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# GENERAL FUZZY RULE BASE FOR ISOLATED TRAFFIC SIGNAL CONTROL – RULE FORMULATION

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Traffic signal control is one of the oldest applications of fuzzy logic, at least in transportation engineering. The aim of this paper is to present a systematic approach to fuzzy traffic signal control and to derive the linguistic control rules based on expert knowledge. Traffic signal programming is generally divided into two problems: firstly, the choice and sequencing of signal stages to be used, and secondly, optimizing the relative lengths of these stages. The rule bases for both problems are introduced in our paper. The results of tested rule bases and field tests of fuzzy control have been promising. The fuzzy signal control algorithms offer better measures of effectiveness than the traditional vehicle-actuated control.

*Keywords*: Fuzzy logic; Traffic signals; Fuzzy rule base; Expert knowledge

## INTRODUCTION

Traffic signals are now a common feature of urban areas throughout the world, controlling millions of vehicles. Careful design of these signals is important for various reasons; it increases the efficiency of the road network, which yields both economic and environmental benefits. Signal design has a direct bearing on safety aspects of road and pedestrian transport.

Fuzzy control has been introduced and successfully applied to a wide range of automatic control tasks. Many subjects in transportation engineering are often characterized as subjective, ambiguous, and vague. The main benefit of fuzzy set theory is the opportunity to model the ambiguity and the uncertainty of decision-making. The fuzzy traffic signal control is one of the oldest applications of fuzzy set theory, at least in transportation engineering. The basic idea of fuzzy traffic signal control is to model the control based on human expert knowledge, rather than the modeling of the process itself. Fuzzy logic has the ability to comprehend linguistic instructions and to generate control strategies based on a priori communication.

The aim of this paper is to present a systematic approach to fuzzy traffic signal control and to derive the linguistic control rules based on expert knowledge. The paper is part of the FUSICO research project in Finland, the subject of which was the application of fuzzy signal control to traffic signal control at the intersection level.

## GOALS AND RULES OF TRAFFIC SIGNAL CONTROL

### Objectives of Traffic Signal Control

Since the inception of traffic signal control in 1913 in Cleveland, the technical and algorithmic developments are continually improving the safety, efficiency, and environmental impact of control (Bell, 1992).

The main goal of traffic signal control is to ensure safety at signalized intersections by keeping conflicting traffic flows apart. However, one of the basic questions of signal control is the measure of performance that is used in the evaluation.

In recent years many diverse measures have been suggested to bring about the new policy objectives, ranging from road pricing to pedestrianisation of city centers. Traffic signal control can contribute to this as part of a wider traffic management system with consistent and well-defined aims. Some of the areas where changing the objectives of traffic signal control could make a difference are:

- pedestrian friendly signals,
- separate signals for cyclists,
- public transport priorities,
- heavy vehicle priorities,
- all other priority systems,

- environmental sensitivity,
- general routing aspect.

The interactional effects between the three goals are shown in Figure 1.

If, according to Figure 1, minimizing delays is the main goal, the effects on other goals are rather negative (−). The only positive effect is between the environment and safety (+). In other words, environmentally effective traffic signal control can also be safe. The biggest problem is that the environmental or safe control strategy does not give a good delay result (−).

## Systematics of Fuzzy Traffic Signal Control

Traffic signal control is used to maximize the efficiency of existing traffic systems. However, even the efficiency of traffic systems can be fuzzy. By providing temporal separation of rights of way to approaching flows, traffic signals exert a profound influence on the efficiency of traffic flow. They can operate to the advantage or disadvantage of the vehicles or pedestrians, depending on how the rights of way are allocated. Consequently, the proper application, design, installation, operation, and maintenance of traffic signals is critical to the orderly, safe and efficient movement of traffic at intersections. In practice, uniformity of control is an important principle followed in signal control for traffic safety reasons. This

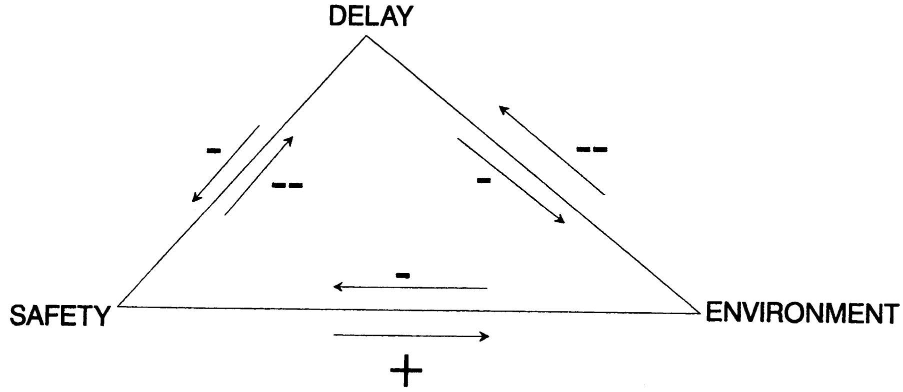


FIGURE 1 Interactions between three main goals of signaling.

consideration sets limitations to the cycle time and sequence arrangements. Hence, traffic signal control in practice is based on tailor-made solutions and adjustments made by the traffic planners. The modern programmable signal controllers with a great number of adjustable parameters are well suited to this process. For good results, an experienced planner and fine-tuning in the field is needed, because of the ability to see many different situations at the same time.

In traffic signal control, we can find uncertainty at many levels. The inputs of traffic signal control are inaccurate, and that means that we cannot handle approach traffic exactly. The control possibilities are complicated and handling these possibilities is an extremely complex task. Maximizing safety, minimizing environmental aspects and minimizing delays are some of the objectives of control, but it is difficult to handle them together in traditional traffic signal control. The cause-consequence relationship is also not possible to explain in traffic signal control. These are typical features of fuzzy 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 useful since real situations are very often not crisp and deterministic, and they cannot be described precisely. Furthermore, fuzzy sets are manipulated by the set theoretic operations of union, intersection and complement *via* their membership functions. The use of fuzzy sets provides a systematic way of manipulating vague and imprecise concepts by introducing linguistic variables, fuzzy relations and fuzzy logic.

Fuzzy-logic based controllers are designed to capture the key factors for controlling a process without requiring many detailed mathematical formulas. Due to this fact, they have many advantages in real time applications. The controllers have a simple computational structure, since many numerical calculations are not required. The "if-then-else" logic of their inference rules does not require much computational time. Also, the controllers can operate on a large range of inputs, since different sets of control rules can be applied to them. If the system related knowledge is represented by simple "if-then-else" fuzzy rules, a fuzzy based controller can control the system with efficiency and ease. The control process for fuzzy signal control is shown in Figure 2.

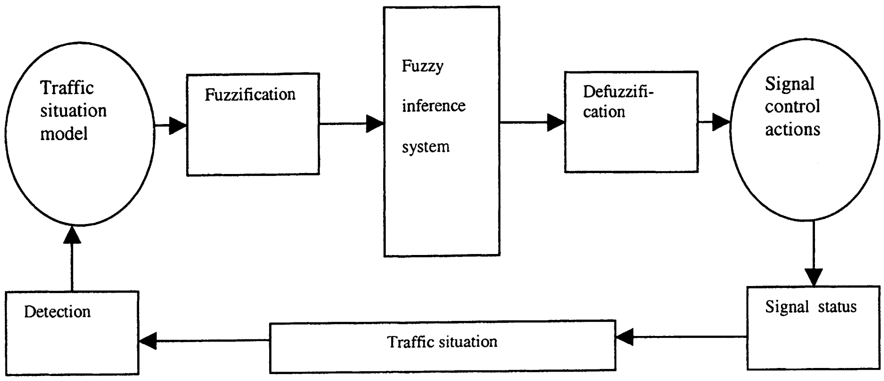


FIGURE 2 Traffic signal control process.

The fuzzy signal control process consists of seven parts: current traffic situation with signal status, detection or measuring part (crisp input), traffic situation modeling, fuzzification interface, fuzzy inference (fuzzy decision making), defuzzification, and signal control actions (for example, extension or termination of signal group).

## PRINCIPLES OF FUZZY CONTROL

### Modeling the Fuzzy Traffic Signal System

Traffic signal programming is generally divided into two problems, firstly, the choice and sequencing of signal stages to be used, and secondly, optimizing the relative lengths of these stages.

Fuzzy control has emerged as one of the most promising areas of research in the application of fuzzy set theory, especially in areas which lack quantitative data regarding input–output relations. Fuzzy logic allows linguistic and inexact traffic data to be manipulated in designing signal timing plans. The purpose of control is to influence the behavior of a system by changing the control of that system according to a rule or set of rules that model how the system operates.

The design of a fuzzy signal controller requires expert knowledge and the experience of traffic control in formulating the linguistic protocol, which generates the control input to be applied to the traffic control system. So, the fuzzy control rules can be derived from expert experience and control engineering knowledge.

**Rule Formulation**

The knowledge base comprises a rule base, which characterizes the control policy and goals. The linguistic rules are the way that fuzzy control models the knowledge. A typical form of the linguistic rules is

| | | |
|---|---|---|
| Rule1 | If x is $A_1$, | then f(x) is $B_1$ |
| Rule 2 | If x is $A_2$, | then f(x) is $B_2$ |
| ... ... | ... | |
| Rule N | If x is $A_N$, | then f(x) is $B_N$, |

where x and f(x) are independent and dependent variables, and $A_i$ and $B_i$ are linguistic constants. These rules are referred to as if-then-rules because of their form. An if-clause is referred to as an antecedent (premise) and a then-clause a consequence. The two most important fuzzy implication inference rules are

- the generalized modus ponens (GMP) and
- the generalized modus tollens (GMT):

| | | |
|---|---|---|
| GMP | premise: | x is (not A) |
| | rule: | if (x is A) then (y is B) |
| | consequence: | y is (not B) |
| GMT | premise: | y is (not B) |
| | rule: | if (x is A) then (y is B) |
| | consequence: | x is (not A) |

The GMP is closely related to the forward (data-driven) inference, which is particularly useful in fuzzy logic controller construction. The GMT rule is closely related to backward (goal-driven) inference, which is commonly used in expert systems.

Fuzzy inference is based on GMP, which states: "If A is true, and A implies B, then B is true". In this statement, A implies B is the inference rule, where A is the antecedent and B is the consequence. Mathematically this can be written

$$(A \wedge (A \Rightarrow B)) \Rightarrow B.$$

Of course with fuzzy sets, the values of A and B can be partially true. In a fuzzy inference based system, the rule base consists of several implications as below

Input: x is A′ and y is B′
Rule: if x is A and y is B then z is C
Consequence: z is C′

and as in terms of the fuzzy relations

$$\mu_{\text{input}}(x, y) = \mu_{A' \cap B'}(x, y) = \mu_{A'}(x) \wedge \mu_{B'}(y)$$
$$\mu_R(x, y, z) = \mu_A(x) \wedge \mu_B(y) \wedge \mu_C(z).$$

The entire knowledge of the system designer about the process, traffic signal control in this case, to be controlled is stored as rules in the knowledge base. Thus the rules have a basic influence on the closed-loop behavior of the system and should therefore be acquired throughly. The development of rules is time-consuming, and designers often have to translate process knowledge into appropriate rules.

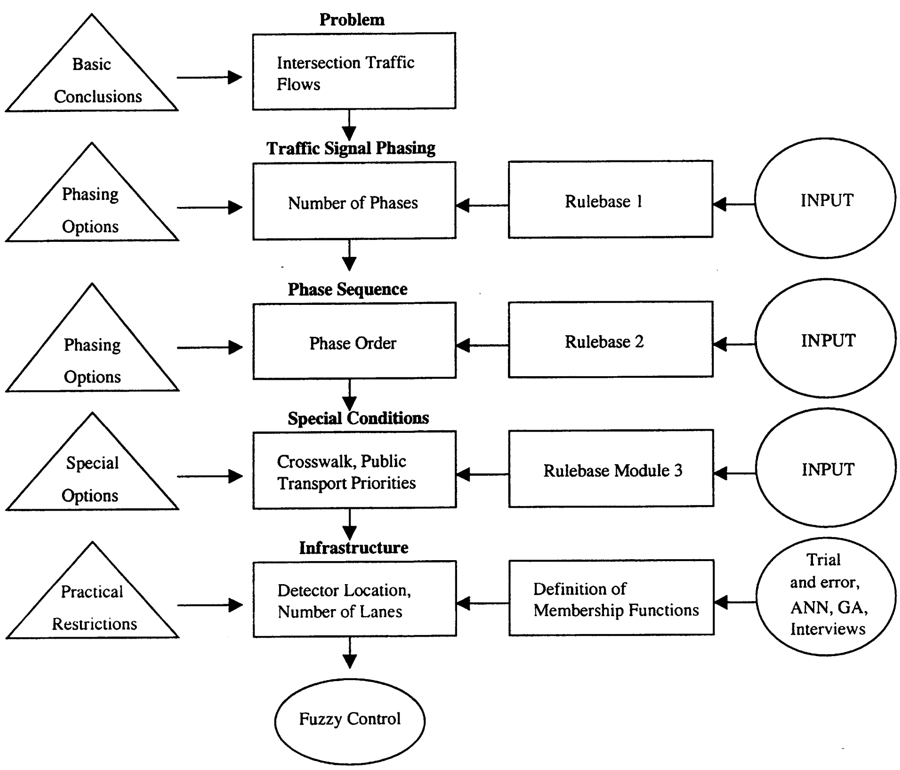


FIGURE 3 Rule derivation.

Sugeno and Nishida (1985) discuss four ways to derive fuzzy control rules, based on: operator's experience, control engineer's knowledge, fuzzy modeling of the operator's control actions and fuzzy modeling of the process. Zimmermann (1996) adds three more source: crisp modeling of the process, heuristic design rules and on-line adaptation of the rules.

Usually a combination of some of these methods is necessary to obtain good results. As in conventional control, increased experience in the design of fuzzy controllers leads to decreasing development times. In our FUSICO-project, the aim was to model the experience of a policeman. The basic rule base development was made during the Fall of 1996 when an experienced traffic signal planner was working at the Helsinki University of Technology. Everyday discussions and working groups helped us to model his experience to our rules. The structure of rule derivation process is shown in Figure 3.

## PRELIMINARY FUZZY RULE BASE

### Signalized Isolated Pedestrian Crossing

Normally, the signals of isolated pedestrian crossings in Finland are traffic actuated, and the rest phase is vehicle green (an important safety aspect). Two detectors are located per lane, one at the stop line and the other $40-100$ meters from the stop line. Pedestrian green time is constant (10 seconds) or even actuated ($6\cdots14$ seconds) in specific conditions if children or elderly people are numerous. The main goal of fuzzy control is to give pedestrians an opportunity to cross the street safely, and with minimum waiting time, but also that the risk of rear-end collisions of vehicles is minimized. It is also important that control does not encourage pedestrians to cross the street during the pedestrian red phase. Controlling the timing of a traffic signal means making the following evaluation constantly: (1) to terminate the current phase and to change it to the next most appropriate phase, or (2) to continue the current phase. In other words, a controller incrementally evaluates these two options and takes the most appropriate option. This means that the output is the decision about the termination (T) or the extension (E) of a vehicle signal group (crisp value). The input parameters in use are:

- *pedestrian waiting time* (*WT*; *short*, *long*, *very long*) (3)
- *maximum number of approaching vehicles/lane* (*A*; *none*, *some*, *many*) (3)
- *discharging queue indicator*, *gap between vehicles at stop line* (*S*; *low*, *high*). (2)

The rule formulation is

*if WT is* (*short/long/verylong*) *and A is* (*none/some/many*) *and S is* (*low/high*) *then T/E*.

WT(waiting time) and A(approaching vehicles) were chosen because they represented the main goals of the rule base. S was chosen because it is not common to terminate vehicle green while the queue is discharging. The total number of rules is 18 (3*3*2). There are 9 rules for the extension and 9 rules for the termination decisions. The final decision (crisp output) is the consequence with the maximum value of membership function. The rules are shown in the format of a decision table in Figure 4.

The objectives of signal control can be different in various traffic conditions. During the peak-hour, the control strategy can be "do not terminate during the discharge process". During low traffic volumes, the main objective can be to consider environmental aspects. This means that arriving traffic (A) is an important part of the decision process.

## Two-phase Vehicle Control

Two-phase control is the most common control strategy to be found in practice. The traffic actuated signals work so that 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 length of passage time interval to the maximum green time. After green extension the signal group cant change to red or remain as passive green, which means that the signal group is ready to terminate. The passive green can be terminated by the demands of conflicting signal groups.

S (Discharge gap) = Small

| | | A (vehicle arrivals) | | |
|---|---|---|---|---|
| | | Very few | Some | Many |
| WT(Ped. Wait Time) | Short | T | E | E |
| | Long | T | T | E |
| | Very long | T | T | T |

S (Discharge gap) = Large

| | | A (vehicle arrivals) | | |
|---|---|---|---|---|
| | | Very few | Some | Many |
| WT(Ped. Wait Time) | Short | E | E | E |
| | Long | E | E | E |
| | Very long | T | T | T |

E: Extend T: Terminate

FIGURE 4 Decision tables for fuzzy signalized pedestrian crossing.

In our application, two detectors are located per each approach lane. The location of the first one is 100 m upstream of the stop line and the second one is at the stop line. This means that we know how many vehicles are approaching the stop line within next 6–8 seconds. The vehicle minimum green time is 5 seconds.

The fuzzy control algorithm is working at two levels. The upper level classifies the traffic situation (TS): oversaturated, normal or low demand conditions. The lower level adjusts the green time and cycle, if there are many phases. The main goals of the lower level rules are: to adjust the cycle time and to divide the cycle into the green times of phases (split). The output is the extension of the signal group (EXT).

There are only two input variables for fuzzy rule base:

*A* = *approaching vehicles at the moment* (*a few, medium, many – for the green approach*)
*Q* = *queuing vehicles at the moment* (*a few, medium, many – for the red approach*).

The rule-formulation is:

*If A is something and Q is something then EXT is something.*

The fuzzy rules for the lower level are:

After minimum green (5 s)
if A is zero then terminate immediately (0 s)
or if A is a few and Q is less than medium then EXT is short (3 s)
or if A is mt (a few) and Q is any then EXT is medium (6 s)
if A is many and Q is any then EXT is long (9 s).

After the first extension ($\text{ext}_1$ + min green 5 s):
if A is zero then terminate immediately (0 s)
or if A is a few and Q is less than medium 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 ($\text{ext}_1 + \text{ext}_2 + 5$ s):
if A is zero then terminate immediately (0 s)
or if A is a few and Q is less than medium then EXT is short (3 s)
or if A is medium and Q is lt(medium) then EXT is medium (6 s)
or if A is many and if Q is lt(medium) then EXT is long (9 s).
...

After the nth extension ($\text{ext}_1 + \text{ext}_2 + \ldots + \text{extn} + 5$ s):
if A is zero then terminate immediately (0 s)
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 parallel additional rule for two-phase control is that "if Q(length) is too long, terminate immediately". It is possible to use the safety rules together with these delay rules, but the main goals of these delay rules are to adjust the cycle time and to divide the cycle into the green times of phases. The preliminary idea of this rule base is that the emphasizing of the main traffic flow can be undertaken using the membership functions for minor and major streets.

**Multi-phase Vehicle Control**

The fuzzy rule base of multi-phase control is preliminary, and the membership functions are not defined yet. Basically, the fuzzy control algorithm of multi-phase control works at three levels:

1. Traffic situation level

The traffic situation is divided into three different levels as two-phase control, but the membership functions will be different. The fuzzy rules for the upper level are:

> 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 intermediate then TS is normal,

VOL = number of vehicles in D10
OCC = occupancy of vehicles in D10.

2. Phase and Sequence Level (Fuzzy Phase Selector)

The main goal of this level is to maximize 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 be terminated.

The second goal of this level is to determine the proper phase order. The basic principle is that a phase can be skipped if there is no request or if the importance (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 rather complicated when there are four phases, but the principle is the same as in the rules governing three phases. For example, we have three phases A, B and C and a situation where phase A has just terminated; we have to decide whether the next phase is B or C. This is achieved by defining weights W(Pi) for each phase. The weight can be, for example, the number of queuing vehicles or the total waiting time of the vehicles in the phase. If phase A has just terminate, the rule base we are using is as follows

*if W* (C) *is oversaturated and W(B) is not oversaturated then next phase is C*
*if W* (C) *is high and W(B) is not high then next phase is C*
*if W* (C) *is not high then next phase is B.*

3. Green Ending Level or Extension Level
The main goal of the fuzzy rules at this level is to determine the first moment to terminate a signal group. The basic idea is not to terminate during queue discharging. This means that each vehicle has to stop only once at each intersection. The input parameters in use are:

*W(red) = weight of red signal groups* *low, medium, high*
*GRN = running time of green signal group* *short, medium, long*
*GAP = last gap between two approaching vehicles according to detection at* 100 m *before stop line* *small, medium, long*
*S = indicator of discharging queue,*
*(minimum discharging gap at the stop line)* *low, high.*

The total number of rules is 54(3*3*3*2), but if S is high (the queue is discharging) then we extend. This means that we have 27 extension rules. The basic idea of the output is that the consequences have some level of uncertainty. Therefore the final consequence of each rule is a fuzzy number, like terminate (0.00), terminate probably (0.25), either-or (0.50), extend probably (0.75) and extend (1.00).

*If W(red) is (low/medium/high) and GRN is (short/medium/long) and GAP is (small/medium/long) then EXT is (terminate/terminate probably/either or/extend probably/extend).*

The rules are located in five groups, and the maximum value of the 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.

## Pedestrian Signal Group Control at Signalized Intersections

The basic procedure for pedestrian signal group phasing depends on signal control policy. For example, the pedestrian signal group can always be green during the corresponding vehicle green even if no pedestrian demand exists. This policy is common during peak hours. Otherwise, during low pedestrian traffic the green aspect is selected by request. This policy should be kept in mind, however, if more sophisticated procedures are developed. The decision of pedestrian phasing is made at two levels. At the higher level, some historical data during the last few cycles is used. At the lower level the actual demand data is used. The input parameters of the higher level are: –need for pedestrian extra green (ExGr), and –pedestrian green skipping (PedPhaSkip), and the input parameter of lower level is: –pedestrian green demand (PedDem).

The parameter in use is the need for extra pedestrian green (*ExGr*). Fuzzy sets of the parameter are: *Often/Sometimes/Seldom*.

The number of pedestrian phases skipped (*PedPhaSkip*) can be expressed as the number of phases without a pedestrian green during the last 10 cycles. Fuzzy sets of this parameter are: *Often/Sometimes/Seldom*.

Pedestrian green demand (PedDem) is the actual request from a pedestrian pushbutton. *PedDem* is a crisp set (*Yes/No*).

An example of fuzzy rules can be described as:

If PedDem = YES or
if ExGr = Often and PedPhaSkip = Seldom or
if ExGr = Sometimes and PedPhaSkip = Sometimes
then Include pedestrian green into the phase.

## ITCARI-control

ITCARI-control (Isolated Traffic Control at Arterial Road Intersections) is a control strategy for roads with a 70 km/h speed limit, like the Swedish LHOVRA-control. The control strategy needs some extra detector(s), like LHOVRA-control (Kronborg, Davidsson and Edholm, 1997). The additional detector(s) are located 200 m (and 300 m) from the stop line.

The fuzzy control strategy carries out four LHOVRA-functions (HOVR). The function H (recall of signal group) is solved earlier in the signal-group control (Niittymäki and Pursula, 1999). The O-function minimizes the number of vehicles in a dilemma zone, for example. The V-function is used to reduce amber times by vehicles and the R-function provides the possibility to extend the clearance period.

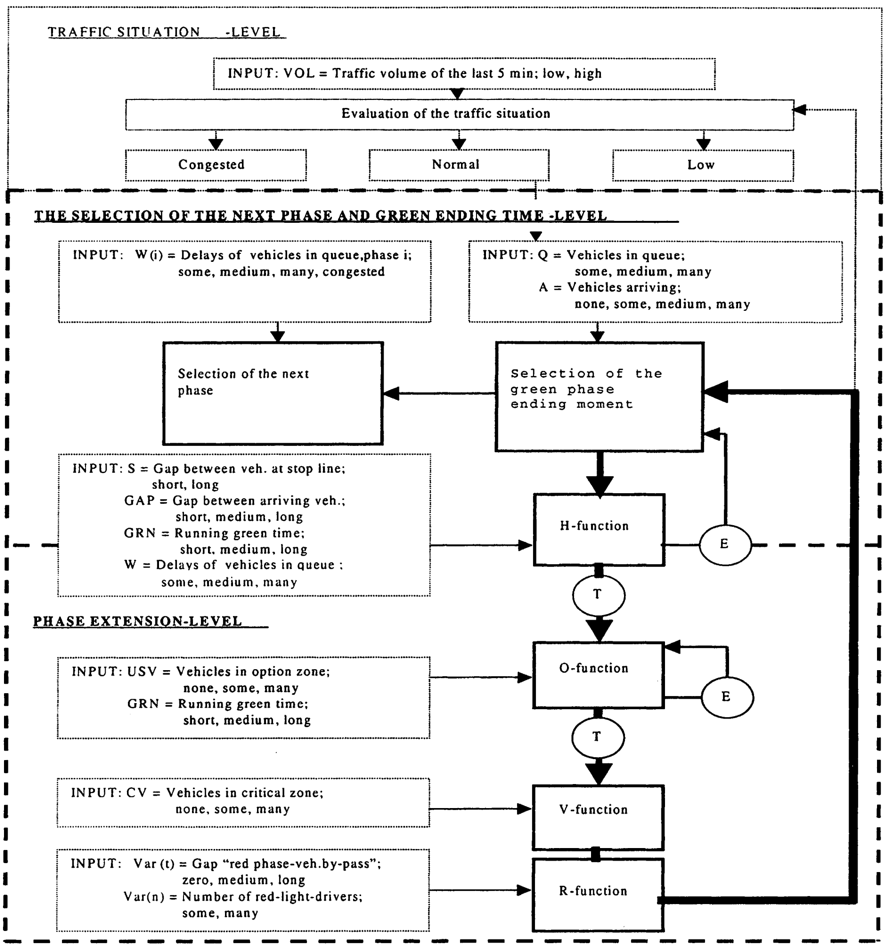


FIGURE 5 Principles of ITCARI-control.

**Priorities for Public Transport**

In the case of public transport priorities, there are reasons to believe that fuzzy public transport priorities can, for the following reasons, be better than the traditional binary-logic priorities:

- Public transport priorities add complexity to control policy, and control policy has at least one additional objective.
- The consequences of a fired public transport priority function are not known.
- Binary-logic calls for public transport priority regardless of the traffic situation.
- There can be large variations in travel time between detectors (uncertainty), especially during peak hours. Travel time can be even longer than the maximum phase extension time.
- Infrastructure (simple detector configuration with traffic situation modeling) and control rules (not many) can be quite simple.
- The rule base can be easily modified for all kinds of isolated intersections, and the rule structure can be extended to coordinated signals.

The main goals of the fuzzy rule base for public transport priority are: to give a correct priority function as a function of the request moment, and to make a correct priority decision, based on the current traffic situation at the intersection.

In our suggested application, a request-exit detector-system is used and two detectors are located per approach. The locations of the request and the first detector define the membership functions. The recommended distances are 100 – 150 meters. The public transport detection (crisp input) and the use of the traffic situation model give an input to fuzzy algorithms. The recommended priority functions are phase extension and phase recall for two-phase control, and phase extension, phase recall, rapid cycle and extra phase for multi-phase control. The two-phase control is a simple control case because the conclusion of the rule base is either to continue the current phase or terminate it. If the public transport request is detected in the approach of a green signal group, the phase extension rules evaluate the current traffic situation based on two fuzzy parameters: detection time of public transport (PT(time); zero, short, medium, long), and weight of red signal group (W(red); short, medium, long).

The W(red) or W(next) is the fuzzy factor for the importance of the next phase-for example, the estimated green time needed in the next phase or just the number of stopped vehicles (Q = queue). The rules are typical if-then-rules, for examples:

If PT(time) is zero and W(red) is short then use basic rules or
if PT(time) is medium and W(red) is medium then extend phase or
if PT(time) is long and W(red) is high then use basic rules.

| | | PT(time) | | | |
|---|---|---|---|---|---|
| | | zero | short | medium | long |
| | short | basic | extend | extend | basic |
| W(red) | medium | basic | extend | extend | basic |
| | high | basic | basic | basic | basic |

If the public transport request is detected in the approach of a red signal group, the phase recall rules evaluate the current traffic situation, based on two fuzzy parameters: – detection time of public transport (PT(time); zero, short, medium, long), and – weight of green signal group (W(green); short, medium, long).

The W(green) or W(next) is the fuzzy factor for the importance of the next phase-for example, in the estimated green time needed for the current phase or simply the number of approaching vehicles (A = arrivals). The phase recall order means that the green signal group is ready to be terminated.

| | | PT(time) | | | |
|---|---|---|---|---|---|
| | | zero | short | medium | long |
| | short | basic | recall | recall | recall |
| W(red) | medium | basic | recall | recall | basic |
| | high | basic | basic | recall | basic |

The multi-phase control is more complicated because there exists the opportunity to affect the phase and sequence order too. The decision rules for priority algorithms are based on the moment (phase) of public transport detection (crisp) and the fuzzy parameter of the next phase (W(next)).

| | | PHASE WHILE PT-REQUEST - (crisp input) A | B | C |
|---|---|---|---|---|
| | low | extension | extra phase | recall |
| W(red) | medium | extension | rapid cycle | recall |
| | high | extra phase | rapid cycle | basic |

If the selected control algorithm is phase extension or phase recall, then we can evaluate the traffic situation using the phase extension and phase recall rules. If the extra phase or rapid cycle is selected, then the control algorithm works as in conventional control.

## TESTS WITH FUZZY CONTROL

In general, we compared the efficiency of our fuzzy control algorithms (FUSICO) with traditional vehicle-actuated control (called the extension principle).

The statistical tests associated with two-phase control are shown in Figure 6. The simulation time of each traffic volume was 32*900 s and the simulated intersection was an isolated intersection of two one way streets with 2+2 lanes. The speed distribution was Gaussian with a mean value about 40 km/h. The simulated traffic was the same in both cases. The testing of the fuzzy rule base was

| Vehicle flow | Average Delay | | Standard Deviation of Delay | | $Z_0$ | P-value | | Difference |
|---|---|---|---|---|---|---|---|---|
| | VA | FUZ | VA | FUZ | | norm dist | t-test | |
| 200 | 4.6 | 4.3 | 0.6 | 0.6 | 1.9 | 0.064072 | 0.068836 | no |
| 400 | 5.1 | 5.3 | 0.7 | 0.6 | -1.1 | 0.267681 | 0.271962 | no |
| 600 | 5.9 | 6.5 | 0.7 | 0.8 | -2.9 | 0.003995 | 0.005474 | yes |
| 800 | 7.7 | 7.9 | 1.0 | 0.6 | -1.1 | 0.292818 | 0.296901 | no |
| 1000 | 9.4 | 9.2 | 1.0 | 0.6 | 0.8 | 0.329565 | 0.45446 | no |
| 1200 | 12.1 | 10.3 | 1.7 | 0.6 | 5.5 | 3.55E-0.8 | 7.29E-07 | yes |
| 1400 | 14.9 | 11.9 | 1.3 | 0.7 | 11.8 | 0.0 | 1.54E-17 | yes |
| 1600 | 17.1 | 13.3 | 1.5 | 0.7 | 12.9 | 0.0 | 3.06E-19 | yes |
| 1800 | 19.3 | 14.6 | 1.9 | 0.8 | 12.7 | 0.0 | 7.07E-19 | yes |
| 2000 | 21.4 | 16.0 | 1.5 | 0.8 | 17.3 | 0.0 | 2.09E-25 | yes |
| 2200 | 23.8 | 17.5 | 1.3 | 0.9 | 22.7 | 0.0 | 9.83E-32 | yes |
| 2400 | 25.0 | 18.8 | 1.2 | 0.9 | 22.9 | 0.0 | 6.56E-32 | yes |
| 2600 | 27.0 | 20.9 | 1.4 | 1.4 | 17.1 | 0.0 | 3.28E-25 | yes |
| 2800 | 28.4 | 25.1 | 1.4 | 4.3 | 4.1 | 3.6E-0.5 | 0.00011 | yes |
| 3000 | 30.6 | 53.3 | 1.8 | 20.8 | -6.1 | 8.05E-10 | 6.33E-08 | yes |

FIGURE 6 Statistical significance of the difference in delay.

undertaken using HUTSIM, a microscopic simulation program, and field tests.

The results show that the extension principle is a reasonable traffic signal control mode in very low traffic volumes, but fuzzy control is a competitive alternative for isolated signal control of traffic signals. All control modes for isolated traffic signal control were assessed using different tests and extensively reported (Niittymäki and Kikuchi, 1998; Niittymäki and Pursula, 1998; Niittymäki, 1999; Niittymäki and Nevala, 1999). The results have shown that fuzzy control can be an effective way to manage isolated traffic signal control.

| APPLICATION | PARAMETERS |
|---|---|
| Pedestrian crossing | WT, A, S |
| Two-phase vehicle control | A, Q |
| Multi-decision control | A, Q |
| Multi-phase vehicle control | GAP, GRN, W(red) |
| Public transport priority | PT(time) |

Where

| | |
|---|---|
| A | Approaching vehicles |
| Q | Queuing vehicles |
| WT | Pedestrian waiting time |
| S | Gap between vehicles at stop line |
| GAP | Last gap between two approaching vehicles |
| GRN | Running time of green signal group |
| W(red) | Weight of red signal groups |
| PT(time) | Time of public transport vehicle between the priority detectors |

PARAMETER CLASSIFICATION

| No. | EXPLANATION | PARAMETERS |
|---|---|---|
| 1 | Number of vehicles in the area between the detectors | A, Q, W(red) |
| 2 | Detector parameter | S, GAP |
| 3 | Timing parameter | GRN, WT |
| 4 | Special | PT |

FIGURE 7 The classification of INPUT-parameters in fuzzy control.

## CONCLUSIONS AND DISCUSSION

Our FUSICO-project continues. The general rule base for traffic signal control will continue develop, and also the fuzzy controller will improve over time. Based on the results in this paper, the simple control process is based on simple and understandable fuzzy inputs (Fig. 7), and the output of the control process can be crisp or fuzzy (as shown *in Niittymäki and Turunen*, 1999).

The benefits of fuzzy logic are based on its ability to handle linguistic information by representing it as a fuzzy set. Fuzzy logic fires many linguistic rules simultaneously and makes a compromise decision from among them. In our study, fuzzy control has to be an effective and systematic way to solve problems with multi-objectives such as minimizing delays, maximizing traffic safety and minimizing fuel consumption. The other advantages of fuzzy control are simple process and maintenance, control adaptivity, fast evaluation time and resource.

At present, we have six fuzzy signalized intersections in test use in Finland. The results have been promising. The fuzzy signal control algorithms offer, in our considered view, better measures of effectiveness than the traditional vehicle-actuated control.

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