

Signal control using fuzzy logic

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Abstract

Applications with fuzzy logic being used in controlling traffic signals have been designed already since the 1970s. The strength of fuzzy logic lies in its capability of simulating the decision-making process of a human, a process that is often difficult to define with traditional mathematical methods. The results of FUSICO-project have indicated that the fuzzy traffic signal control can be the potential control method for signalized intersections. © 2000 Elsevier Science B.V. All rights reserved.

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1. Introduction

Traffic signal control is one of the oldest application areas of fuzzy sets in transportation engineering. The published applications are mainly theoretical, but there is active research going on in this area [2,3,5,6,8-10].

The subject of our FUZZY SIGNAL CONTROL (FUSICO) project at the Helsinki University of Technology, Laboratory of Transportation Engineering, is the application of fuzzy control to traffic signals at the individual intersection level. The main goals of the research are

- to make a general theoretical analysis of fuzzy traffic signal control
- to formulate generalized fuzzy control rules for signal-group control using fuzzy logic

- to validate the fuzzy control principles and to calibrate the membership functions of the linguistic variables using simulation and field trials, and
- to develop the principles of the fuzzy adaptive signal controller.

The aim of this paper is to discuss the fuzzy signal control in general, to present the first results of our research project, and to show the preliminary general rule base and the structure of control algorithms for complicated intersections, especially for the signal-group control.

2. Framework of fuzzy signal control

2.1. Application for traffic signal control

The theory of fuzzy sets is based on graded concepts to handle uncertainties and imprecision in a particular domain of knowledge. The graded concepts are

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useful since real situations are not very often crisp and deterministic, and they cannot be described precisely.

Fuzzy logic control allows linguistic and inexact traffic data to be manipulated as a useful tool in designing signal timings. The fuzziness of signal control can be divided into three levels: input, control, and output level. In the input level, we have only a partial picture of the prevailing traffic situation through measurements. In the control level, we have many possibilities, and we do not know which one of them is exactly the right or the best one, because we cannot explain the cause–consequence relationship of signal control. In the output level, the correct control criteria are not known (for example, extension gap). In general, fuzzy control is found to be superior in complex problems with multi-objective decisions. In traffic signal control, several traffic flows compete for the same time and space, and different priorities are often set to different traffic flows or vehicle groups.

The base principle of fuzzy signal control is to model the control based on human expert knowledge, rather than modeling of the process itself. 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.

2.2. Signal group control

In Finland, Germany, The Netherlands and in other Nordic Countries, the principle of signal group control is used in traffic signal control. Signal group control is more flexible than the traditional stage control and therefore more adaptive to various traffic conditions. The signal group control does not have exactly defined stages, it has only primary phase pictures (Fig. 1).

The traditional vehicle-actuated control of isolated intersections attempts continuously to adjust green times. Detectors give the input-data. The basic timing parameters at each phase in traditional vehicle-actuated control are minimum green, passage time interval (extension interval) and maximum green. In the base situation, the green signal group gives at least the minimum green time. If the demand is sufficient, the green time can be extended stepwise with the lengths of extension interval to the maximum green. After green extension, the signal group can go

to red or remain as a passive green. The passive green can be terminated by conflict signal groups.

Fuzzy signal group control in our case works in the same way as the traditional control, but the extensions are adjusted by a fuzzy extender, and the phase sequences are selected by a fuzzy selector. The main principles of fuzzy control with the main principles of phase ring control are compared in Fig. 2.

In general, the fuzzy rules are working at three levels:

2.2.1. Traffic situation level

The traffic situation is divided into three different categories: oversaturated, normal and low demand. The definition of traffic situation is done using upper level fuzzy rules:

*if VOL is any and min(OCC) is high
then TS is oversaturated or
if VOL is low and max(OCC) is zero
then TS is low or
if VOL is any and max(OCC) is normal
then TS is normal,*

where VOL is the traffic volume of the last 5 min, vph; OCC is the occupancy of the first detector during the last 5 min, %; and TS is the traffic situation.

The control policy of the different traffic situations is different. The control policy of oversaturation is the capacity maximizing, and the control policy of low traffic situations is First In First Out (FIFO).

2.2.2. Phase and sequence level (fuzzy phase selector)

The main goal of this level is to maximize the capacity by minimizing intergreen times. The basic principle is that “signal group can be kept in green while no disadvantages to other flows occur”. This is also called “the method to use extra green”. The main decision of this level will be the right termination moment of the green.

The decision moment is the moment, when the green of the first signal group of phase A can be terminated, so that the first signal group of phase B/C/D can be started. Secondly, the decision will be checked when the last signal group of phase A is ready to terminate.

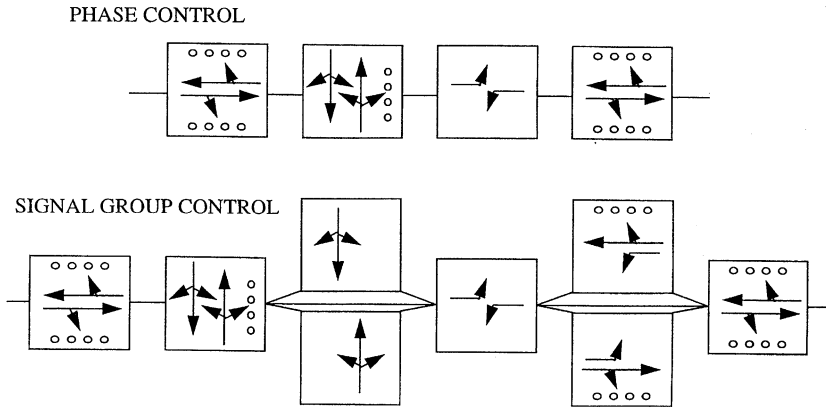
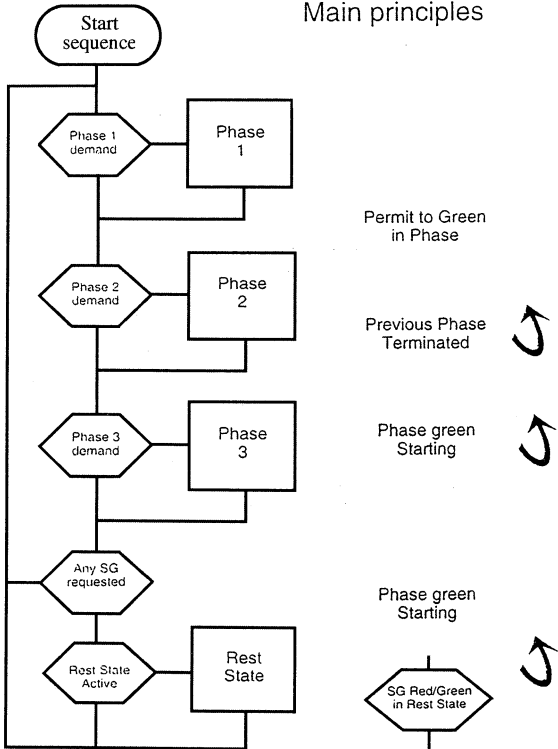


Fig. 1. Signal group control vs. phase control.

Phase Ring Control

Main principles



Fuzzy Control

Main principles

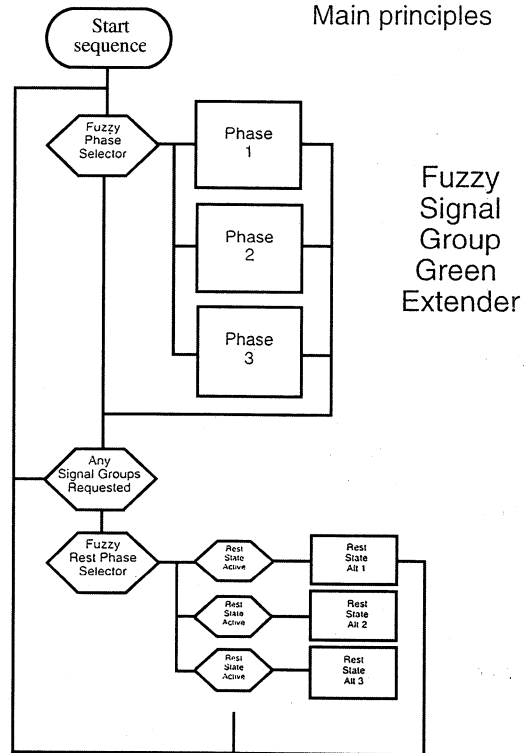


Fig. 2. Main principles of fuzzy control and phase ring control.

The second goal of this level is to determine the right phase order. The basic principle is that the phase can be skipped if there is no request or if the weight ($W(p)$) of this phase is low. This means that if the normal phase order is A-B-C-A the fuzzy phasing can for example give the orders A-B-A-C-A or A-C-A-B-C. The rules are a little bit complicated, when there are four phases, but the principle is the same as in the rules of three phases. The general principles of the rules are

- if $W(p)$ is very high then phase p will be the next one,
- if $W(p_i)$ is high and $W(p_j)$ is zero then (i) will be the next one,
- the maximum waiting time of each vehicle cannot be too long,
- otherwise the order will be as planned.

The rules of four phase control are

*if $W(B)$ is high
then next phase is B or
if $W(B)$ is medium and $W(C)$ or $W(D)$ is oversat
then next phase is $W(\text{higher})$
if $W(B)$ is medium and $W(C) + W(D)$ is very high
then next phase is C or
if $W(B)$ is low and $W(C)$ or $W(D)$ is high
then next phase is $W(\text{higher})$ or
if $W(B)$ is low and $W(C) + W(D)$ is *mt*(medium)
then next phase is C or (*mt* = more than)
if $W(B)$ is zero
then next phase is C.*

The fuzzy factor $W(X)$ is the fuzzy factor for required green time/phase. The exact specification will be done later. The first suggestion could be the sum of the queued vehicles' waiting time. Basically the second and the third signal group are working together. The green extension need is discussed in the third level (Fig. 3).

2.2.3. Green ending level or extension level (fuzzy green extender)

The main goal of fuzzy rules of this level is to determine the first moment to terminate a signal group. The basic idea is not to terminate during the queue discharging. This means that each vehicle has to stop only once at each intersection. The fuzzy rules are

if S is high then extend certainly or

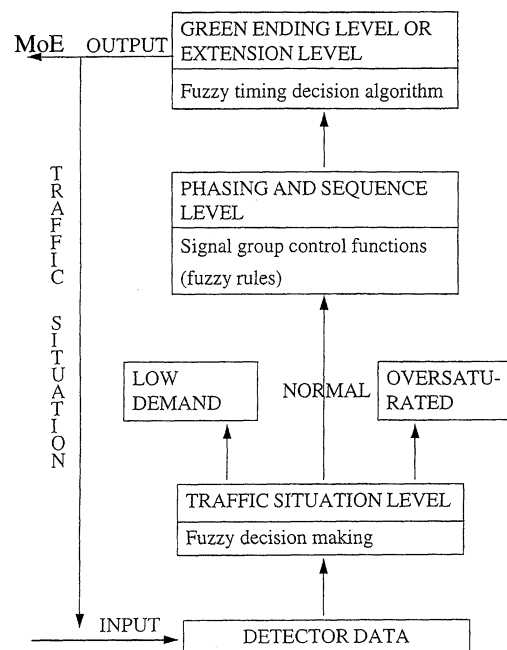


Fig. 3. The three levels of fuzzy signal control.

W(red) is low	GRN			
	GAP	short	medium	long
	small	1.00	1.00	0.75
	medium	1.00	0.75	0.50
	long	0.75	0.50	0.25
W(red) is medium	GRN			
	GAP	short	medium	long
	small	0.75	0.50	0.25
	medium	0.50	0.50	0.25
	long	0.25	0.25	0.00
W(red) is high	GRN			
	GAP	short	medium	long
	small	0.50	0.25	0.00
	medium	0.25	0.00	0.00
	long	0.00	0.00	0.00

Fig. 4. Decision tables for multi-phase control.

if S is low

- (1) and $W(\text{red})$ is low and GRN is short and GAP is long then extend probably
...
- (27) and $W(\text{red})$ is big and GRN is long and GAP is small then terminate certainly,

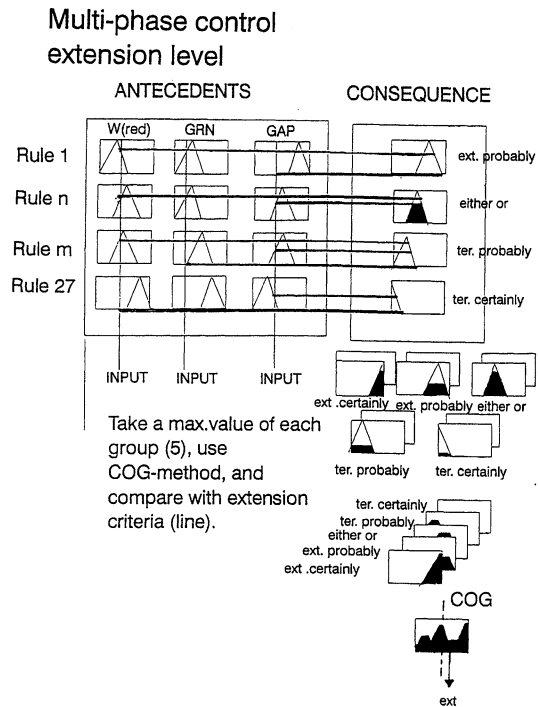


Fig. 5. Fuzzy inference of multi-phase control.

where $W(\text{red})$ is the weight of red signal groups, GRN is the running time of the green signal group, GAP is the last observed gap between two approaching vehicles according to detection at 100 m before the stop line and S is the indicator of the discharging queue (minimum discharging gap at the stop line).

The basic idea is that the consequences have some kind of uncertainties. Therefore the final consequence of each rule could be terminate certainly (0.00), terminate probably (0.25), either or (0.50), extend probably (0.75) and extend certainly (1.00). The decision tables of multi-phase control are shown in Fig. 4.

After rule modification, the rules are located in these five groups, and the maximum value of membership function of each group will be selected. The COG-method (center of gravity) calculates our extension ratio, which will be compared with the extension criteria (for instance 0.50). The extension criteria can be different for each control policy. The fuzzy inference of multi-phase control is shown in Fig. 5.

3. The first applications of FUSICO-project

3.1. Signalized pedestrian crossing

The essence of fuzzy logic lies in its ability to handle linguistic information by representing it as a fuzzy set. As such, it is known to be suited for emulating the control process normally done by a human being. The developed algorithm of the signalized pedestrian crossing attempts to emulate the decision process of an experienced crossing guard. The crossing guard is always faced with two conflicting objectives: minimum delays to the pedestrians and minimum delays to the vehicles while keeping maximum safety for both parties. As the number of pedestrians and the number of vehicles increase, the decision becomes increasingly difficult. Fuzzy logic control fires many soft rules at the same time and takes the decision, which is in the compromised position.

Based on the observations of Niittymäki and Kikuchi [6], the proposed fuzzy control algorithm appears to work well. The results show that the fuzzy controller provides the pedestrian friendly control while keeping vehicle delay smaller than the conventional controls. In other words, the fuzzy controller provides a compromise between the two opposing objectives, minimum pedestrian delay and minimum vehicle delay, in accordance with the proportion of the pedestrian and vehicular volumes. The theory of signalized pedestrian crossing, the fuzzy algorithm, the membership functions, and the results are given in the paper of Niittymäki and Kikuchi [6].

The conventional controls that are tested in the paper represent two opposite cases: The pedestrian friendly case (so-called "fast pedestrian signal", which gives only one extension interval after the signal group is ready to terminate) and the vehicle friendly case (traditional gap-seeking method). The fuzzy control, on the other hand, represents a compromise of these two cases by providing friendliness to both clients (pedestrians and vehicles) depending on the traffic volume. This finding is consistent with the characteristics of most other applications of fuzzy control; the fuzzy control looks for a compromise in the multi-objective problem environment. Further, it is interesting to note that such a compromised control is executed without specific limits imposed on the rules of the fuzzy control.

Another aspect that is worth examining when comparing fuzzy control with conventional control is robustness and adaptivity. The conventional signal control requires setting of a large number of parameters, like minimum and maximum times of each signal group and the logic of detectors. In the case of the fuzzy logic controller, the number of parameters can be reduced, and the meaning of each parameter can be realized easily. This is possible due to the use of the membership function that covers a range and, as a result, the conclusions of the rules overlap. This fact makes more than one rule to fire for a given input, and the outcome is derived as a compromise of the conclusions of more than one rule.

3.2. Two-phase vehicle control with pedestrian signal-group

The general rule at the signalized intersection is “the fewer phases, the better”. Two are as few as you can have and still have a meaningful traffic signal installation. It turns out that two phases is the ideal number. It is still true that there are more two-phase intersections than any other type. This is because signals with two phases do the basic job of assigning the right-of-way and leave the motorist and pedestrian on their own from there [7].

The results of Pursula and Niittymäki [9] showed that the fuzzy control algorithm can be competitive against traditional vehicle actuation with the extension principle. The compared fuzzy algorithm was the algorithm of Pappis and Mamdani since 1977. These results without any calibration of membership functions were fairly good and showed that this kind of fuzzy control is suitable for many other applications.

The aim of our study is to compare our FUSICO with the “best-known vehicle actuation algorithm”. The traditional algorithm has two detectors 140 and 60 m before stop line. The algorithm works using the “gap seeking” method. In our fuzzy application, two detectors are located per each approach lane. The location of the first one is 100 m (D10) and the second one is at the stop line (D01). This means that we know how many vehicles are approaching the stop line within next 6–8 s. The minimum time of signal group is 5 s.

There are only two input variables for the fuzzy rule base:

A = number of approaching vehicles at the moment t (veh), or vehicles between detectors D01 and D10 of green phase approaches

Q = number of queuing vehicles at the moment t , or stopped vehicles of red phase approaches.

The fuzzy rules of our application are

After minimum green (5 s)

if A is zero then terminate immediately

or if A is a few and Q is a few

then EXT is short (3 s)

or if A is $mt(a\text{ few})$ and Q is any

then EXT is medium (6 s)

or if A is many and Q is any

then EXT is long (9 s).

After the first extension ($ext_1 + \min\ gr$)

if A is zero then terminate immediately

or if A is a few and Q is a few

then EXT is short (3 s)

or if A is medium and Q is any

then EXT is medium (6 s)

or if A is many and Q is any

then EXT is long (9 s).

After the second extension ($ext_1 + ext_2 + \min\ gr$)

if A is zero then terminate immediately

or if A is a few and Q is a few

then EXT is short (3 s)

or if A is medium and Q is $lt(\text{medium})$

then EXT is medium (6 s)

or if A is many and if Q is $lt(\text{medium})$

then EXT is long (9 s).

After the third extension ($ext_1 + ext_2 + ext_3 + \min\ gr$)

if A is zero then terminate immediately

or if A is $mt(a\text{ few})$ and Q is a few

then EXT is short (3 s)

or if A is medium and Q is $lt(\text{medium})$

then EXT is medium (6 s)

or if A is many and Q is $lt(a\text{ few})$

then EXT is long (9 s).

After the fourth extension ($ext_1 + ext_2 + ext_3 + ext_4 + \min\ gr$)

if A is zero then terminate immediately

or if A is *mt(a few)* and Q is *a few*
 then EXT is *short* (3 s)
 or if A is *medium* and Q is *lt(a few)*
 then EXT is *medium* (6 s)
 or if A is *many* and Q is *lt(a few)*
 then EXT is *long* (9 s).

The basic principles of these rules are to adjust cycle time and to divide the cycle into the green times of phases, and to emulate the performance of an experienced policeman.

3.3. Multi-objective decision making

Fuzzy control has proven to be successful in problems for which an exact mathematical modeling is hard or impossible but an experienced human operator can control the process. The traffic signal control is a problem of this category. In particular, fuzzy logic control is suited for problems, which have many and often conflicting objectives with information (input) given in linguistic terms. This trait is suited for dealing with a control problem at a complex intersection with many approaches and vehicle movement requirements. Therefore, the result in this paper should provide an impetus to develop fuzzy control logic for more complex intersections.

There are three main objectives of signal control: maximize safety, minimize delays and minimize environmental disadvantages. The problem is that the optimum of each objective is achieved in different cycle times [1]. The problems of signal control can be described as a triangle, where the main objectives are on the corners. Each main goal affects other goals as shown in Fig. 6.

The figure means that if the minimizing of delays is the main goal, the effects to other goals are little negative (–). The only positive effect is between the environment and safety (+). In other words, the environmentally effective traffic signal control can also be safe, because the cycle times of the environmentally effective traffic signals are quite long. The long average cycle time means that the number of amber intervals is smaller, and the risk of rear-end collisions is smaller. The biggest problem is that the environmental or safe control strategy does not give a good delay result (–). The average delay can be even 40% bigger than the optimum delay.

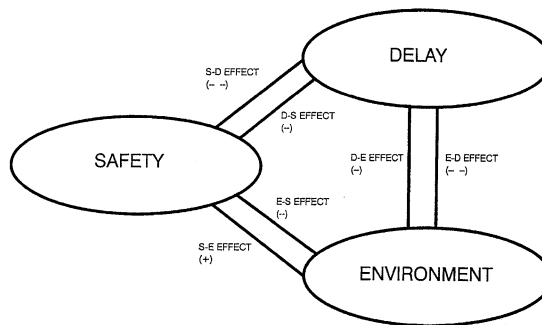


Fig. 6. Main objectives of traffic signal control and their effects on other goals.

There are many ways to determine the cost function of traffic signals

$$C = C(\text{time/delay}) + C(\text{environment/fuel}) + C(\text{safety/accidents}).$$

In our project, the aim is to use fuzzy logic in decision making. Basically, there are two ways to do that:

- (1) A rule base, where the input-parameters take into account the goals of the control algorithm. An example of this is the control algorithm of a fuzzy signalized pedestrian crossing given in this paper.

or

- (2) A rule base, where the final decision will be done using the fuzzy methods among the multi-objectives. The example is that the final decision will be done using the fuzzy methods between three objectives; traffic fluency (delay), traffic safety and environmental effects. Good traffic fluency means that the average delay is small and the length of maximum queue is not long. Good traffic safety means that the percentage of stops is not high and the risk of rear-end collision is small and the pedestrian waiting time is not long. Good environmental effects can be achieved, if the percentage of stops is small and the number of zero delay vehicles is high. The final decision can be made using, for example, the min–max method among these three multi-objectives. The defuzzification should be planned carefully. It is not even

important that all objectives are acting at the same time. For example, during the rush hour the traffic fluency and the traffic safety can be more important than the environmental aspects.

We have these three objectives in our application, and each objective has its own rule base. The first detector of each approach is located sufficiently far away (approx. 160 m) from the stop line. The early detection and the knowledge of vehicle kinematics make it possible to model the traffic situation during the next 9 s (maximum extension is 9 s in each interval). Combining these three different rule bases is the determination of extension made. The number of intervals can be determined using the estimation of the maximum green time, $N = \text{max.green}/9$. For instance, the final membership function values of each rule base for each extension are as shown in Table 1.

The extension of this multi-objective case is 5 s (maximum) in this interval. The extension according to delay rules would have been 5 s, according to environmental rules 6 s, and according to safety rules 4 s. This kind of multi-objective decision procedure with fuzzy logic can be used both in the extension level and the phasing level. The first results of the fuzzy multi-objective signal control have been very promising. The systematical testing and development of the rule base will continue. In this case, we need more experience to define a correct defuzzification method, because the centroid methods (like COG) are also available.

4. Simulation study of two-phase vehicle control

4.1. Simulation in traffic signal control evaluation

The testing of a new control scheme such as the problem at hand requires not only the algorithm for control but also a microscopic simulation model, which allows testing of many control schemes under a realistic setting. In this respect, a sophisticated simulation model is indispensable for development and testing of an advanced signal control algorithm. Our simulation package HUTSIM gives versatile possibilities to test different traffic signal control algorithms with each other. HUTSIM is a simulation package that has been developed at the Helsinki University of Technology. In the original design, the

simulation of adaptive signal control is done by connecting a real controller to the microcomputer (PC) based simulation system. For the development of new control methods, an internal controller system has been included into HUTSIM. This system, called as HUTSIG, works so that the controller object has some measurement functions that are used to collect and analyze incoming detector data. The calculated indicators of the traffic situation are then transmitted to the control logic for timing decisions which are put into force by the group oriented signal control [4].

4.2. Theoretical background for simulations

The fuzzification process involves the scale mapping of the measured input variables into the corresponding universes of discourse. The preliminary membership functions for two-phase vehicle control are shown in Fig. 7. The functions were formulated by trial and error. The basic ideas of the theory of fuzzy sets are used for the quantitative interpretation of these instructions as well as for the decision making process. The operators *mt*(more than) and *lt*(less than) are defined as follows. If A is a fuzzy set defined on the real line

$$R^1 = \{x_i\},$$

$\mu_A(x_i)$, is its grade of membership function and x_0 is the element of R^1 for which $\mu_{A(x_i)}$ is maximum, then $lt(A)$ and $mt(A)$ are fuzzy sets defined as

$$\mu_{lt(A)}(x_i) = \begin{cases} 0, & \text{for } x_i \geq x_0, \\ 1 - \mu_{A(x_i)} & \text{for } x_i < x_0, \end{cases}$$

and

$$\mu_{mt(A)}(x_i) = \begin{cases} 0, & \text{for } x_i \leq x_0, \\ 1 - \mu_{A(x_i)} & \text{for } x_i > x_0. \end{cases}$$

This means that $lt(A)$ or $mt(A) = \text{not}(A)$, and $lt(A)$ and $mt(A) = 0$.

Since the output of rules is a set of membership functions associated with the output sets, the defuzzification strategy is required in order to obtain a crisp control action. There are several commonly used defuzzification strategies, even though there is no systematic procedure for selecting a defuzzification strategy. The defuzzification method of our two-stage control algorithm is the center of gravity

Table 1

	Extension (s)									
	0	1	2	3	4	5	6	7	8	9
Delay	0.0	0.3	0.5	0.7	0.9	0.9	0.8	0.6	0.4	0.3
Environ.	1.0	1.0	1.0	1.0	1.0	1.0	1.0	0.8	0.8	0.8
Safety	0.0	1.0	1.0	1.0	1.0	0.9	0.8	0.8	0.8	0.8
Result (min)	0.0	0.3	0.5	0.7	0.9	0.9	0.8	0.6	0.4	0.3

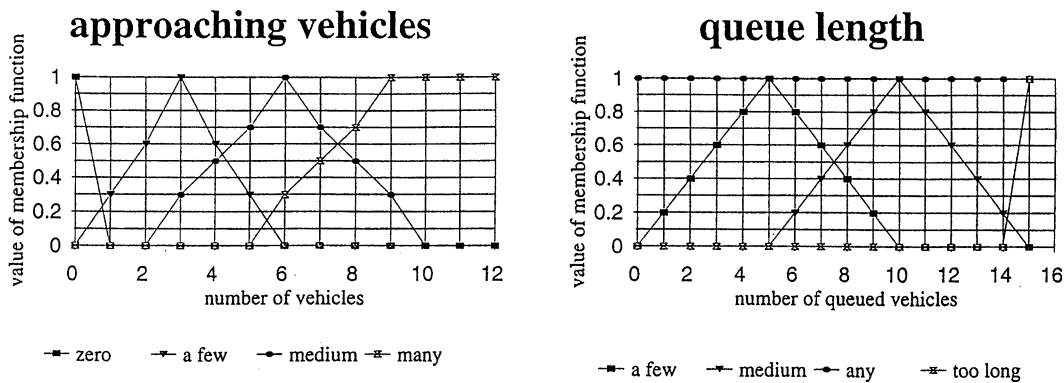


Fig. 7. Preliminary membership functions of two-stage control.

method (COG) because we are looking for some kind of compromise for the different extensions. The centroid-defuzzification method finds the output's center of mass (= compromise).

4.3. Results of the simulations

We compared the efficiency of our FUSICO with the traditional vehicle-actuated control (called extension principle), since this algorithm is as realistic as possible, and we do not know of any more effective control algorithms at the moment. Fig. 8 gives the average delay and percentage of stops of the intersection with two equal approaches as a function of traffic volume (traffic volumes N–S and W–E are approximately the same). The simulation time of each case was 7200 s and the simulated intersection was an isolated intersection of two one-way streets with 2 + 2 lanes. The speed distribution of approaching vehicles was a Gaussian with mean value about 40 km/h. The simulated traffic was exactly the same in both the cases.

The results showed that the extension principle is quite a good traffic signal control mode in the area of very low traffic volumes. The results also indicated that the application area of fuzzy control is wide. This result is the same as the result indicated in the paper of Pursula and Niittymäki [9].

In 1996, we compared the traditional extension principle with the fuzzy control algorithm of Pappis–Mamdani [8]. The biggest difference between the results of our control algorithm and the control algorithm results of Pappis–Mamdani is that the percentage of stops of our control algorithm is smaller than the percentage of stops of the extension principle. The delays are also slightly smaller (–10–20% in the tested area 100–1200 vph) in our case than the delays of the Pappis–Mamdani algorithm.

5. Conclusions and discussion

Our FUSICO-project continues. The aim is to move step by step to more complicated traffic signal

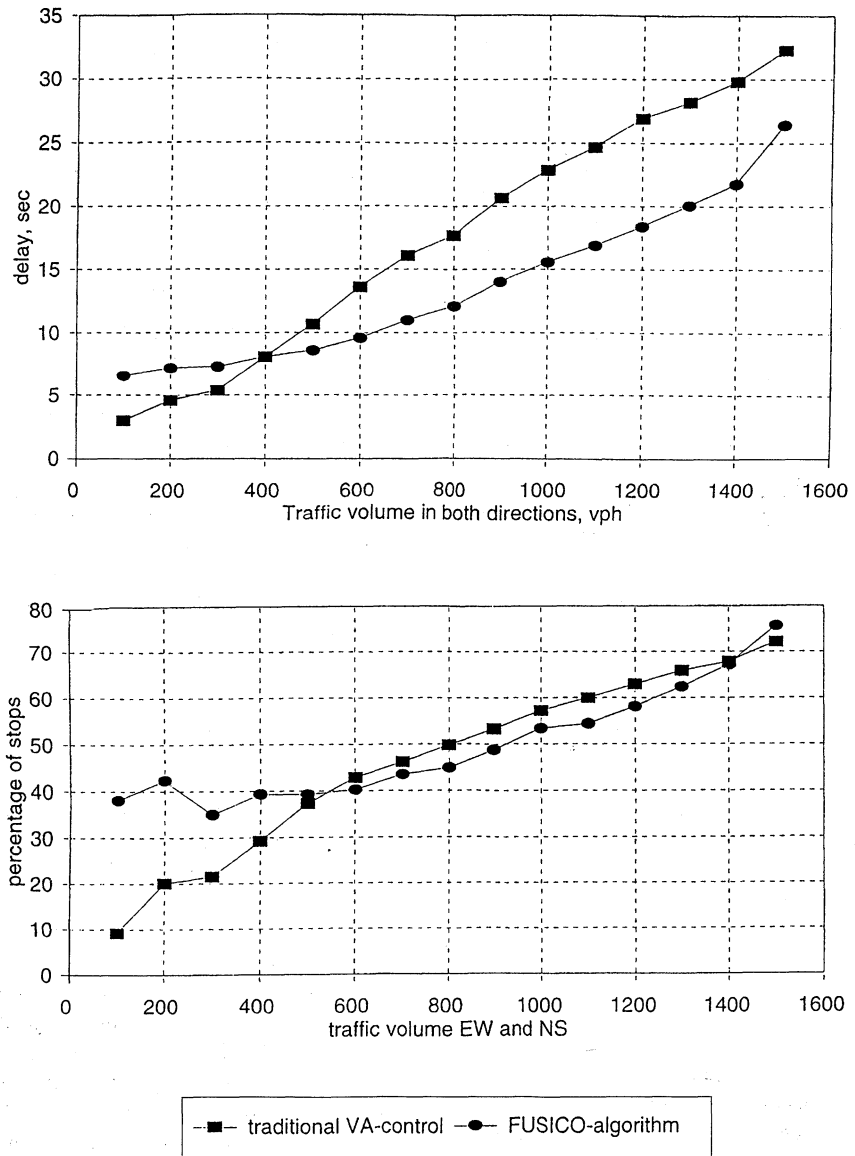


Fig. 8. Comparison of the FUSICO-algorithm and the traditional extension principle.

systems. The general rule base for traffic signal control will develop with time, and also the fuzzy controller will become better with time. So far, the published applications of fuzzy control have been mainly theoretical. The fuzzy control has been tested sometimes in the real intersections, but the test results

are not reported. One important step in the evaluation project of fuzzy control will be the field test at a real intersection. This test will be done at the signalized intersection of Helsinki City.

The results between Pappis–Mamdani fuzzy control algorithm and traditional vehicle-actuated control

indicated that fuzzy control is suitable for many other control algorithms. The long cycle times of the traditional extension principle indicated the weakness of this kind of gap-seeking control. However, the results of stopped vehicles of Pappis–Mamdani control were higher than the results of traditional vehicle-actuated control. Based on these experiences, we developed our own control algorithm for two-phase vehicle control. The main goals of this control were to adjust the cycle time and to divide the cycle into the green times of phases. According to these results, the extension principle is good in the area of very low traffic volumes, but the results indicated that the application area of fuzzy control is very wide. The difference between our FUSICO-control algorithm and Pappis–Mamdani control algorithm is that our control algorithm gives smaller number of stops than the extension principle or Pappis–Mamdani control. Basically, this means that the FUSICO-algorithm should also have smaller fuel consumption and better traffic safety than the traditional vehicle-actuated control algorithms or Pappis–Mamdani control algorithm. The comparison between the FUSICO-algorithm and the SOS-algorithm (fuzzy logic against mathematical optimization) could be very interesting in the near future because at the moment both the algorithms have proved to be better than traditional control algorithms.

The results of this paper and our past work have indicated that fuzzy signal control can be the potential control method for isolated intersections. Nakatsuyama et al. [5] and Chiu [2] have shown that fuzzy control will be competitive at coordinated signal systems and networks. We believe that fuzzy methods are well suited to almost all kinds of signal control, and the biggest benefits can be achieved in more complicated intersections and environments than our applications at the moment. The specific plans for more complicated isolated intersections are already available, and the first plans for aerial fuzzy signal control have been done. Theoretically, fuzzy control has also proved to be superior in complex problems with multi-objective decisions. Traffic signal control is a typical process, where traffic flows compete for the same time and space, and different objectives can be reached in different traffic situations. The results of the fuzzy signalized pedestrian crossing have proved that fuzzy control provides timing, which is a compro-

mise of the results of these two conventional controls. One basic advantage of fuzzy control is that it fires many soft rules simultaneously and makes a decision, which offers the compromise. The control algorithm with three different main goals (minimize delay, maximize safety and minimize environmental effects) has already been developed as a part of the next phase. The testing of this algorithm is in progress.

The calibration of membership functions is one important sub-goal of our project. Normally, the preliminary calibration of the membership functions is done by trial and error. One goal of the future is to calibrate used membership functions using the neural networks or some other relevant systematic method. Neural networks have recently been recognized as an important tool for constructing membership functions, performing operations on membership functions, constructing fuzzy inference rules, and other context dependent entities in fuzzy set theory. In general, constructions by neural networks are based on learning patterns from sample data. The data for the calibration comes from simulations.

The important step in the evaluation project of fuzzy traffic signal control will be a field test at a real intersection. This test will be done at the signalized intersection of Helsinki City. This step is very important because a successful test means that the fuzzy controller is ready to work in reality.

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