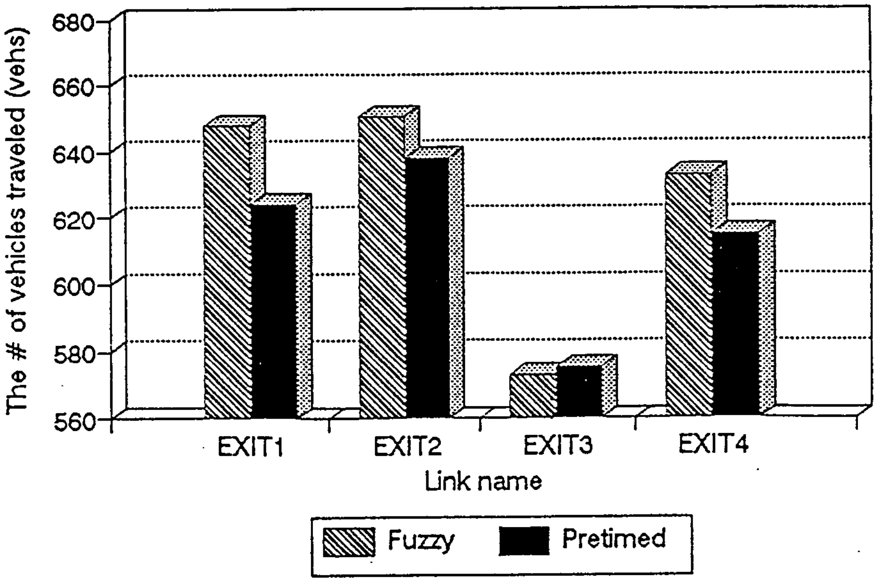

Figure 3.20: Total number of vehicles traveling out of link exits (Case 3).

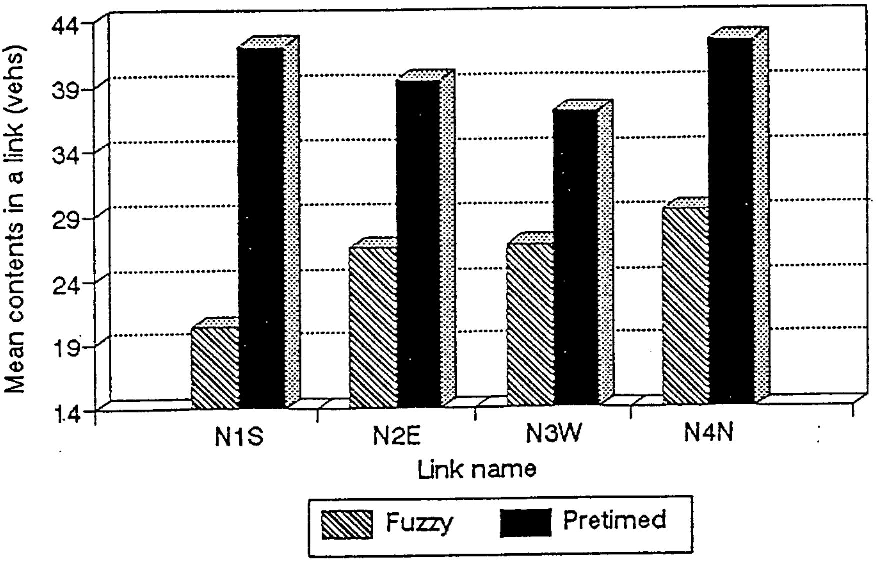

Figure 3.21: Mean contents in all entry links (Case 3).

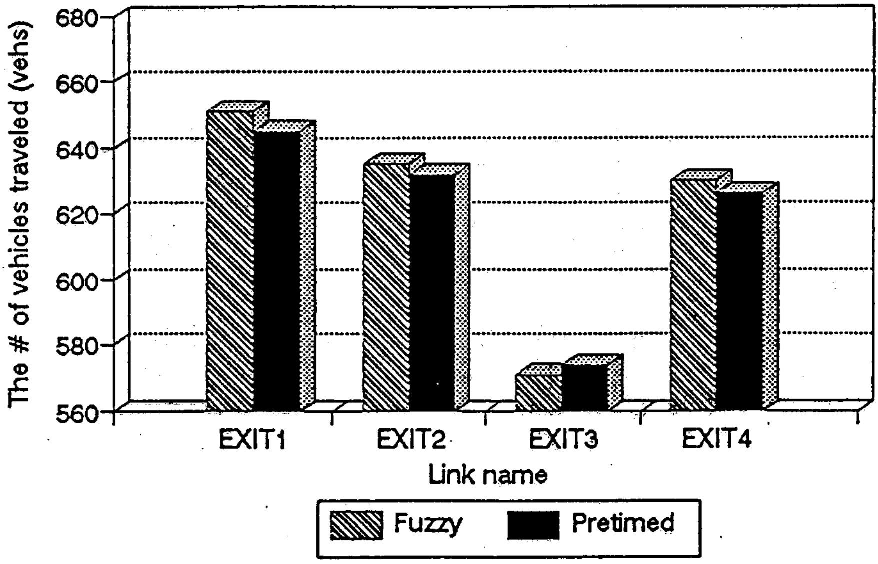

Figure 3.22: Total number of vehicles traveling out of link exits (Case 4).

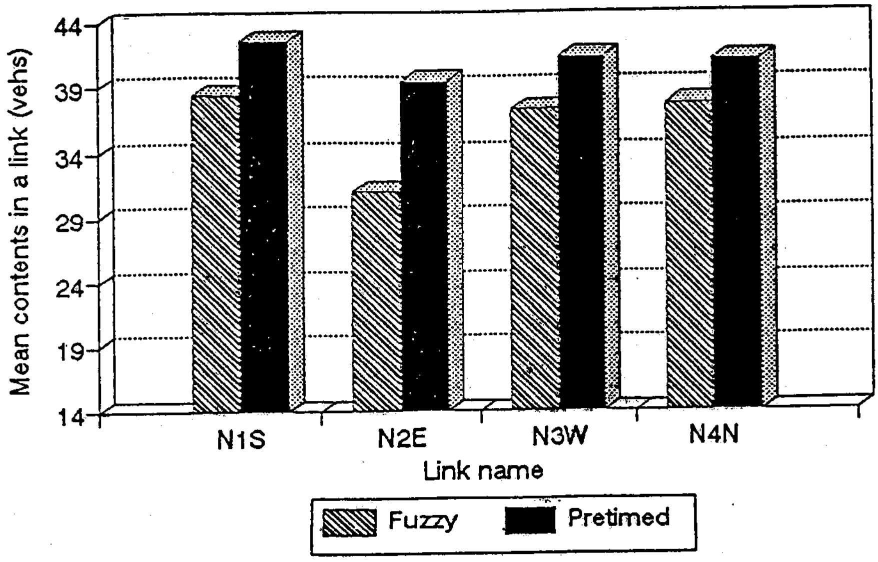

Figure 3.23: Mean contents in all entry links (Case 4).

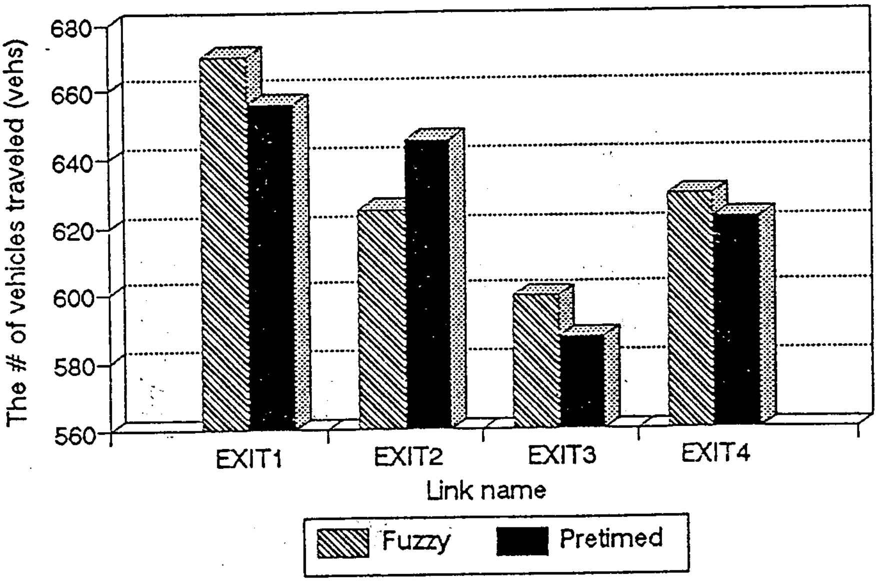

Figure 3.24: Mean contents in all entry links (Case 5).

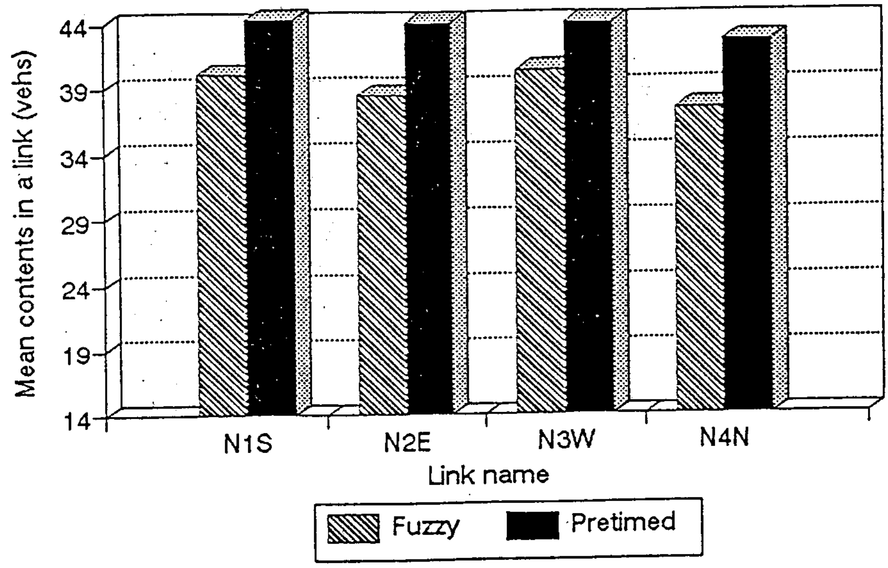

Figure 3.25: Mean contents in all entry links(Case 5).

[BG] J. F. Baldwin and N.C.F. Guild. Modelling controllers using fuzzy relations. Kybernetes 9, 223-229,1980.

[BR79] M.Brace and D.Rutherford. Theoretical and linguistic aspects of the fuzzy logic controller. Automatica, 15(5): 553-557,1979.

[DP80] D. Dubois and H. Prade. Fuzzy sets and systems: Theory and Applications. Academic Press,1980.

[End87] T. Endo. Fuzzy control of transportation systems. IEEE proc. int. Workshop on industrial Automation Systems, Seiken Symposium, 33-38, 1987.

[Gaz64] Denos C. Gazis. Optimum control of a system of oversaturated intersections. Operations Research, 815-831, 1964.

[Hig85] Highway capacity manual. Transportation Research Board SR209, 1985.

[Ini89] R. Inigo. Application of machine vision to traffic monitoring and control. IEEE Trans. on Vehicular Technology, 38(3): 112-122, 1989.

[KLD92] Associates Inc. KLD. Traf-Netsim user's guide. 1992.

[LL89] Y. Li and C. Lau. Development of fuzzy algorithms for servo systems. Proc. of IEEE, 65-72, 1989.

[MA75] E. H. Mamdani and S. Assilian. An experiment in Linguistic syvthesis with a fuzzy logic controller. Int J. Man-Machine Studies, 7:1-13, 1975.

[Mam76] E. H. Mamdani. Advances in the Linguistic synthesis of fuzzy controllers. Int J. Man-Machine Studies, 8(6):669-678, 1976.

[Mam77a] E. Mamdani. Application of fuzzy logic to approximate reasoning using linguistic synthsis. IEEE Trans. on Computers, C-26(12) : 1182-1191, 1977.

[Mam77b] E. Mamdani. Application of fuzzy set theory to control systems: A survey. fuzzy Automata and Decision processes. New York, NY, 1977.

[MWB90] P. Michalopouplos, B. Wolf, and R. Benke. Testing and field implementation of the Minnesota video detection system. Transportation Research Record (1287),1990.

[Pet67] J L. Petterman. Timing Progressive signal systems. Traffic Engineering, 194-199, February 1967.

[Pig78] Louis J. Pignataro. Traffic control in oversaturated street networks.

National cooperative highway research program report 194, 1978.

[PM79] T. J. Procyk and E.H. Mamdani. A linguistic self-organizing process contr-oller. Automatica, 15:15-30, 1979.

[TM87] K. Tand and R. Muholland. Comparing fuzzy logic with classical controller designs. IEEE Trans. on System, Man, and Cybernetics. SMC-17(16) :1085-1087, 1987.

[Ton77] R. Tong. A control engineering review of fuzzy systems. Automatica, 13:559-569, 1977.

[TS85] T. Takagi and M. Sugeno. Fuzzy identification of systems and its application to modelling and control. IEEE Trans. Syst., Man, Cybern., SMC-1 :116-132, 1985.

[Zad65] L.A. Zadeh. Fuzzy Sets. Information and control, 8 : 338-353, 1965.

[Zad73] L.A. Zadeh. Outline of a new approach to the analysis of complex system and decision processes. IEEE Trans. SMC -3-1,5:28-44,1973.

APPENDIX

THE FIRST SET

FOR THROUGH-MOVEMENTS ONLY

1ST INTERVENTION

if S.THRU = SMALL AND
C.THRU = SMALL
then EXTENSION = SHORT
also
if S.THRU = SMALL AND
C.THRU = MT(SMALL)
then EXTENSION = MEDIUM
also
if S.THRU = MT(SMALL) AND
C.THRU = ANY
then EXTENSION = LONG

2ND INTERVENTION

if S.THRU = SMALL AND
C.THRU = LE(SMALL)
then EXTENSION = SHORT
also
if S.THRU = MEDIUM AND
C.THRU = ANY
then EXTENSION = MEDIUM
also
if S.THRU = MT(MEDIUM) AND
C.THRU = ANY
then EXTENSION = LONG

3RD INTERVENTION

if S.THRU = MEDIUM AND
C.THRU = LE(MEDIUM)
then EXTENSION = MEDIUM
also
if S.THRU = MT(MEDIUM) AND
C.THRU = ANY
then EXTENSION = LONG

4TH INTERVENTION

if S.THRU = MEDIUM AND
C.THRU = LE(MEDIUM)
then EXTENSION = MEDIUM
also
if S.THRU = MT(MEDIUM) AND
C.THRU = ANY
then EXTENSION = LONG

5TH INTERVENTION

if S.THRU = MT(SMALL) AND
C.THRU = VERY LARGE
then EXTENSION = SHORT
also
if S.THRU = MT(SMALL) AND
C.THRU = LARGE
then EXTENSION = MEDIUM
also
if S.THRU = MT(SMALL) AND
C.THRU = LE(MEDIUM)

```
        then    EXTENSION = LONG
```

THE SECOND SET

FOR LEFT AND THRU MOVEMENTS
FOR LEFT-TURN SIGNAL

1ST INTERVENTION

```
        if      S.LEFT    = SMALL          AND
                S.THRU    = ANY            AND
                C.LEFT    = ANY            AND
                C.THRU    = ANY
        then    EXTENSION = SHORT.
also
        if      S.LEFT    = MEDIUM         AND
                S.THRU    = ANY            AND
                C.LEFT    = ANY AND
                C.THRU    = ANY
        then    EXTENSION = SHORT PLUS
also
        if      S.LEFT    = MT(MEDIUM)     AND
                S.THRU    = VERY LARGE     AND
                C.LEFT    = VERY LARGE     AND
                C.THRU    = ANY
        then    EXTENSION = SHORT PLUS
also
        if      S.LEFT    = MT(MEDIUM)     AND
                S.THRU    = LARGE          AND
                C.LEFT    = VERY LARGE     AND
                C.THRU    = ANY
        then    EXTENSION = MEDIUM
also
        if      S.LEFT    = MT(MEDIUM)     AND
                S.THRU    = LE(LARGE)      AND
                C.LEFT    = LE(LARGE)      AND
                C.THRU    = ANY
        then    EXTENSION = LONG
```

2ND INTERVENTION

```
        if      S.LEFT    = SMALL,         AND
                S.THRU    = ANY            AND
                C.LEFT    = ANY            AND
                C.THRU    = ANY
        then    EXTENSION = SHORT
also
        if      S.LEFT    = MEDIUM         AND
                S.THRU    = ANY            AND
                C.LEFT    = ANY            AND
                C.THRU    = ANY
        then    EXTENSION = SHORT PLUS
also
        if      S.LEFT    = MT(MEDIUM)     AND
                S.THRU    = LE(LARGE)      AND
                C.LEFT    = LE(LARGE)      AND
                C.THRU    = ANY
        then    EXTENSION = LONG
```

FOR THROUGH SIGNAL

1ST INTERVENTION

```
        if      S.THRU    = SMALL          AND
                C.LEFT    = SMALL          AND
                C.THRU    = SMALL          AND
                S.LEFT    = ANY
        then    EXTENSION = SHORT
also
        if      S.THRU    = SMALL          AND
                C.LEFT    = LE(MEDIUM)     AND
                C.THRU    = MT(SMALL)      AND
                S.LEFT    = ANY
        then    EXTENSION = MEDIUM
also
        if      S.THRU    = MT(SMALL)      AND
                C.LEFT    = MT(MEDIUM)     AND
                C.THRU    = MT(MEDIUM)     AND
                S.LEFT    = ANY
        then    EXTENSION = MEDIUM
also
        if      S.THRU    = MT(SMALL)      AND
                C.LEFT    = LE(MEDIUM)     AND
                C.THRU    = LE(MEDIUM)     AND
                S.LEFT    = ANY
        then    EXTENSION = LONG
```

2ND INTERVENTION

```
        if      S.THRU    = SMALL          AND
                C.LEFT    = ANY            AND
                C.THRU    = SMALL          AND
                S.LEFT    = ANY
        then    EXTENSION = SHORT
also
        if      S.THRU    = MEDIUM         AND
                C.LEFT    = VERY LARGE     AND
                C.THRU    = LARGE          AND
                S.LEFT    = ANY
        then    EXTENSION = SHORT PLUS
also
        if      S.THRU    = MEDIUM         AND
                C.LEFT    = LE(LARGE)      AND
                C.THRU    = LE(LARGE)      AND
                S.LEFT    = ANY
        then    EXTENSION = MEDIUM
also
        if      S.THRU    = MT(MEDIUM)     AND
                C.LEFT    = LE(LARGE)      AND
                C.THRU    = LE(LARGE)      AND
                S.LEFT    = ANY
        then    EXTENSION = LONG
```

3RD INTERVENTION

```
        if      S.THRU    = MEDIUM         AND
                C.LEFT    = VERY LARGE     AND
                C.THRU    = VERY LARGE     AND
                S.LEFT    = ANY
```

```
        then    EXTENSION = SHORT
also
        if      S.THRU    = MEDIUM         AND
                C.LEFT    = ANY            AND
                C.THRU    = LE(MEDIUM)     AND
                S.LEFT    = ANY
        then    EXTENSION = MEDIUM
also
        if      S.THRU    = MT(MEDIUM)     AND
                C.LEFT    = LE(LARGE)      AND
                C.THRU    = LE(LARGE)      AND
                S.LEFT    = ANY
        then    EXTENSION = LONG
also
        if      S.THRU    = VERY LARGE     AND
                C.LEFT    = ANY            AND
                C.THRU    = ANY            AND
                S.LEFT    = ANY
        then    EXTENSION = LONG
```

4TH INTERVENTION

```
        if      S.THRU    = MEDIUM         AND
                C.LEFT    = LE(MEDIUM)     AND
                C.THRU    = LE(MEDIUM)     AND
                S.LEFT    = ANY
        then    EXTENSION = MEDIUM
also
        if      S.THRU    = MT(MEDIUM)     AND
                C.LEFT    = LE(LARGE)      AND
                C.THRU    = LE(LARGE)      AND
                S.LEFT    = ANY
        then    EXTENSION = LONG
```