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FUZZY TRAFFIC SIGNAL CONTROL

Principles and Applications

Jarkko Niittymäki

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Abstract of
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The FUSICO (Fuzzy Signal Control)-research project was started in 1996 at the Helsinki University of Technology. The main goals of the project are theoretical analysis of fuzzy traffic signal control, generalized fuzzy rules using linguistic variables, validation of fuzzy control principles, calibration of membership functions, and development of a fuzzy adaptive signal controller.

This thesis discusses four hypotheses for fuzzy traffic signal control. They are I) generality of fuzzy control, II) competitiveness of fuzzy control III) multilevelity, -dimensionality and -objectiveness and IV) realisticity in real traffic signal control.

The control principles and rules for the fuzzy control are modeled based on the actions of an experienced policeman represented by knowledge of an experienced signal control planner. According to the results the control parameters of fuzzy traffic signal control can be divided into three different groups: traffic volume, capacity, and level of service parameters. The fuzzy control algorithm of isolated traffic signal control can be derived based on these parameters. The fuzzy inference is perhaps the most important part of fuzzy control, but also the methods of fuzzification and defuzzification have to be introduced. Some artificial methods, like genetic algorithms and neural networks, have been tested without any benefits in comparison with the empirical membership functions. The fuzzy similarity method, which is based on Lukasiewicz's logic, has been introduced as a potential defuzzification method.

In the development phase, the testing of fuzzy control has been done by simulation. Several different control strategies have been tested in different isolated control environments. The results of signalized pedestrian crossing indicated that the fuzzy control provides pedestrian friendly control keeping vehicle delay smaller than the conventional control. Based on the experiences of the Pappis-Mamdani control algorithm, a new control algorithm for two-phase vehicle control was developed. According to the statistical tests, the application area of fuzzy control is wide. The results of multi-phase control indicated that the traditional extension principle still is a better traffic signal control mode in the area of very low traffic volumes. However, an application area of fuzzy control is available. The experiences of fuzzy public tranport priorities and fuzzy control on major arterials have been promising.

The multilevel (traffic situation, phase selection and extension inference) fuzzy control makes adaptivity possible. This also means that the number of control programs can be smaller than in the traditional VA-control. The most significant difference between traditional and fuzzy control methods is that the extension principle in VA-control looks at only the green signal groups, but the fuzzy control analyzes also the queues behind the red signal groups. This multi-dimensionality, the opposite input-parameters and the free rule-base development enable the multi-objective control.

Finally, the fuzzy control methods have been tested in several real intersections. The proposed controller consists of traffic and control models, and it is justified that this kind of on-line simulation or simulation based traffic control is a working method. According to the statistical tests of before-and-after studies, the fuzzy control has proven to be a potential control method in real isolated traffic signal control.

TEKNILLINEN KORKEAKOULU
Rakennus- ja ympäristötekniikan osasto

Väitöskirjan tiivistelmä

Tekijä: Jarkko Niittymäki
Aihe: Sumea liikenteen valo-ohjaus - periaatteet ja sovellukset (in English)

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FUSICO- tutkimusprojekti (Fuzzy Signal Control) käynnistyi Teknillisessä korkeakoulussa vuonna 1996. Tutkimusprojektin tavoitteita olivat sumean valo-ohjauksen teoreettinen tarkastelu, yleisten ohjaussääntöjen ja periaatteiden muodostaminen, ohjausperiaatteiden ja jäsenyysfunktioiden kalibrointi ja validointi sekä todellisen sumean ohjauskojeen kehittäminen.

Väitöstutkimuksen tavoitteena on neljän hypoteesin todistaminen: I) sumean ohjauksen yleistettävyys, II) sumean ohjauksen toimivuus, III) monitasoisuus, -ulotteisuus ja tavoitteisuus sumeassa ohjauksessa sekä IV) sumean ohjauksen realistisuus todellisena ohjauskeinona.

Ohjausperiaatteet ja -säännöt voidaan muodostaa mallintamalla ihmisen ajattelua. Tässä tutkimuksessa on käytetty esimerkkinä liikennettä ohjaavaa kokenutta poliisia. Tulosten perusteella sumeassa liikennevalo-ohjauksessa tarvittavat ohjausparametrit voidaan jakaa kolmeen luokkaan: liikennemäärä-, välityskyky- ja palvelutasoparametreihin. Yksittäisten tutkimuksessa esitettyjen ohjausparametrien avulla voidaan muodostaa erillisohjauksisen liittymän ohjausalgoritmi. Sumeassa ohjauksessa on sumean päättelyn lisäksi kaksi olennaista osaa: sumeuttaminen ja täsmentäminen. Sumeuttamisessa on kokeiltu erilaisia systemaattisia menetelmiä kuten neuroverkkoja ja geneettisia algoritmeja saavuttamatta kuitenkaan merkittäviä etuja kokemusperäisiin jäsenyysfunktioihin verrattuna. Täsmentämisessä on esitetty sumeaan similaarisuuteen perustuva täsmentämismenetelmä, joka perustuu Lukasiewiczin logiikkaan.

Kehitysvaiheessa sumean ohjauksen toimivuutta on tutkittu simuloimalla erilaisissa liikenneympäristöissä ja -tilanteissa. Valo-ohjauksisen suojatien tulosten perusteella sumea ohjaus toimii monitavoitteisesti sallien jalankulkijaystävällisen ohjauksen ilman, että ajoneuvojen viivytykset tai pysähdykset kasvavat. Pappis-Mamdanin valo-ohjauksen pohjalta kehitetty sumea ajoneuvoliikenteen kaksivaiheohjaus toimii tilastollisesti merkitsevästi paremmin laajalla liikennemääräalueella. Sumean monivaiheohjauksen tulokset osoittavat samaa, mutta tulosten perusteella hiljaisen liikenteen valo-ohjauksessa perinteiset menetelmät toimivat paremmin. Sumeilla joukkoliikenne-etuuksilla saavutetut tulokset ovat olleet hyviä. Myös sumean valo-ohjauksen soveltuvuutta korkealuokkaisille väylille on kokeiltu ja alustavat tulokset ovat olleet lupaavia.

Sumeassa valo-ohjauksessa tapahtuva monitasoinen päätöksenteko (liikennetilanteen tunnistaminen, vaiheen valinta ja pidennyksen säätö) mahdollistaa ohjauksen adaptiivisuuden, jolloin myös tarvittavien ohjausohjelmien määrä on pienempi kuin perinteisessä ohjauksessa. Merkittävin ero työssä verrattujen ohjausmenetelmien välillä on, että perinteinen liikennetieto-ohjaus tarkastelee vain vihreänä olevia opastinryhmiä, kun tarkasteltu sumea ohjaus tarkastelee myös punaisten opastinryhmien toimintaa. Tällainen moniulotteisuus sekä keskenään eri tavoitteiset syöteparametrit ja mahdollisuus kehittää haluttu sääntökanta mahdollistavat monitavoitteisen ohjauksen.

Sumeaa valo-ohjausta on testattu useassa eri liittymässä. Kenttäkokeissa käytetty ohjauskoje koostuu liikennemallista ja ohjausmallista sekä käyttää näin hyödykseen simulointipohjaista liikenteen ohjausta (on-line simulation). Menetelmä on osoittanut toimivuutensa adaptiivisessa ohjauksessa. Tehtyjen tilastollisten testien perusteella sumea valo-ohjaus on myös todellisissa liittymissä toimiva ohjausmenetelmä.

PREFACE

It is said that four conditions are essential to complete a doctoral thesis: an interesting topic, sufficient financial funding, an insightful supervisor and patient, understanding and loving near and dear. I have been lucky to have all of them.

This doctoral thesis has been done at Helsinki University of Technology, Laboratory of Transportation Engineering. Supervisor of this thesis has been professor Matti Pursula. I am grateful for his critical review and continuous encouragement during my studies. Without him, this research would not have been possible.

I also would like to express my thanks to D.Sc.(Tech) Iisakki Kosonen and M.Sc.(Tech) Kari J. Sane for their invaluable work in our FUSICO-project. This thesis has been mostly financed by project grant of the Academy of Finland and the Finnish Technology Development Centre (TEKES), but I would like to thank all supporting partners and my colleagues for being given the possibility to do this research. Many foundations have also given their financial support to the thesis. Special thanks belong to all of them. Especially, I would like to thank professor Shinya Kikuchi. He gave me an opportunity to work with him at the University of Delaware. His knowledge in the area of fuzzy logic was a great help to me when starting this thesis.

I give my best gratitude to our grandparents, without them and their help in childcare during my business trips, this research could not have been finished.

My family Jaana, Miikka and Pinja deserve my loving appreciation. As you know ice-hockey, football, good wine and food, playing with dolls, legos, Bionicles, Pokemons and Digimons are much more important to me than this thesis.

It is time to celebrate, and start a new scientific life,

In Espoo, January 31, 2002

Jarkko Niittymäki

ALKUSANAT

Väitöskirja on monivuotinen projekti, jonka loppuunsaattaminen edellyttää riittävää motivaatiota. Motivaatio ei kuitenkaan yksistään riitä vaan tarvitaan innostava aihe, kannustava valvoja ja esimies, riittävä rahoituspohja sekä ymmärtämystä ja rakkautta läheisiltä. Olen ollut onnekas ja onnellinen, koska kaikki nämä elementit ovat olleet kunnossa viimeisen 10 vuoden aikana.

Väitöskirjani olen tehnyt Teknillisen korkeakoulun liikennelaboratoriossa professori Matti Pursulan valvonnassa. Viimeisen reilun yhdeksän vuoden aikana olen saanut olla mukana laboratoriomme kehityksessä ja useissa haastavissa projekteissa. Sinä aikana olen valmistunut niin diplomi-insinööriksi kuin lisensiaatiksi professori Pursulan ohjauksessa ja valvonnassa. Ilman hänen ammattitaitoaan ja kokemusta en varmasti olisi tässä. Olen kiitollinen hänelle saamastani luottamuksesta.

Väitöskirjani on osa laboratorion monivuotista sumean valo-ohjauksen hanketta FUSICO-projektia. Kiitän TkT Iisakki Kososta ja DI Kari J. Sanea yhteistyöstä ja kaikesta siitä mitä olette tehneet tämän väitöskirjan eteen. Projektin rahoitus on tullut pääosin Suomen Akatemialta ja TEKESiltä, joille haluan esittää parhaimmat kiitokseni luottamuksesta. Tämän projektin aikana sain myös mahdollisuuden työskennellä University of Delawaressa professori Shinya Kikuchin ohjauksessa. Haluan kiittää professori Kikuchia mahdollisuudesta opiskella hänen ryhmässään sekä monivuotisesta yhteistyöstä.

On ollut hienoa työskennellä sellaisessa työyhteisössä kuin laboratoriomme on. Erityisesti haluan kiittää kaikkia oman tutkimusryhmän jäseniä vuosien varrella. Toivottavasti se työ mitä olette tehneet näkyy ainakin osin tässä väitöskirjassa. Kannustan teitä kaikkia eteenpäin valitsemallanne uralla ja toivottavasti voimme tehdä yhteistyötä myös tulevaisuudessa. Tietenkin haluan kiittää myös Annelia, Karia ja Åsaa aamukahviseurasta ja vähän muustakin.

Elämän tärkein osa on kuitenkin työn ulkopuolella. Haluan kiittää monivuotisia ystäviäni ja entisiä opiskelutovereita, nykyisiä kollegoita, joista on tullut perhetuttavia ja lasteni kummeja. Kanssanne vietetty vapaa-aika on tärkeä vastapaino ja paristojen lataamiskeino.

Suuret kiitokset menevät Karhusuontielle, Espooseen, jossa elämäni 20 ensimmäistä vuotta pidettiin huolta hyvinvoinnistani ja kuljetettiin harrastuksiin. Viimeiset seitsemän vuotta olette pitäneet sitten huolta omista lapsistani, mikä on mahdollistanut minun työskentelyni useissa kansainvälisissä projekteissa. Kiitokset myös Karhuosuontielle, Helsinkiin, tekin olette aina olleet valmiit auttamaan ja tyttärenne on elämäni tärkein henkilö.

Kuitenkin perheeni Jaana, Miikka ja Pinja ansaitsevat suurimmat halaukset. Olette joutuneet olemaan paljon keskenänne kun isä on ollut työmatkoilla. Toivottavasti tämä kirja todistaa ainakin joidenkin työmatkojen tärkeyden. Lasten kanssa leikkiminen ja lasten harrastusten tukeminen on sellainen elämän korkeakoulu, joka on antanut minulle paljon enemmän kuin tämä väitöskirja. Jaanalta saamani rakkaus ja tuki ovat olleet vertaansa vailla.

Nyt juhlitaan ja sitten asetetaan seuraavat tavoitteet !

Jupperissa 31.01.02

Jarkko Niittymäki

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Author's contribution and publications in the thesis

Authors contribution

The scientific contribution of the author of this thesis is in the development of the principles and detailed functions of the fuzzy signal control, and in the testing and analysis of the control systems. Thus, the author has introduced fuzzy logic as a control method, presented control systematics for isolated signal group control, made general theoretical analysis of fuzzy traffic signal control, derived rule base for isolated traffic signal control by using practical expert knowledge and formulated the fuzzy control rule-base for traffic signal control using linguistic variables. In addition, the author together with his co-authors has discussed fuzzification and defuzzification in the control process, and developed all membership functions for this thesis. The author has designed simulation and field tests, and analyzed the results using statistical methods. Some parts of this work are shown in this summary.

This Thesis for Doctor of Science in Technology summarizes the following publications:

1.) **Niittymäki J., Kikuchi S. (1998).** *Application of Fuzzy Logic to the Control of a Pedestrian Crossing Signal*. Transportation Research Record No. 1651. Washington D.C. pp. 30-38.

> *The paper was written during the author's study period at University of Delaware, USA. The study was designed and accomplished by the author together with Professor Shinya Kikuchi. The rule derivation, the membership functions and conclusions were derived by the author and further developed and refined in discussions with Dr. Kikuchi. Simulations and data analysis were done by the author. The necessary modifications of HUTSIM and development of the FUSICO-system were done by Dr. I. Kosonen.*

2.) **Niittymäki J., Pursula M. (2000).** *Signal-group control using fuzzy logic.* Fuzzy Sets and Systems, International Journal of Soft Computing, Vol. 116, No 1, November, 2000. pp. 11 - 22.

> *This study was designed and accomplished by the author. The rule derivation, the membership functions, the principles of multi-objective and multi-level control. and systematics for signal-group control were developed by the author. Professor M. Pursula's contribution is in discussing the basic ideas of fuzzy reasoning in traffic signal control and in the fuzzy control systematics in isolated traffic signal control. The basic simulation and control system was developed by Dr I. Kosonen.*

3.) **Niittymäki J. (2001).** *Installation and Experiences of Field Tests of a Fuzzy Signal Controller.* European Journal of Operational Research, Vol. 131/2, June 2001. pp. 45-53.

> *The author is fully responsible for this publication. The software interface to the field controller was implemented by student of technology M. Lehmuskoski under instructions of Dr I. Kosonen. Laboratory technician K. Hintikka took care of the hardware installations. Student of technology M.Granberg, worked as a research assistant of the author and did the test simulations and basic processing of field data. The basic principles of the fuzzy signal controller were introduced by Dr I. Kosonen.*

4.) **Niittymäki J. (1999).** *Using Fuzzy Logic to Control Traffic Signals at Multi-Phase Intersections.* In: Reusch B. (Ed.). Computational Intelligence - Theory and Applications. International Conference, 6th Fuzzy Days, Proceedings. Springer, Berlin-Heidelberg. pp. 354-362.

> *This paper is the extension of paper 2 for multi-phase traffic signal control. Student of technology M. Lehmuskoski has programmed parameters to the fuzzy controller. The author is fully responsible for rule-base, membership functions, multi-level systematics and simulation results.. The HUTSIM-FUSICO framework was provided by Dr I. Kosonen.*

5.) **Niittymäki J. (2001).** *General Rule Base for Isolated Traffic Signal Control - Rule Formulation.* Journal of Transportation Planning and Technology, Vol 24, no 3, August 2001. pp. 227-247.

> *The author is fully responsible for this publication. The rule-base development is based on the experience of M.Sc. K. J. Sane. The rule-base was derived from his experience through numerous discussions. The paper is based on this cooperation between the author and Mr. Sane.*

6.) **Niittymäki J., Turunen E. (2001).** *Traffic Signal Control on total Fuzzy Similarity Based Reasoning.* Paper accepted for publication in the Journal of Fuzzy Sets and Systems, International Journal of Soft Computing. (19.7.2001).

> *The author is responsible for all transportation aspects, fuzzy rules, membership functions and simulation tests. The paper is written together with Dr. E. Turunen. Dr. Turunen provided ideas and theory about fuzzy similarity. The statistical tests, recommendations and conclusions were done together. M. Sc. V. Könönen programmed the necessary defuzzification modifications into the FUSICO-system provided by Dr I. Kosonen.*

7.) **Niittymäki J., Könönen V. (2000).** *Traffic Signal Controller Based on Fuzzy Logic*. SMC2000 Conference Proceedings, 2000 IEEE International Conference on Systems, Man & Cybernetics, ISBN 0-7803-6583-6, October 8 - 11, 2000, Nashville, Tennessee, USA. pp. 3578 -3581.

> *The author is responsible for applications of fuzzy traffic signal control. The basic systematics is based on author's work. The real controller described in the paper has been an important part in the author's hypotheses proving . The paper is written together with M.Sc. Ville Könönen, who in his diploma thesis further developed and applied the mathematical theory of fuzzy similarity. The necessary features needed in the fuzzy signal controller were developed by Dr I. Kosonen and enhanced by the co-author.*

8.) **Niittymäki J., Mäenpää M. (2001).** *The role of fuzzy logic public transport priority in traffic signal control.* Traffic Engineering and Control, International Journal of Traffic Management and Transportation Planning, January 2001, Vol. 42. No. 1. pp. 22-26.

> *The author has derived fuzzy rules and developed all control principles in the paper. The paper is written together with student of technology M. Mäenpää. This paper based on author's earlier paper (Niittymäki 1998a). The co-author has tested these principles by simulation and field tests in his diploma thesis, which the author instructed. M.Sc. V. Könönen has programmed the priority systems to the fuzzy controller.*

The basic methodology of the simulation and control system that provides a basis for the fuzzy signal control research at the Helsinki University of Technology was developed by Dr I. Kosonen. This methodology is based on unique combination of simulation model, signal group control principle, and fuzzy logic. The method can be used for both laboratory testing and for operational traffic signal controller in the field. Therefore Dr I. Kosonen's work is an essential basis for the research published in this thesis. The author admits that the contribution of Dr I. Kosonen's work to the successful accomplishment of this research and thesis has not been sufficiently recognized in the author's publications (by means of references or being as co-author).

1 INTRODUCTION

1.1 Background

Many subjects in transportation engineering are often characterized as subjective, ambiguous, and vague. Traditionally, such problems have been dealt with in a framework of mathematics based on binary logic. Although it has already been over 30 years since *Zadeh (1965)* introduced fuzzy set theory, the theory has seen an increasing level of acceptance in transportation engineering during the last decade. The FUSICO (Fuzzy Signal Control)-research project was started in 1996 at the Helsinki University of Technology (*Pursula 1995*, *Niittymäki et al. 1999*). The subject of the project was the application of fuzzy control to traffic signal control at isolated intersection level. The main goals were:

- to make a general theoretical analysis of fuzzy traffic signal control,
- to formulate generalized fuzzy control rules for traffic signal control using linguistic variables,
- to validate the fuzzy control principles and to calibrate the membership functions of the linguistic variables using simulation and field trials and,
- to develop a fuzzy adaptive signal control system.

In isolated traffic signal control, the intersection operates independently from other intersections. This means that the control algorithm can be much simpler than algorithms for coordinated networks, and that the system controlling the intersection has a higher degree of freedom to choose a control strategy. 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. Normally, the optimization includes several simultaneous criteria, like average delays, maximum queue lengths and percentage of stopped vehicles. Hence, in practice, traffic signal control is based on tailor-made solutions and adjustments made by traffic planners. The modern programmable signal controllers with their great number of adjustable parameters are well suited to this process. For good results, both an experienced planner and fine-tuning in the field are needed. Fuzzy control has proven to be successful in problem areas where exact mathematical modeling is hard or impossible, but the process can also be controlled by an experienced human operator. Thus, traffic signal control seems to be a suitable task for fuzzy control. Indeed, one of the oldest examples of the potential of fuzzy control is a simulation of traffic signal control in an intersection of two one-way streets. Even in this very simple case, the fuzzy control was at least as good as the traditional adaptive control *(Pappis and Mamdani 1977*).

Generally, fuzzy control has emerged as one of the most promising areas for research in the application of fuzzy set theory, especially in areas that lack quantitative data regarding input-output relations such as traffic signal control. The theory of fuzzy sets is based on concepts graded to handle uncertainties and imprecision in a particular domain of knowledge. The graded concepts are useful since real situations are very often neither crisp nor deterministic, and 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. (*Kikuchi 1991*.)

In general, fuzzy control is found to be superior in complex problems with multi-objective decisions (*Kosko 1993*).

1.2 Objectives and scope of the thesis

The detailed objectives of this thesis are

1) to present fuzzy logic as a control method in adaptive traffic signal control,
2) to present systematics for isolated traffic signals and signal group control,
3) to derive and introduce a general rule base for isolated traffic signals in different cases,
4) to discuss fuzzification and defuzzification in the control process,
5) to test the efficiency of fuzzy signal control using simulation and field tests,
6) to introduce and test in practice a prototype of a fuzzy controller (FSC).

This thesis consists of eight academic papers:

Paper 1 is an application paper for a signalized pedestrian crossing, which also discusses the problems of traffic signal timing, and the fuzzy nature of this. *Paper 2* is a basic paper that discusses signal-group control as used in Finland, with special emphasis on two-phase control. *Paper 3* is based on the theory presented in *Paper 2*, but also describes the successful application of fuzzy control at a real intersection. *Paper 4* sets out fuzzy rules together with the results of multi-phase control tests. *Paper 5* discusses the basic principles of fuzzy isolated traffic signal control, with the aim of presenting a systematic approach to fuzzy traffic signal control and of deriving linguistic rules based on expert knowledge. *Paper 6* is a theoretical paper that presents a new defuzzification method called *fuzzy similarity*. *Paper 7* introduces a current version of a fuzzy controller (FSC), and, finally, *Paper 8* presents the advantages of fuzzy public transport priorities while demonstrating that fuzzy control really can be applied at different kinds of intersections. This study concentrates on isolated intersection control, a part of the application area of traffic signal control. Further on, simulations and field measurements compare fuzzy algorithms with the traditional vehicle-actuated control using the extension principle (*FHWA 1985*) or with the fixed timing (*Webster 1958*). This thesis consists of the results and experiences from four real installations of a fuzzy controller. The estimated simulation time for this thesis is about 900 hours.

2 PROBLEM DEFINITION - ISOLATED TRAFFIC SIGNAL CONTROL

2.1 Signal control framework

Transport planners have traditionally concentrated on the movement of vehicles as the major target of traffic management. The impetus for the introduction of the earliest traffic signals was to ensure safety at intersections by keeping conflicting traffic flows apart. Nowadays, the traffic signal design can be viewed through measures of performance of intersection operation criteria or desirable outcomes. Hence, a decrease in delay, number of stops, fuel consumption, pollutant emissions, noise, vehicle operating costs and queue length, as well as an increase in consideration for pedestrian, bicycle and public transport vehicles, and also in safety, are all desirable. (*Newell 1989, Davidsson 1990, Austroads 1993, Anderson et al. 1998*.)

Traditionally, the main performance measure for judging the efficiency of traffic signal control systems has been the reduction of vehicle delay and stops (*Webster 1958, Akcelik 1981, Garber and Hoel 1988*). Other considerations, such as convenience and safety for pedestrians, or bus priorities, have usually been incorporated into the systems later in their development as pragmatic features required for on-street operation, but have not been used as performance measures during the development and optimization phases (*Bång 1976, Peirce and Webb 1990*).

Signal group control has been the most commonly used control principle in the Nordic countries since the late sixties, and it has recently spread to other countries as well. Signal group control is more flexible than phase control, and is therefore better able to adapt to traffic conditions. In phase control, the signal groups are divided into a number of phases. Each signal group has to belong to at least one phase. The phases are put into a sequence, with a minimum green time for each phase. With signal group control, phases are not defined in the usual way, but are instead represented by primary phase pictures. The controller is free to form secondary phase pictures in real time from the primary phase pictures. The minimum green times are given only for the signal groups, allowing quick transitions between the phase pictures. Each signal group operates individually, and tends to go green when requested by traffic and permitted by other groups. In signal group control, it is important to check that conflicting groups cannot go green at the same time, and that there is also a sufficient time margin between non-conflicting groups. Having started green, a signal group determines the green length by itself according to its control modes and extension signal. (*Davidsson 1990, Sane 1997*.)

The signal group control at local level normally represents a decentralized control strategy. This approach makes it more difficult to handle mathematically than the traditional fixed stage control. This is because the signal group control has more freedom making interactions more difficult to model than in the phase control. Probably for this reason, the existing signal group timings are based on rather simple logic algorithms, like the extension principle (*FHWA 1985*).

2.2 From fixed timing to vehicle-actuation

The simplest control method uses pre-set fixed cycle times. The optimum cycle time is often calculated with the Webster formula, which minimizes the total delays for the pre-known traffic volumes. The optimum cycle time is shared with green times according to the occupancy levels of each phase. The Webster formula is as follows (*Webster 1958*):

$$C = \frac{1.5 * F + 5}{1 - \sum \{\max(\frac{q_i}{s_i})\}} \tag{1}$$

where C = optimum cycle time, s
F = sum of the lost times, s
q_i = traffic flows of each direction (lane) in phase i, veh/h
s_i = saturation flows of each direction (lane) in phase i, veh/h.

In many cases, for isolated intersections, the fixed time control when abandoned and replaced by vehicle-actuated control (VA). The most important elements of vehicle-actuated control are demand and extension. The traditional vehicle-actuated control of isolated intersections attempts continuously to adjust green times, and sometimes to adjust the sequence of phasing (*FHWA 1985*). The main disadvantage is that the control algorithm looks only at the vehicles on green while not taking into account the number of vehicles waiting at red.

Since the late 70's, the LHOVRA-technique (*Vägverket 1983*) has developed from being an experimental initiative by the Swedish National Road Administration to a more or less standard technique at Nordic signal controlled intersections on high-speed roads. The LHOVRA technique is based on refinement of the traditional gap-seeking extension. The technique assumes an increased knowledge of traffic density, speed and composition along a considerably longer stretch of road than is used in traditional installations. This is achieved by using several detectors placed further upstream (200 - 300 m) in the approach. (*Peterson et al. 1987*.)

2.3 Adaptive control methods based on mathematical optimization

With the introduction of microprocessor controllers it became possible to have more advanced control algorithms based on mathematical models. The optimization function can be chosen to reach a predefined goal, which usually is the minimization of vehicle delays. *Miller (1963)* suggested a self-optimizing strategy based on the criterion of minimizing the total vehicle delay. In his strategy, the decision to extend a phase is made at regular intervals by the examination of a control function. *(Miller 1963*.)

Miller's function (*equation 2*) represents the difference in vehicle-seconds of delay between the gain made by extra vehicles that can pass the intersection during an extension (*the first part*), and the loss to the queuing vehicles in the cross-street resulting from that extension (the second part).

$$T = \left\{ \left[\delta_N + \delta_S - q_N \frac{1 - \dfrac{\delta_N}{s_N}}{1 - \dfrac{q_N}{s_N}} - q_S \frac{1 - \dfrac{\delta_S}{s_S}}{1 - \dfrac{q_S}{s_S}} \right] (a + r_{NS} + l_{NS}) \right\} - \left\{ h \left[n_W + n_E + \sum_{i=1}^{k_W} q_W + \sum_{i=1}^{k_E} q_E \right] \right\} \quad (2)$$

T = control function, delay difference, s
h = estimated extension interval, s
δ_I = number of vehicles expected to pass through during the h seconds extension,
q_I = arrival rates of vehicles in the next h seconds, veh/s
s_I = saturation flow rates in the next h seconds, veh/s
a = length of the amber phase, s
r_I = length of the next red phase, s
l_I = time lost during acceleration after the end of the red phase, s
n_I = number of vehicles waiting on red approaches,
k_I = time for queue discharging, s
I = index of approaches (N(orth), S(outh), W(east), E(ast)).

Bång (1976) developed TOL (Traffic Optimisation Logic) based on Miller's work (*equation 3*).

$$\begin{aligned} \phi_A = {} & r_A \left(a_v \delta_{Av} + a_b \delta_{Ab} + a_p \delta_{Ap} \right) + b_v \delta_{Av} + b_b \delta_{Ap} \\ & - h \left(a_v n_{Bv} + a_b n_{Bb} + a_p n_{Bp} \right) - \left(b_v \Delta n_{Bv} + b_b \Delta n_{Bp} \right) \end{aligned} \quad (3)$$

ϕ_A= control function
r_A = time interval until phase A turns green again if terminated immediately
a = cost of delay
δ = number of additional cars (v), buses (b), pedestrians (p), etc., that can pass the intersection if the green is extended by h s
b = vehicle operating cost for a vehicle to resume normal speed after being brought to a complete stop and to resume normal speed
h = time interval between the calculations of control function, i.e., extension interval
n = number of queuing vehicles in approaches with red that will suffer an increased delay of *h* s, if the prevailing green is extended
Δn = number of additional vehicles that will be forced to a full stop if the prevailing green is extended by *h* s.

The British MOVA, developed by the Transport Research Laboratory, is obviously the only commercial application in isolated traffic control based on mathematical optimization (*Vincent and Peirce 1988, Kronborg 1992*). MOVA, Modernised Optimised Vehicle Actuation, uses two vehicle detectors per approach lane, one at 40 m and the other at 100 m before the stop line. Initially each lane receives sufficient green to discharge vehicles queued back to the 40 m detector. The control strategy of MOVA is a mixture of mathematical optimization and heuristic algorithms. When a phase has become green there are four consecutive steps (*Vincent and Peirce 1988*).

1. There is one minimum green time for each phase (normally 7 seconds in the UK) and one for each link (signal group).
2. A variable minimum green time takes care of the vehicles that are between the first detector and the stop line.
3. The phase is kept green as long as at least one relevant approach is still discharging at saturation flow. To check for saturation flow, MOVA checks the current gap and sometimes the sum of the current gap and previous gap against pre-specified critical gap values.
4. When the end of the saturation flow has been observed for all relevant links the optimization process starts. The reason for waiting to start the optimization process until the end of saturation for all relevant links is that the TRL-simulations have shown that minimum delay usually is achieved if the traffic discharging at saturation rate receives enough green to clear the queue completely. The optimization algorithm is inspired by *Miller (1963)*, but is more complex. In the optimization, MOVA uses a microscopic traffic model. The position of each vehicle is predicted between the IN-detector (100 m) and the stop line. Every half second MOVA makes a calculation whether the total delay will be minimized if the current stage continues to be green during 0.5 s, 1.0 s, 1.5 s,.... MOVA recognizes automatically the over saturated conditions, and, instead of the Miller algorithm, a heuristic capacity maximizing algorithm is used.

Kronborg et al. (1997) developed the Swedish SOS (Self Optimizing Signal Control) and tested it in the field. After the green phase has started, the SOS-method begins to count the delay, stopping, environmental and safety costs of changing the phase red. The calculations are made with a cost function, which expresses the variables in monetary terms. The costs are compared to the corresponding costs of the red phases waiting for the green phase. The calculation is based on the near-future (0.5-20 sec) traffic prediction made by the traffic and intersection model. If continuation of the current phase provides lower costs at some point in the near future, the phase will not be terminated. Otherwise, the phase will be terminated. The calculations and predictions are updated twice a second. (*see Miller 1963, Bång 1976, Vincent and Young 1986, Vincent and Peirce 1988*.) Also this function (*equation 4*) represents the difference of gain made by extra vehicles that can pass the intersection during an extension, and the loss to the queuing vehicles from that extension.

$$\Delta\_benefit\,(h) = \sum_{\forall v,i}\Big[\mathrm{cos}t\_dly(v,i)\cdot(S\_d(v,i,h) - D\_d(v,i,h)) + \mathrm{cos}t\_stop(v,i)\cdot(S\_s(v,i,h) - D\_s(v,i,h))\Big] \\ + \sum_{\forall i}\Big[\mathrm{cos}t\_option\cdot D\_o(i,h)\Big] + \mathrm{cos}t\_ped\cdot(S\_pd(h) - D\_pd(h)). \tag{4}$$

Δ_benefit(h) = total benefit difference between issuing a stop order now and issuing a stop order at time = h
v = vehicle type index
h = extension interval, s
cost_dly = passenger time and driver time cost + vehicle time cost + vehicle emission cost for vehicle type v in lane i
S_d(v,i,h) = reduced delay for vehicles of type v if the stop order is issued at time h instead of now, s
D_d(v,i,h) = increased delay for vehicles of type v if the stop order is issued at time h instead of now, s
cost_stop = vehicle stop cost + traffic safety cost for vehicle stop + vehicle emission stop cost for vehicle type v in lane i
cost_option = separate cost for the accident risk when stopping vehicles currently in the option zone in lane i
S_s(v,i,h) = reduced number of stopped vehicles of type v if the stop order is issued at time h instead of now
D_s(v,i,h) = increased number of stopped vehicles of type v if the stop order is issued at time h instead of now
D_o(i,h) = a factor relating to the increase in the number of stopped vehicles in the option zone when the lane goes red if the stop order is issued at time = h instead of now
cost_ped = pedestrian time cost + pedestrian safety cost
S_pd = reduced pedestrian delay if the stop order is issued at time = h instead of now
D_pd = increased pedestrian delay if the stop order is issued at time = h instead of now.

After the optimum phase termination moment is found, the SOS-algorithm gives 12 seconds to the incident reduction function to find a safe final termination moment. In oversaturated conditions the algorithm tries to balance the waiting times of each direction (*Kronborg et al. 1997, Kronborg and Davidsson 1996*).

2.4 Conclusions

The difficulty of the traffic control process lies in the fact that it must be repeated with very short time intervals. Secondly, because traffic conditions in the immediate future cannot be predicted precisely, the control action is based on optimizing the current state only; as a result, the individual control actions do not necessarily yield optimal conditions in the long term. Thirdly, the detectors cannot capture details of the prevailing conditions on the approaches (not as good as a human); for example, vehicle type and speed changes. When the intersection is complex in terms of geometric design, channelization and types of vehicles to be handled, the control process must consider many usually mutually conflicting objectives, of which safety is the most important requirement.

According to the experiences of SOS-control, the main problems of optimizing control are the fairly high number of detectors, difficulty of understanding control and its parameters, and sensitivity to detector errors. (*Kronborg et al. 1997*.)

How to weight the objectives is also an issue. Signal control deals with a complex multi-objective and multi-constraint problem in which the optimization performed is based mainly on recent information. All this means that "as the complexity of a system increases, our ability to make precise and yet significant statements about its behaviors diminishes, and significance and complexity become almost mutually exclusive characteristics" (*Kosko 1993*). This is true in traffic signaling, especially at complicated intersections. A better solution might be the mechanism of human thinking with linguistic fuzzy values rather than numbers (0/1).

3 CONTROL METHOD - FUZZY LOGIC

3.1 Principles of fuzzy control

The fuzzy logic based control that was developed in this research study would emulate the manual or human process as much as possible in a computerized environment. The aim is to "soften" the decision making-process by accepting "human like" acquisition of information and executing "soft" decision rules. Such a control would be robust and adaptive in terms of handling various objectives at the same time, while being able to choose the parameters relatively simply. (*Kikuchi 1991.*)

Fuzzy control has been developed in the context of fuzzy inference. Fuzzy inference is the inference process based on the multi-value logic of inference; in other words, the truth values of input and the rules of the inference process are not singular (yes or no), but, rather, they are multi-valued. As a result, the truth of the conclusion is given a value between 0 and 1, which more closely resembles the inference performed by the human decision-making process, which involves a greater or less degree of ambivalence. The essence of this inference is the use of fuzzy sets to represent the input and the rules (relation). A number of reference materials relating to fuzzy sets, inference and control are available.(*Klir and Folger 1988, McNeil and Freiberger 1992, Yager and Filev 1994, Orlovski 1994, Klir et al. 1997, Zimmermann 1996.*).

It has been known through various experiments and real world applications of control products that use of fuzzy control is more suited than the use of traditional control for problems that involve human perception, ambiguous rules and compromise between conflicting objectives (*Kartalopoulos 1996*). Normally, an inference is based on the notion of similarity. In the following a simple inference process consisting of input and rules is presented:

Input: x is A and y is B.

Rules: (1) if x is A1 and y is B1 then z is C1.
(2) if x is A2 and y is B2 then z is C2.

Under the fuzzy inference, the conclusion is drawn on the basis of the similarity between the input and the premise. The exact match of the two is not necessary. The degree of similarity between them determines, in turn, the degree of validity of the conclusion. This is called the generalized modus ponens. Under such a scheme, the input and the elements of the rules can be represented by fuzzy sets, which are defined by membership functions. Similarity is measured by a set operation of three sets involving input, premise and conclusion.

Mathematically the operation used in this thesis is:

$$\mu_C(z) = \mathrm{Max}\,\{\mathrm{Min}\,[\mu_A(x), \mu_R(x,y)]\} \quad (5)$$

where $\mu_C(z)$ is the membership function of the conclusion; $\mu_A(x)$ and $\mu_R(x,y)$ are the membership functions of input and the rules, respectively (*Zimmermann 1996*).

3.2. Basic principles of fuzzification

In everyday situations, linguistic terms whose definitions are not entirely clear are used for easy and efficient communication. Equivalent expressions with exactly defined terms are very difficult to achieve. The linguistic terms are normally easy to select and to use in our daily lives. However, they include some kind of uncertainty, because we understand them in common terms (not exact) and in a context-dependent way.

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 ratio of the crisp input x_0 with respect to each fuzzy set x of the input universe

$$x = \text{fuzzifier}(x_0), \tag{6}$$

where the fuzzifier represents a fuzzification operator. The operator converts the crisp values into suitable linguistic labels of fuzzy sets. The most important aspects relating to the fuzzification are the universe divided into a certain number of segments (fuzzy variables) and the membership functions of the fuzzy sets.

The fuzzy sets describe terms of linguistic variables. The meaning of a fuzzy linguistic term is defined by the membership function, because it indicates a grade of membership of each element in a fuzzy linguistic set of interest. This means that the physical meaning of a linguistic term is characterized by the membership function, which is assigned by a person intending to use this term. The shape of a membership function is quite free, but its typical feature is some kind of smoothness (Z-shaped, Bell-shaped, S-shaped). The triangle-shaped (trapezoidal) functions, used in the traffic signal control application of this study, are also commonly used. When the shapes of the fuzzy sets are determined, several other parameters have to be adjusted. (*Jang and Sun 1995*.)

The choice of fuzzy variables has a substantial influence on the sensitivity of the control, but there is no unique solution for that. The optimal partition can be achieved by a heuristic method, but the basic principle might be to use our real life linguistic terms. For example, the pedestrian waiting time at a signalized intersection can be short, long or very (too) long. The membership functions representing linguistic values of a linguistic variable should describe the nature and properties of the linguistic variable in question. The methods of constructing membership functions can be divided into direct and indirect methods.

The direct method means that experts try to find answers to the following questions:
- What is the membership degree of x in S ?

- Which elements x have the degree of membership $\mu_S(x)$?

By answering these questions, a set of pairs $\{x, \mu_S(x)\}$ can be defined, and the membership functions can be constructed using some curve-fitting method. On the other hand, sometimes it is easier to compare the degrees to which elements belong to S than to give the actual degree of membership for each element as in the direct methods. An expert makes pair wise comparisons between elements $x_1, x_2, \ldots, x_n$ of the universal set U with respect to how much they belong in S. (*Zimmermann 1996.*)

3.3 Fuzzy inference and rule base development

The conventional demand-actuated control relies on a number of rigid rules of the type: "if... antecedent: (particular traffic condition), then... conclusion (specific action)". When information on the prevailing conditions matches the antecedent of a rule, then the rule is 'fired'. Because the conclusion of the rule is either to continue the current phase or to terminate it, the evaluation process is implicitly built into the rules. In this case, the doubt and hesitation that are experienced in manual control do not exist; the determination is binary with no room for indecision. For this type of control, many rules are necessary to cover all possible situations. As a result, most signal controllers require the setting of a large number of parameters.

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

Rule 1:	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, respectively, and A_i and B_i are respectively 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 as 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)

GMP is closely related to the forward (data-driven) inference, which is particularly useful in the fuzzy logic controller construction, while GMT 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

$$(A \wedge (A \Rightarrow B)) \Rightarrow B. \tag{7}$$

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 (*Zimmermann 1996*)

$$\mu_{input}(x,y)=\mu_{A'\cap B'}(x,y)=\mu_{A'}(x)\wedge\mu_{B'}(y) \tag{8}$$
$$\mu_R(x,y,z)=\mu_A(x)\wedge\mu_B(y)\wedge\mu_C(z).$$

The entire knowledge of the system designer about the process to be controlled, traffic signal control in this case, 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 thoroughly. The development of rules is time-consuming, and designers often have to translate process knowledge into appropriate rules. *Sugeno and Nishida (1985)* mentioned four ways to derive fuzzy control rules:
- from an operator's experience,
- from a control engineer's knowledge,
- by fuzzy modeling of the operator's control actions,
- by fuzzy modeling of the process.

Zimmermann (1996) added three more sources:
- crisp modeling of the process,
- heuristic design rules,
- 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.

3.4 Defuzzification methods

Because the outputs of the decision rules are fuzzy, we need some kind of defuzzification method to achieve a crisp output for the final control action. The defuzzification process is an important step. In general, there is no systematic procedure to choose a defuzzification strategy. *Yager and Filev (1994)* called it as a "selection problem". The defuzzification process involves a mapping from a space of fuzzy control actions into a space of crisp control actions. This procedure is the inverse of that of fuzzification. The initial data value, y, consists of the membership value of the current output with respect to all the output fuzzy subsets of the output space,

$$y_0 = \text{defuzzifier}(y), \tag{9}$$

where y_0 is the crisp control output and the defuzzifier is the defuzzification operator. Several techniques have been developed to produce an output (*Yager and Filev 1994*). The three used most frequently used are the following:

- *Mazimizer*, by which the maximum output is selected; the max criterion method (MC).
- *Average (or measured average)*, which averages measured possible outputs; the mean of maximum method (MOM).
- *Centroid (and its variations)*, which finds the output's center of mass; the center of gravity method (COG).

Clearly, each of the three methods has its own features that are suitable, respectively, for slightly different kinds of problems. According to *Brase and Rutherford (1978)*,

- the MOM strategy yields a better transient performance,
- the centroid (COG) strategy yields a better steady-state performance,
- the centroid (COG) yields a lower mean square error than MOM,
- MOM strategies yield a better performance than the MC strategy.

In the MC method, the crisp output is the point where the membership function $\mu_Y(y)$ reaches its maximum value. The control action may be expressed as

$$y_0 = \{ y_k \mid \mu_Y(y_k) = \max(\mu_Y(y)) \}. \tag{10}$$

In the MOM, the produced action corresponds to the mean value of all local control actions, whose membership functions reach their maximum. In the case of a discrete universe, it can be expressed as

$$y_0 = \frac{\sum_{k=1}^{m} y_k}{m} \tag{11}$$

where m is the number of points in the universe of discourse with maximum membership function value.

The center of the area of the membership function of the output control section fuzzy set is produced in the COG method. For the discrete case, it may be written as:

$$y_0 = \frac{\sum_{k=1}^{m} \mu_Y(y_k) * y_k}{\sum_{k=1}^{m} \mu_Y(y_k)} \tag{12}$$

where $\mu_Y(y_k) = \max_y(\mu_Y(y))$; k = 1, …, m, and m is the number of points in the universe of discourse with maximum membership function value.

3.5 Introduction of fuzzy similarity

All other parts of a fuzzy control system except the defuzzifier have sufficient mathematical background. An output of the system seems to make sense if "everything goes fine", but nothing guarantees that this will be the situation. In a new method called maximal fuzzy similarity this is not really a problem as it is based on a well-defined Lukasiewicz multi value logic. In fact, this method is a true generalization of the equivalence relation. (*Turunen 1999, Niittymäki and Turunen 1999.*)

The main idea of maximal fuzzy similarity is to calculate a similarity value, which can also be partial, for every IF- part of a rule R_i:

$$\text{Let } X = (x_1, x_2, ..., x_N) \text{ be the vector of input variable}$$

$$\text{SIM}(X, R_i) = \frac{\sum_{k=1}^{N} W_k \mu_{A_k}(x_k)}{\sum_{k=1}^{W} W_k} \tag{13}$$

where R_i refers to rule number i , μ_{Ak} is the membership function of fuzzy set A_k . W_{Ak} :s are weights($\in$N) for different input values. The final decision is the *THEN*-part of the rule that has the largest similarity value (MAXSIM(X,R_N)). Thus, the uncertainty of the defuzzification method is not relevant in this case.

3.6 Literature review of fuzzy traffic signal control

Fuzzy logic allows linguistic and inexact data to be manipulated as a useful tool in designing signal timings. It also provides a means 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 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 signal controller requires the expert knowledge and experience of traffic control in formulating the linguistic protocol, which in turn generates the control input to be applied to the traffic signal control system. (*Kim 1994*.)

Niittymäki et al. (1997a) presented a literature review of fuzzy traffic signal control. *Teodorovic (1999)* presented "the state of the art" of fuzzy logic systems in transportation engineering. More references can be found there, but the literature review of this thesis is discussing the adaptive traffic signal control, only.

The first known attempt to use fuzzy control in traffic signal control was made by *Pappis and Mamdani (1977)* who made a theoretical simulation study of a fuzzy logic controller in an isolated signalized intersection (2+2 lanes, one-way intersection). In their study, Pappis and Mamdani compared their fuzzy method to a delay-minimizing adaptive signal control with optimal cycle time. According to the results, the fuzzy controller was equal to, or slightly better than, the adaptive method used for comparison. In Pappis's and Mamdani's study (1997), the heuristic approach to the control problem was employed, which resulted in a set of linguistic control statements. The basic ideas of the theory of fuzzy sets were used for the quantitive interpretation of these instructions as well as the decision-making process. The fuzzy control instructions are of the form

if T(ime) = medium
and A(rrivals) = mt(medium) mt= more than
and Q(ueue) = lt(small) lt = less than
then E(xtension) = medium.

A total of 25 rules used (5 for each intervention). Every rule is a fuzzy relation between the inputs T, A, Q and the output E. In this application, since each fuzzy rule is represented by a four-dimensional array, the fuzzy algorithm employed at each intervention for deciding the control action is represented by the union of five such arrays, as five rules operate at each intervention. Twentyfive rules provide for a maximum of five interventions taking place at 7th, 17th, 27th, 37th and 47th s. Thus the maximum effective green time is 57 s. At each intervention, the five rules are invoked ten times (i.e., for each of the next 10 s). It should be noted that the detectors are located sufficiently far away from the intersection that the traffic situation data is available for each of the next 10 s.

Kim (1994) has also studied the fuzzy algorithms of isolated intersections. He has discussed the problems of turning traffic. His fuzzy algorithm adjusts the duration of the green traffic signal by evaluating the traffic conditions at the end of each phase. The green time for each phase is divided into a number of interventions. Every fuzzy 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 (see also *Tzes et al. 1995*).

In 1990's fuzzy traffic signal control was also studied by *Favilla et al. (1993), Sayers et al. (1995, 1996, 1998), Trabia et al. (1999*), as well as others.. *Favilla et al. (1993)* presented a fuzzy traffic controller with adaptive strategies for fuzzy urban traffic control systems combined with two different defuzzification and decision-making criteria. The simulation results indicated that fuzzy control is adaptive without statistical proof. *Trabia et al. (1999)* presented a fuzzy logic-based adaptive traffic signal controller for an isolated four-approach intersection with through- and left-turning movements. The controller had an ability to make adjustments to signal timing in response to observed changes in the approach flow. The information was used in a two-stage fuzzy logic procedure to determine whether to extend or terminate the current signal phase. During the first stage, the controller estimated the traffic intensity on each approach. This intensity information was then used in the second stage to determine whether to extend or terminate the current phase. The controller produced fewer vehicle delays than the traffic-actuated controller while maintaining the percentage of stopped vehicles of the same order. *Sayers et al. (1995, 1996, 1998)* had aimed to develop a flexible signal controller which could be configured so that it embodied the objectives appropriate to the situation in which it was to be used. They used a multi-objective genetic algorithm (MOGA) optimization technique to derive optimal solutions for fuzzy control.

Table 1. Summary of earlier experiences in isolated fuzzy traffic signal control.

Study	**Application**	**Study method**	**Results of fuzzy control performance**
Pappis and Mamdani 1977	Fuzzy two stage signal control of one-way intersection	Simulation: comparison to ideal adaptive control with optimal cycle	Equal or slightly better
Kim 1994	Isolated fuzzy signal control	Simulation: comparison to fixed signal timing	5-33% better efficiency
Sayers et al. 1995-98	Isolated fuzzy signal control	Simulation: comparison to VA-control	Better flexibility, promising results
Trabia et al. 1999	Two stage fuzzy control	Simulation: comparison to VA-control	9.5% improvement in average delays, 1.3% improvement in stopping percentage

Nakatsuyama et al. (1984) clarified the validity of the fuzzy logic phase controller in the signal control of two successive signalized intersections of an arterial road under conditions such as when a fairly large number of vehicles is passing an intersection. The fuzzy logic phase controller is composed of fuzzy control statements, which determine the termination of a green or amber periods. Co-operation between a fuzzy logic controller and a fuzzy logic phase controller always results in good performance, especially when the number of cars varies by a large margin as observed before or after the rush hour. *Kim (1994)* has also studied the fuzzy controlled coordination. The fuzzy rule base needs to take into account the possible blockage at the intersection due to potentially heavy traffic conditions. The results of fuzzy coordination have shown about a 10 % larger capacity than the results of conventional coordination. *Kaczmarek* has studied coordinated traffic signals in theory during the last 20 years in Poland (*Kaczmarek and Rakiewicz 1980*).

From the network point of view, the signal timing at an intersection is defined by three parameters: cycle time, phase split and offset. *Chiu (1992)* used fuzzy decision rules to adjust these three parameters based on local information only. A set of 40 fuzzy decision rules was used for adjusting the signal timing parameters in a network of 3 * 3 intersections. The rules for adjusting cycle time, phase split and offset are decoupled so that these parameters are adjusted independently. The effectiveness of the fuzzy method against traditional methods has been shown by simulations. The results have shown improvement as early as when only 3 intersections are adaptive, although such improvement only becomes significant when all 9 intersections are adaptive compared to the fixed timing. Lately, *Kosonen I and Bång (2001)* have introduced a fuzzy control system based on a multi-agent idea.

As a summary, the fuzzy signal control has been developed in the context of fuzzy inference. The fuzzy statement protocol is a fruitful technique for modeling the knowledge and experience of a human operator. Thus, traffic signal control is a suitable task for fuzzy control. Although, the problem found in past efforts is that the comparison with the traditional control is not conducted in a realistic environment. It is usually made with the classic fixed time signals, not with the more advanced vehicle-actuated signal controls. Further, the simulation models used for comparison are rather crude considering the microscopic simulation models available in traffic engineering today. The achieved results are based on single cases, which means that the systematics of fuzzy traffic signal control is at least partly missing. In addition, the tests in real intersections are often missing.

4 RESEARCH HYPOTHESES, METHODS AND DATA

4.1 Introduction to fuzzy traffic signal timing

Controlling traffic signal timing involves making the following evaluations continuously: Whether to (1) terminate the current phase/signal-group and change to the next most appropriate phase/signal-group, or to (2) extend the current phase/signal-group. In other words, a controller continuously (or at regular intervals) gathers information and evaluates the status of each approach and selects the most appropriate option. Like most practical control problems, this control process involves the following elements: input, processor, output, the desired goal, evaluation criteria and a feedback loop. In feedback control, inputs are the desired state of the system and the information about the current state. The processor is the knowledge base (or rule base) that, given the input, provides the decisions as to whether to continue or terminate the current phase. Output is the predicted consequence of the control prescribed by the processor. The desired goal is the target that establishes the tolerable conditions before the current phase needs to be changed. Evaluation criteria and the feed-back loop represent the process of comparing the output and the target, after which the output is sent back to become part of the new input in the next time increment. (*Evans 1980, Bell 1992*.)

The fuzzy signal control process in this thesis consists of seven parts: the current traffic situation with signal status, the detection or measuring part (crisp input), the traffic situation modeling, the fuzzification interface, fuzzy inference (fuzzy decision-making), defuzzification, and signal control actions (for example, extension or termination of signal group) (*Figure 1*).

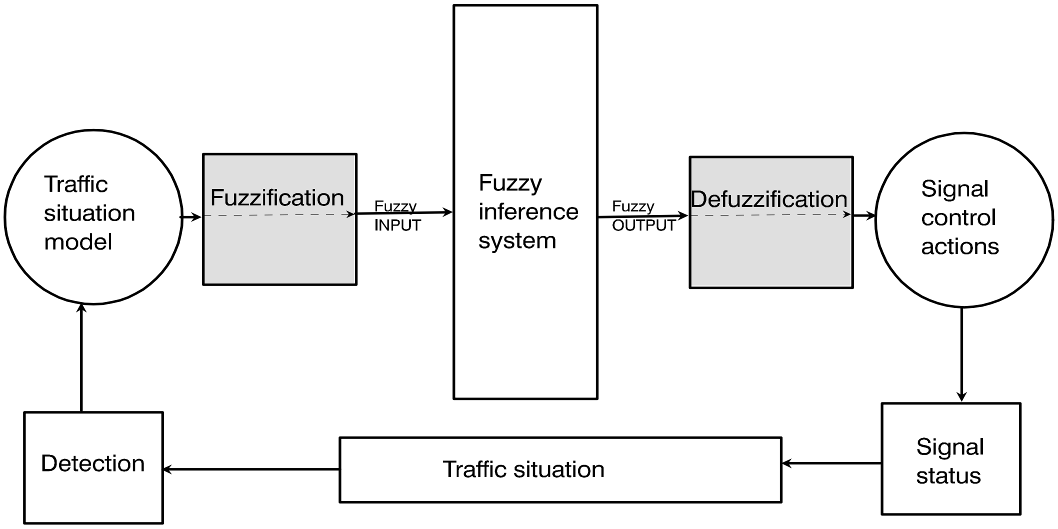


Figure 1. Structure of fuzzy traffic signal control (Niittymäki 1997).

4.2 Research hypotheses

This thesis has four basic hypotheses that are based on the objectives of the FUSICO - research project and the literature of previous studies:

Hypothesis I: *It is possible to derive general systematics, control principles and a rule-base for fuzzy traffic signal control*.

Hypothesis II: *Fuzzy control can be a competitive control method in isolated traffic signal control.*

Hypothesis III: *Fuzzy control can be a multiobjective, -level and -dimensional control method.*

Hypothesis IV: *The developed fuzzy controller and fuzzy control principles can be used in real intersections as a control method.*

4.3 Research methods

The three main methods used to test the hypotheses are rule derivation, simulation, and field tests of a fuzzy controller using on-line simulation and before-and-after measurements. For different hypothesis different methods are used. In the following, the methods are described hypothesis by hypothesis.

1. Rule base derivation by using practical expert knowledge for hypotheses I and III [*Paper 5*]

Kosko (1993) has said that "a fuzzy rule defines a fuzzy patch". He introduced three steps for fuzzy system building (variables, fuzzy sets and rules). Our fuzzy systems were built in five steps (objectives, measures, variables, fuzzy sets and rules) because we had to discuss our objectives (step 1; multi-objective control problem) and measures of each objective (step 2). In general, it is possible to have three main objectives for traffic signal control (fluency, safety, environment), and a number of factors can be called sub objectives, such as delay, waiting time, percentage of stops, risk of rear-end-collisions, amount of emissions etc. Based on this, we can choose fuzzy variables (step 3; X_i is input and Y is output). The rule can be *if X, then Y* (cause-effect or stimulus-response). For example, let X be pedestrian waiting time (WT) and let Y be the status of the pedestrian signal group (red/green). We accept red if the waiting time is short, but, if the waiting time is long, then we have to give green for pedestrians (traffic safety rule). In step 4, we have to define fuzzy sets for variables. We decide that the pedestrian waiting time can be *short*, *long* or *very long*. Then we have to define the membership functions for fuzzy sets (see fuzzification). After that we define the fuzzy sets for other inputs and output. In our pedestrian crossing example case, we define fuzzy sets for approaching vehicles (fluency and partly environment rule) and discharge gap (fluency rule). If output Y is fuzzy, then we have to define fuzzy sets for Y. Finally, we can define rules (step 5). We have to assign input sets to the output set. In our case, we have to define output (in our case, crisp) for each cell of a 3D-matrix (WT, Arrivals and Saturation rate). After that, it is possible to combine a number of rules.

In the FUSICO-project, the aim was to model the actions of an experienced policeman represented by knowledge of an experienced signal control planner. The basic rule base development was completed during the fall of 1996. M.Sc. Kari J. Sane, an experienced traffic signal planner, was working at the Helsinki University of Technology at this time. Everyday discussions and working groups helped us to model his experience to our rules. Five types of environment of isolated traffic signal control were selected for the rule-base development; signalized pedestrian crossing, two-phase control, multi-phase control, public transport priority and signal control of high-speed roads (70 km/h). (*Sane 1997*.)

2. Simulation as a test method for hypotheses II and III [*Papers 1,2,4,6*]

Nowadays, simulation is an important method in traffic modeling. The main advantage of simulation, as opposed to field measurements, is that it enables the experimenter to control the variables. As with a controlled laboratory experiment, a number of tests can be run with pre-selected values for the independent variables. Simulation has given some new possibilities to test and evaluate strategies of signal control. An overview of traffic simulation is given by *Pursula (1999).*

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. The simulation package HUTSIM gives versatile possibilities to test different traffic signal control algorithms against each other. HUTSIM is a simulation package that has been developed at the Helsinki University of Technology. In the original design, the adaptive signal control was simulated 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. This system, known as HUTSIG, works in such a way that the controller object has some measurement functions that are used to collect and analyze incoming detector data (*Figure 2*). The calculated indicators of the traffic situation are then transmitted to the control logic for timing decisions, put into force by the group oriented signal control. (*Kosonen I 1996a*, *1996b*, *1999*.)

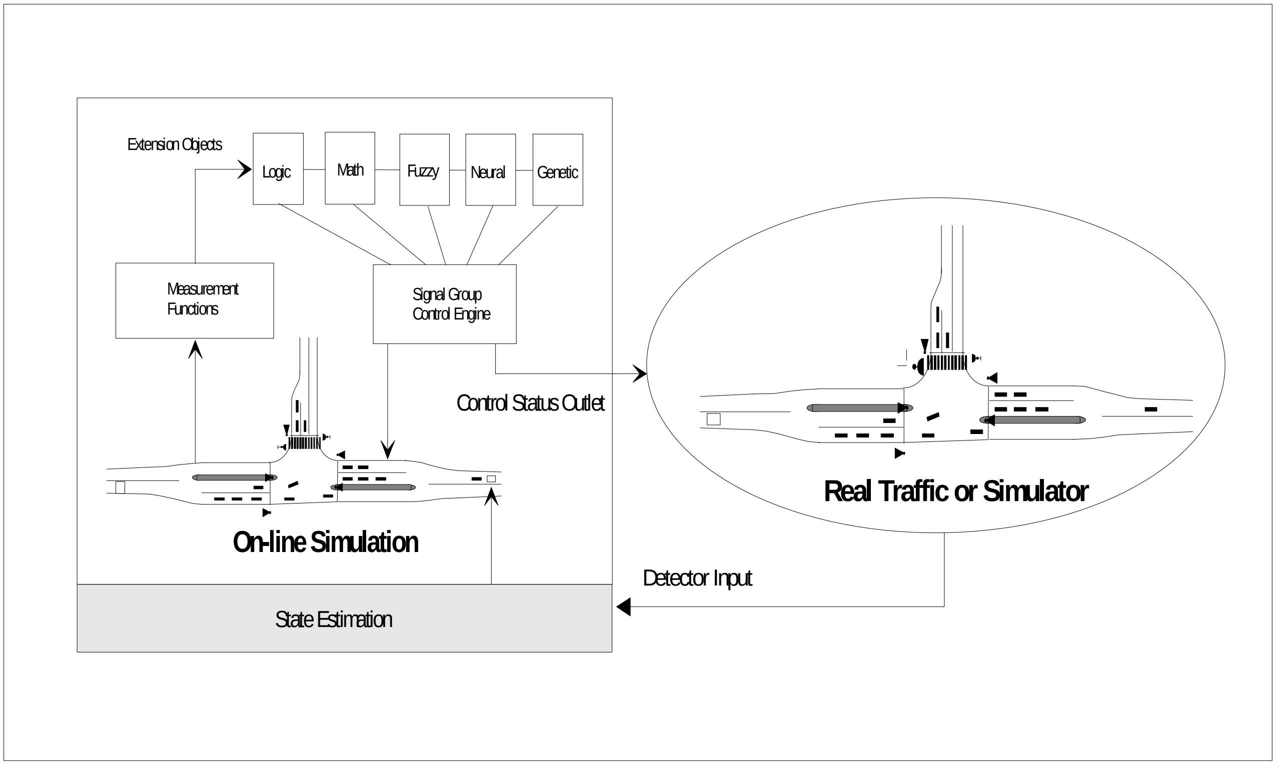


Figure 2. HUTSIG on-line simulation based signal control with a signal group control engine and alternative inference objects (Kosonen I 1999).

<u>3. Field tests of a fuzzy controller using on-line simulation to test hypothesis IV [*Papers 3,7,8*]</u>

Kosonen I (1999) has presented principles of on-line simulation and simulation-based traffic signal control. The basic idea is that the simulated traffic represents the real traffic, thus providing the control unit with all necessary information, while reflecting the effects of control operations. The real-time detector and control data are used to keep the state estimation as accurate as possible. The software used for traffic modeling is HUTSIM, which is modified for real-time use. When a vehicle passes a detector, a vehicle is generated in the simulation model. After that, no additional information about the vehicle is collected, as the simulation model only propagates vehicles from the generation point to their destinations. This idea leads to one key benefit of the system: the whole intersection can be handled with very few traffic detectors. A fuzzy controller, a control object inside HUTSIG, is able to receive inputs, to make fuzzy decisions and to generate output (*Figure 3*). *(Kosonen I 1996b, 1999.)*

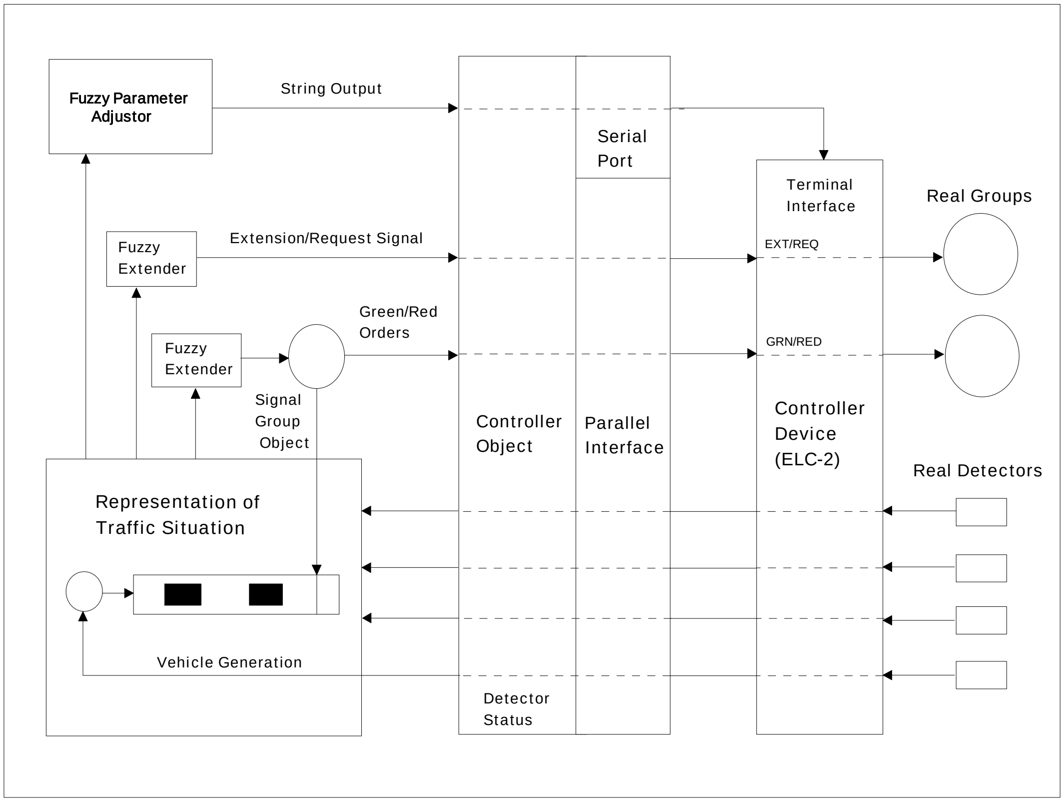


Figure 3. The fuzzy signal controller and its connection to field operation, called HUTSIG (Kosonen I 1999).

4.4 Tested cases

The summary of tested cases and related data is given in *Table 2*. The experimental design of each case is shown and discussed in the papers of this thesis.

Table 2. Summary of compared control methods in this thesis.

	Control environment	Control modes	Cases (no: characteristics)	Compared measures	Methods
1	Signalized Pedestrian Crossing [paper 1]	Traditional VA Modified VA Basic fuzzy	27: 15,50,150 ped/h 200-1800 veh/h	Pedestrian WT Vehicle Delay Vehicle Stop %	Simulation
2	Two-phase Vehicle Control [paper 2]	VA Basic fuzzy	15: 200-300 veh/h	Delay Stop % Cycle length Queue length	Simulation
3	Two-phase Vehicle Control [paper 3]	VA (4 timings) Basic fuzzy Multi-objective fuzzy	**Real intersection in Helsinki** Traffic volume/ Weekday 7am-10pm	Delay Stop % Cycle length Queue length	**Field test**/ simulation
4	Multi-phase Vehicle Control [paper 4]	VA Basic fuzzy	18: 200-1200 veh/h minor/major: 1:2, 1:5, 1:10	Delay Stop % Cycle length Queue length	Simulation
5	Signalized Pedestrian Crossing Multi-phase Vehicle Control [paper 6]	Basic fuzzy Fuzzy similarity	See cases: (1) + (4)	See cases: (1) + (4)	Simulation
6	Public Transport Priority [paper 8]	No priority Active priority Fuzzy priority	**3 real intersections Lahti, Vantaa, Jyväskylä**	PT-time Delay Stop %	**Field tests**/ simulation

5 RESULTS - VERIFICATION OF HYPOTHESES

5.1 Hypothesis I - Generality of fuzzy control

To verify this hypothesis we have to show that using the developed systematics, the control parameters and principles, and the input parameters it is possible to derive a functioning control algorithm for any isolated signal controlled intersection.

In the following, each tested control case is shortly discussed beginning with the objectives of traffic signal control and ending with rule derivation. More thorough discussion is given in the corresponding papers.

Signalized pedestrian crossing [*Paper 1*] and pedestrian signal group control

Perhaps the simplest fundamental traffic signal control problem is controlling a pedestrian crossing. The main issue of control here is, given the prevailing conditions of vehicle arrivals on the roadway and of the pedestrians wishing to cross the street, when to terminate the vehicle green phase and give green to pedestrians (constant in our case). The main goal of fuzzy control is to give pedestrians an opportunity to cross the street safely, and with minimum waiting time, but also to minimize the risk of rear-end collisions (minimize the number of approaching vehicles at the termination moment). It is also important that the control does not encourage pedestrians to cross the street during the vehicle green.

The signal operates as follows: when no pedestrian wishing to cross the street is present, the signal phase is green for the vehicular traffic (called the rest phase). When a pedestrian arrives and presses the button (or pad detector), the controller starts to evaluate the state of vehicle arrivals and the waiting time of the pedestrians. If specified criteria are met, the vehicle green is terminated and a green phase is provided for the pedestrians; otherwise the current vehicle green phase continues. The input parameters are naturally based on the objectives of control, i.e., pedestrian waiting time (WT) and the number of approaching vehicles (A). The additional parameter, the discharging queue indicator (S), was selected because it is not appropriate to terminate vehicle green while the queue is discharging (method of one stop per intersection). The rules and results are reported *in* [*Paper 1*] .

Two-phase vehicle control [*Paper 2*]

According to *Orcutt (1993)*, the general rule at the signalized intersection is "the fewer phases, the better". Two are as few as there can be while still maintaining a meaningful traffic signal installation. According to *Orcutt* two is the ideal number of phases. 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 then leave the motorist and pedestrian on their own. (*Orcutt 1993*.)

The main goals of our fuzzy control are
- to adjust the cycle time, and,
- to divide the cycle into the green parts of the phases.

In principle, this means that we are looking for the best possible termination moment by comparing the traffic situations of simultaneous green and red phases. The fuzzy signals work so that the green signal group gives at least the minimum green time. If the demand (fuzzy ratio/scale between green and red or approaching and queuing vehicles) is sufficient, the green time can be extended stepwise. Based on human reasoning, there are two input variables for the fuzzy rule base, which seem to be sufficient:

A = number of approaching vehicles at the moment t (veh),
Q = number of queuing vehicles at the moment t (veh).

The parallel additional rule for two-phase control would be that "if Q (length) is too long, then change immediately". The rules are reported in [*Paper 2*].

Multi-phase vehicle control [*Paper 4*]

The fuzzy rule base of multi-phase control works at three levels:

1. *Traffic situation level (not discussed in this thesis):* The traffic situation is divided into three different levels (low demand, normal, and over saturated)

2. Phase and sequence level: The main goal of this level is to maximize the capacity by minimizing intergreen times. 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 more 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 a vehicle cannot be too long.

3. Green ending level or extension level: The main decision of this level will be the right termination moment of the green. The goal of fuzzy rules of the third level is to determine the first moment to terminate a signal group based on the traffic situation (fluency and safety). The basic idea is not to terminate during the queue discharge. This means that each vehicle has to stop only once at each intersection. The main principle is that "a signal group can be kept in green while no disadvantages to other flows occur". This is also called “the method of additional green". *(Sane 1997.*)

Public transport priority [*Paper 8*]

Public transport priorities are usually tailor-made using a number of special principles. The most important ones of these are phase extension, phase recall, extra phase and rapid cycle. A public transport priority is given when a public transport vehicle is detected (active priority).

Our basic idea of the fuzzy approach to public transport priorities is that PT-requesting (the first approach detection, PT(time) > 0) starts rule combinations. In this case, PT is the general term for public transport. PT(time) is the most important fuzzy variable for the time of public transport requesting, and it means the travel time that a public transport vehicle spends between the priority detectors or the first detector and the exit detector. It starts while requested in the call detector and it stops when requested in the exit detector. If two or more PT-vehicles are approaching, the fuzzy variable is the smaller value, because all buses can get the priority.

The main goals of the fuzzy rule base of public transport priority are
- to give a correct priority function as a function of the request moment,
- to make a correct priority decision based on the current traffic situation at the intersection,
- to minimize the disturbance of public transport priority to other traffic flows.

Mäenpää (2000) and [*Paper 8*] discuss more in detail about the rules. In the case of public transport priorities there are some reasons to believe that the fuzzy public transport priorities can be better than the traditional binary-logic priorities (*Niittymäki 1998a* and [*Paper 8*]).

Traffic signal control on high-speed roads or major arterials

The traffic signal control on major arterials is an important part of isolated control, but it has its own features. Normally, the major arterial control gives preference to progressive traffic flow along the major arterial. In our study, four functions from the LHOVRA-control (HOVR) have been selected. The H-function gives priority to the main flow and belongs partly to the level two (green ending decision). The three other functions, OVR (O - incident detection, V - variable yellow time, R - variable red time) concentrate on the safety aspects. *Niittymäki and Nevala (2000b)* have further discussed the rule-base. The H-function is closely related to the selection of the green phase ending moment. The O-function adds the important safety aspect to the fuzzy control method. The V- and R- functions are basically fine-tuning instruments of the control, because they do not affect the terminating moment of the green phase. Nevertheless , the V-function reduces delays, and the R-function decreases the risk of severe accidents between major and minor road vehicles. *Kosonen T (2001)* has done his Master-thesis based on this background.

Summary of control parameters and principles

The summary of the control principles and input-parameters discussed in this thesis is shown in *Table 3*. The input parameters used for the fuzzy control are discussed here. Using the traffic situation model, the processed input about the "picture of traffic", means that input-data can be versatile and simple. Simple and rough input data is usually enough for fuzzy algorithms.

Table 3. Control principles of test cases of isolated fuzzy signal control.

FUZZY CONTROL	**REQUEST OF SIGNAL GROUP**	**EXTENSION OF SIGNAL GROUP (*1*)**	**TERMINATION OF SIGNAL GROUP (*2*)**	**SECONDARY REQUEST OF SIGNAL GROUP (*3*)**	**REST PHASE**	**INPUT PARAMETERS**
PEDESTRIAN CROSSING	Ped: push button Veh: fixed	Ped: fixed Veh: fuzzy	Ped: fixed Veh: remain green	-	Vehicle: green	WT, A S
TWO-PHASE CONTROL	Fuzzy	Fuzzy	Remain green (*4*)	Possible	Not available	A, Q
MULTI-PHASE CONTROL	Fuzzy or 2. level fuzzy	Fuzzy	Remain green	Always possible	Main green	A, Q, W
PUBLIC TRANSPORT PRIORITY	Fuzzy	Fuzzy	Go to normal after priority	Always	-	PT, A, Q
MAJOR ARTERIAL CONTROL	Fuzzy or 2. level fuzzy	Fuzzy	Remain green	Never	Main green	A, Q, GRN, Others

(1) - Determines the principles when there is a request on a green signal group,
(2) - Determines the principles when there is no more need to extend the signal group green,
(3) - The signal group can get a request and go green if the primary signal group is requested,
(4) - The signal group green is terminated only if no extension exists or no more time to maximum green is left and after green termination some conflicting green can start.

The number of input parameters in our rule bases is quite small, and can be classified. The classes are (class name, *point of human reasoning*): the number of vehicles in the area (traffic volume, *overall view*), detector or gap parameters (capacity, *local view*) and timing parameters (level of service, *feeling*).

CLASS 1: Traffic volume

Number of vehicles in zone (VEH) describes the number of vehicles in a zone of the intersection area. The area can be an option zone, a dilemma zone, or some area between the detectors, for example. *Approaching traffic (A)* is a typical application of VEH. This input parameter shows the number of vehicles in the approach zone. The approach zone can be specified separately for each lane. There are three ways to use this parameter:

- total *A* (all approaching vehicles of all green signal groups),
- maximum A (number of vehicles at the most saturated approach or lane),
- a combination of both.

The specification depends on the objective and the goal of the rule. *A* is basically used to recognize the approaching vehicles during the green signal, but it can also be used in a more generalized form, like approaching vehicles during the red signal or approaching vehicles during the amber.

Queuing traffic (Q) describes the amount of the traffic queuing on the red signals. The parameter is then based on the detection of a distant detector and on the estimation of the traffic model (deceleration and maximum deceleration models). It is similar to the previous input *A*, but it only includes vehicles in a stopped or nearly stopped (v < 5 km/h) queue. It can also be the number of vehicles between detectors.

CLASS 2: Capacity
Discharge gap (GAP) describes the queue discharge. The GAP is the time interval from the end of the detection of the previous vehicle to the moment of the next detection. The last gap is maintained, and if the signal-group has many lanes, then the minimum value is selected. The end of detection restarts counting from zero. The general way to use the parameter *GAP* is the recognition of queues at the intersection area. *Indicator of discharging queue S* is one application of GAP.

CLASS 3:Level of service
Waiting time (WT) describes the waiting time of the first vehicle or pedestrian. The calculation of waiting time starts when a pedestrian pushes the button or the first queued vehicle reaches the detector. The input data will be counted as a one second steps after the first detection. The green start of the signal group resets the counter to zero. The first detection after green restarts counting. This parameter can also be used as a request for a signal group.

Running green time (GRN) describes the length of the ongoing green time. The start of the green time restarts counting from zero and it terminates when the amber flashes on.

As shown in *Figure 1,* our fuzzy traffic signal control systematics has three crucial parts in fuzzy control; *fuzzification, fuzzy inference system and defuzzification.* These are discussed in the following.

Fuzzification

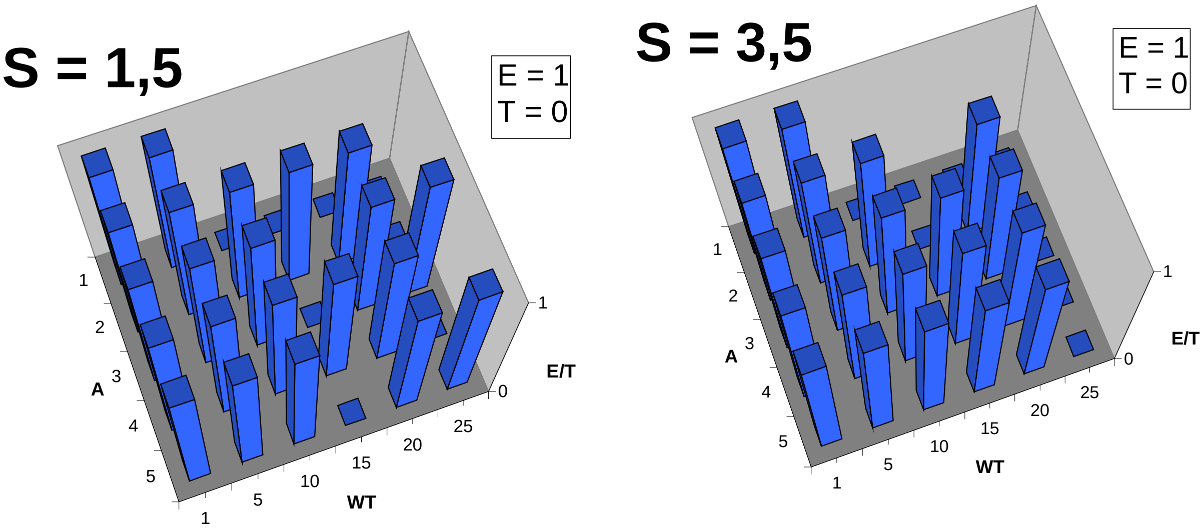
By applying fuzzy logic to traffic signal control, and by using input parameters presented in *Table 3*, it is possible to use concepts such as "long", "short" and "medium". Obviously, the choice of fuzzy variables and determination of fuzzy sets have a substantial influence on the sensitivity of control, and yet there is no unique method for choosing them. *Bingham (1998) and Niittymäki and Granberg (2000)* have made studies on optimizing the membership functions with neural networks and genetic algorithms. The results were not as good as assumed. However, these methods could be useful when an intersection with certain special characteristics is concerned. Such characteristics could be, for example, multiple lanes or varying detector locations, where the membership functions perhaps should be different from our present ones.

Fuzzy inference system

A number of fuzzy rule bases or fuzzy inference systems have been presented in this thesis [*Paper 5*]. It is possible that some of them suffer ill-defined foundations, even if they mostly perform better than traditional VA-control. The control maps describe the real performance of the system in terms of the relation between inputs and output. We can present any fuzzy if-then inference system as a control map. The control maps are available for two purposes in this study: the performance and comparison of defuzzification. The basic goal is that the performance of an expert system should be equivalent to that of a human expert.

The control maps of signalized pedestrian crossing (2 different cases; high and low discharge ratio) are shown in *Figure 4*. The first figure (S=1,5) is a typical case during the discharge process of queuing. In this case, it is very difficult to terminate vehicle green signal group. Only when the number of approaching vehicles (A) is small, and the pedestrian waiting time (WT) is long, can the control decision be termination. Otherwise, when the queue has discharged (case S=3,5, A = small), the termination can be achieved with the medium waiting time (approx. 15 seconds). As a comparison, the traditional vehicle-actuated control extends until maximum green time, if vehicle-demand exists (A > 0).

The control maps are a competitive method of rule derivation analysis. It is possible to control rule errors by using control maps or use them for rule derivation. A detailed analysis of control maps in signalized pedestrian crossings shows some important features:
- The rule 14 "if WT is long and A is very few and S is large, then E" should be "…then T".
- The rule 13 has the same error.
- The rule 12 "if WT is long and A is many and S is low, then E" could be "then T".



S=1.5		Pedestrian Wait Time (sec)					
		1	5	10	15	20	25
Approaching vehicles (veh)	0	E(13)	E(13)	E(14)	E(14)	E(14)	T(7)
	1	E(10)	E(10)	T(4)	T(4)	T(5)	T(5)
	2	E(11)	E(11)	E(12)	E(12)	E(12)	T(6)
	3	E(18)	E(17)	E(18)	T(9)	E(18)	E(18)
	4	E(15)	E(17)	E(18)	E(16)	E(18)	T(8)
	5	E(18)	E(17)	E(18)	T(9)	E(18)	E(18)

S=3.5		Pedestrian Wait Time (sec)					
		1	5	10	15	20	25
Approaching vehicles (veh)	0	T(1)	E(14)	E(14)	T(2)	E(14)	T(3)
	1	E(10)	E(10)	T(4)	T(4)	T(5)	T(5)
	2	E(10)	E(11)	E(12)	T(4)	E(12)	T(5)
	3	E(11)	E(11)	E(12)	E(12)	E(12)	T(6)
	4	E(11)	E(11)	E(12)	E(12)	E(12)	T(6)
	5	E(11)	E(11)	E(12)	E(12)	E(12)	T(6)

Figure 4. Control maps of signalized pedestrian crossing case.

The results of two-phase control [*Paper 2*] show that the control system works reasonably well, although, *Bingham (1998)* found one error and recommended that the rules "if A is not zero and Q is not too long, then E extend" or "if Q is too long, then terminate" should be added.

Könönen (1999) introduced a mathematical background for stability analysis. The stability of control means that a small change in the input variable causes only a small change in the output of the system. Based on this and our control maps, we can say that our two-phase control is quite stable. We can find only a few steps where the control goes directly from the short extension (3 s) to long extension (9 s). An example of a control map for two-phase control is shown in *Figure 5*. One important finding of control is the lack of rest-phase (A and Q are zero or small). The rules do not work effectively if the traffic demand is low.

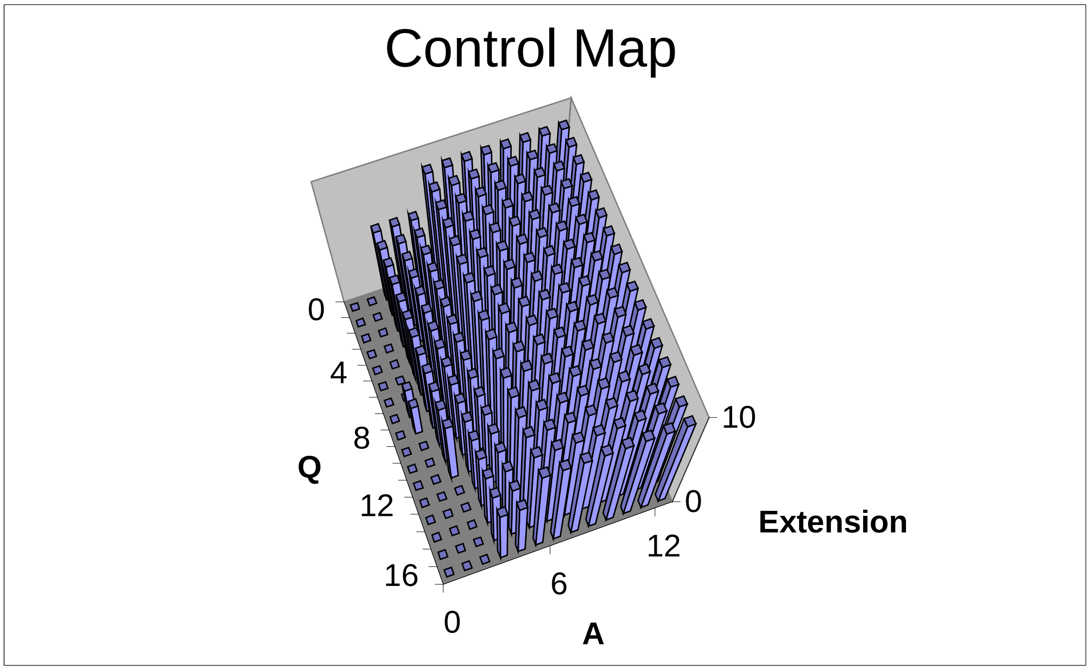


Figure 5. Example of control map of two-phase control.

The fuzzy-rule base of two-phase control works as illustrated in *Figure 6.* In the first intervals, it is easy to get medium extension and the number of queueing vehicles is not such an important factor. In the next phases, if the number of approaching vehicles is higher, then the extension is longer. Later, if the number of queuing vehicles is growing, then the extension is short or even, in many cases, zero. The extension criteria (A vs. Q) can be seen here (compare to extension principle in VA).

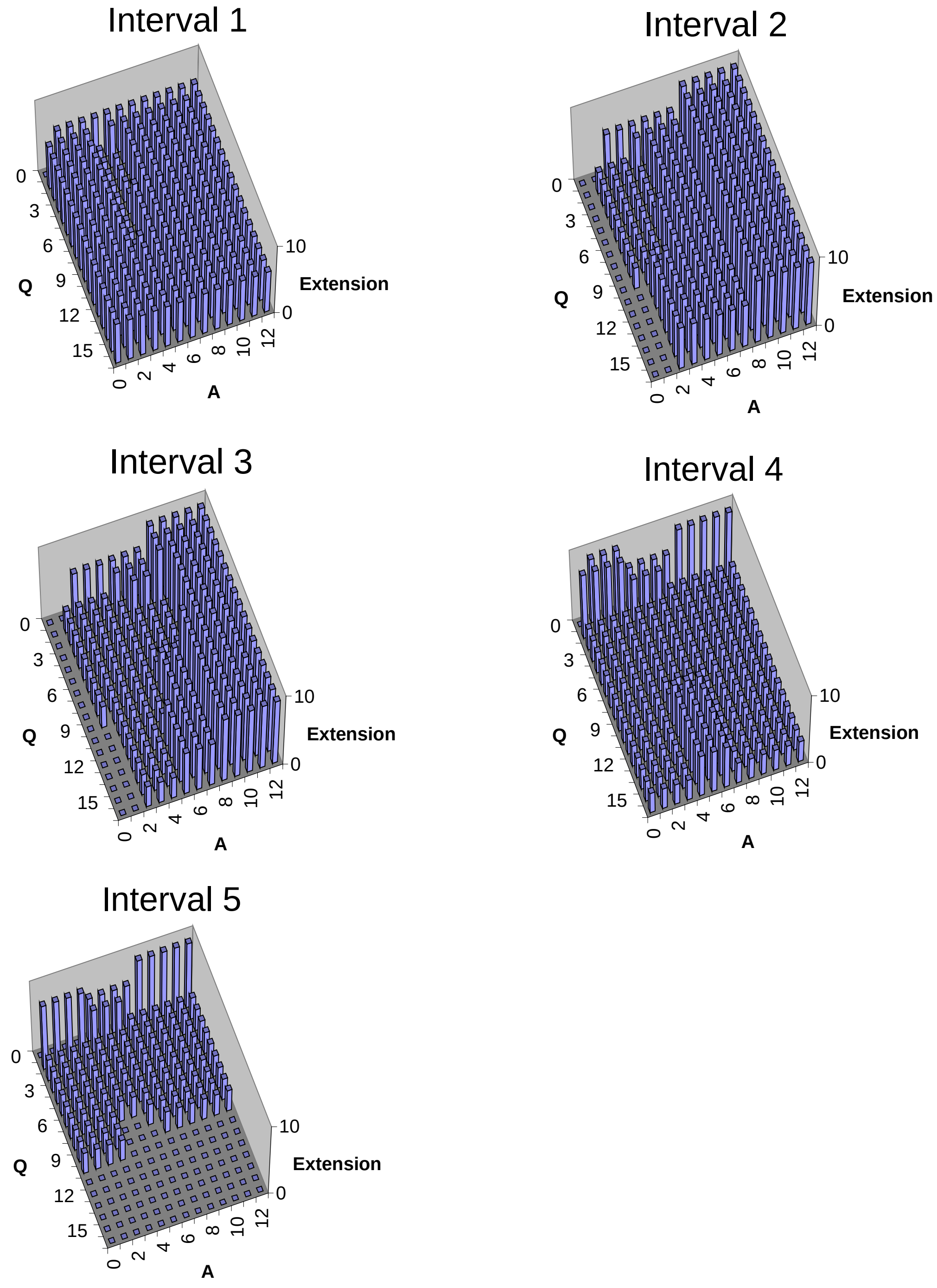
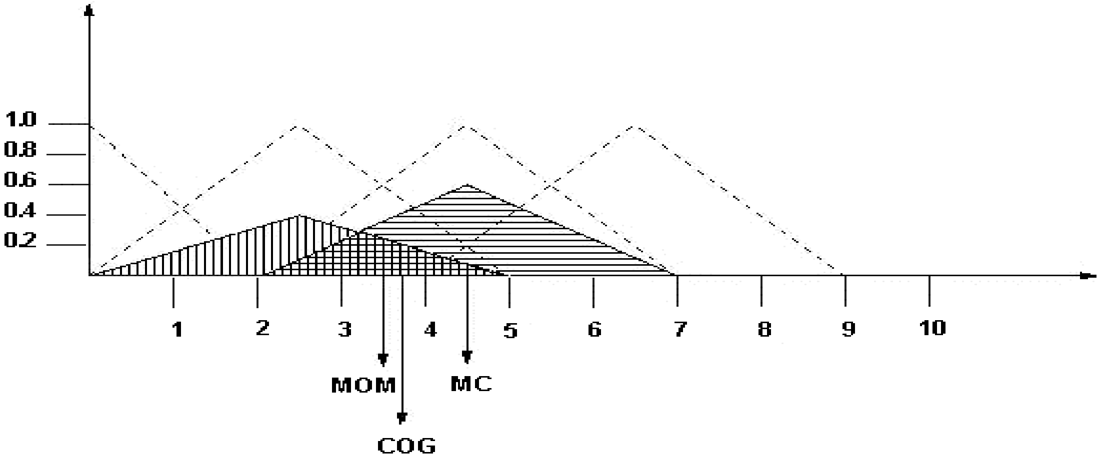


Figure 6. Control maps for each of the intervals (1-5) in two-phase control.

Defuzzification

The example in *Figure 7* shows that it is not possible to find an unequivocal solution; consequently we have to use practical experience as the basis for deciding the defuzzification method. In [*Paper 6*] we compared fuzzy similarity and the Mamdani-style min-max-defuzzification method, and found that fuzzy similarity gives smaller delays in most cases, and that the difference is statistically significant if vehicle flow is high. The approximate t-test was done on the risk level $\alpha = 0.01$.



Extension Interval, s

Figure 7. Comparison of three different defuzzification methods with the same input values in the definition of the extension interval (*Niittymäki 1998b*).

As a conclusion of hypothesis I, we can say that using the developed systematics, the control parameters and principles, and the input parameters, it is possible to derive a control algorithm for different types of isolated traffic signal control. However, it is difficult to give any recommendations for the fuzzification or defuzzification methods. The control maps are an essential way to analyze fuzzy inference systems, because they describe the real performance of the system in terms of the relation between input and output.

5.2 Hypothesis II - Competitiveness

The main objective of this hypothesis is to test fuzzy control methods using simulation, and to find application areas for fuzzy traffic signal control.

Signalized pedestrian crossing [*Paper 1*]

The performances of the three controls (traditional vehicle-actuated, modified vehicle-actuated, fuzzy) are compared with three pedestrian volumes: 15 pph, 50 pph and 150 pph. The modified traditional VA control algorithm means that only one extension interval will be given after pedestrian request, while the traditional VA control algorithm means that the maximum green extension period is predefined (30 s). The results are based on simulation of more than 120 hours.

The result shows a comparison of the three controls in terms of the performance measures. The average pedestrian delay is found to be significantly smaller for fuzzy control than for the conventional vehicle-actuated control. However, it is slightly higher than that of the modified vehicle-actuated control. The vehicle delays are similar for all cases with the modified vehicle-actuated controller being slightly higher than the others, and the fuzzy control case being the lowest.

Two-phase vehicle control [*Paper 2*]

We compared the efficiency of our fuzzy control algorithm with the traditional vehicle-actuated control, called the extension principle (*FHWA 1985*). The main concern was that the traditional algorithm was written as realistically as possible. The minimum green time was 5 s in both cases and the extension interval was optimized on the basis of detector distance and speed distribution. The maximum green time for vehicle-actuated control was 60 s. The results indicate that the application area of fuzzy control is very wide. This result is the same as the result shown in comparison to Pappis and Mamdani control algorithm presented by *Pursula and Niittymäki (1996).*

To compare two control methods (vehicle-actuated and fuzzy), identical simulations were run on both controllers. As the vehicles were generated at the same instants in both simulation runs, any change in their behavior resulted only from a change in control. Thus the observations of delays in these two simulation runs were paired, and a t-test on paired observations was used to compare the means of the delays in the simulation runs of two-phase control. In situations involving a small sample from a normal population with an unknown standard deviation, we can use students distribution (*Milton and Arnold 1990*). The statistical test of two-phase control is shown in *Table 4*. We can base the formula on the following hypotheses:

$$H_0 : \mu_D = 0$$
$$H_1 : \mu_D \neq 0$$

The statistical significance of the results in *Table 4* is determined by a t - test on paired observations with the formula

$$Z_0 = \frac{\overline{D}}{S_D / \sqrt{n}}; df = n - 1 \qquad (14)$$

where D is the mean of the difference, S_D is the sample standard deviation and n is the number of observations of D. The results proved that the traditional extension principle is a fairly good traffic signal control mode in the area of very low traffic volumes (no statistical difference), and fuzzy control is a competitive alternative for isolated signal control in traffic signals (statistical difference). The capacity in vehicle-actuated control seems to be slightly higher than the capacity in fuzzy control, because the cycle times of vehicle-actuated control are longer. The fuzzy control works in a more democratic way.

Table 4. Statistical significance of vehicle-actuated (VA) and fuzzy (FUZ) algorithms in two-phase control test, $\alpha = 0.05$.

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

Multi-phase vehicle control [*Paper 4*]

The comparison between fuzzy (FUZ) and vehicle-actuated (VA) control was made at a real intersection in Helsinki. The VA-timing was the same as that used in reality. The minimum green times were 5 s and the maximum green times 15 s for minor signal-groups, and 30 s for major signal-groups. The simulation results indicate that fuzzy control was competitive compared to traditional control methods. The compared measures of effectiveness (MoE) were average delay and percentage of stops. In total, 18 different cases were tested.

The results show that the extension principle is a better traffic signal control mode in the area of very low traffic volumes. However, the results indicate that the application area of fuzzy control is available. If the major traffic flow is more than 500 veh/h, the results of fuzzy control were at least as good as the results of traditional control. According to the field measurements in the test intersection, the real traffic volume of major flows varies between 600 – 900 veh/h and the minor/major-ratio is approximately 1:5. Based on this, we can say that fuzzy control principles can be competitive in isolated multi-phase traffic signal control.

Better results in fuzzy control for low traffic volumes can be achieved by using a second level fuzzy decision-making with the fuzzy phase selector. Our simulations are based only on the decision-making of the signal group extension. The main goal of the fuzzy phase selector is to maximize the capacity by minimizing intergreen times [*Paper 7*].

Traffic signal control on major arterials

The test simulations were completed using the HUTSIM-model of the real test intersection in Huddinge, a suburb of Stockholm. The fuzzy method was compared to a vehicle-actuated control and to a pre-set fixed-time control. The fixed-time control was optimized for each simulation situation separately with the Webster algorithm. The intersection capacities were exceeded with the largest traffic volumes in all the control methods, due to the fact that the left turning traffic from the minor flows had the green phase at the same time. In other situations, the control methods caused approximately the same delays. The number of stopping vehicles is also an important indicator of the performance of signal control on arterial roads. The fuzzy logic controller clearly provided better results except for the highest main flow and lowest minor flow volumes. Even with these volumes, the stopping percentages of the fuzzy controller are competitive. (*Niittymäki and Nevala 2000b*.)

The fuzzy and normal vehicle actuated control methods were also compared with the Swedish SOS-method. The Swedish SOS-method uses mathematical optimization in signal controlling (*Kosonen I and Davidsson 1994*). These results are only trend-setting because of the different test environments and counting methods of the delays and stopping percentages. However, the results indicate that the simple fuzzy control method works at the same level as the complex SOS-method in the case of daytime traffic. During the rush hours, the SOS-method seems to have given much better results. As an example of this comparison, the delays in morning rush hour and daytime traffic are presented in *Figure 8.*

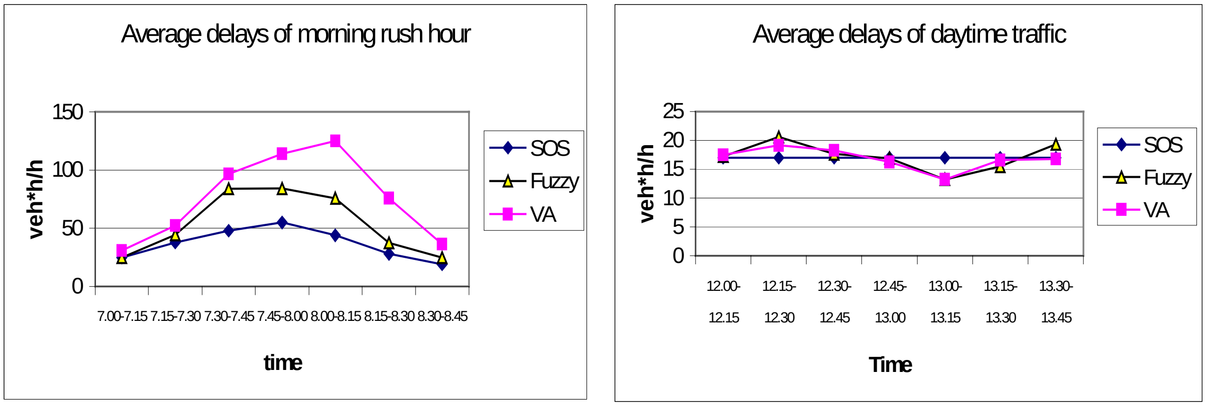


Figure 8. Delays of the SOS-, fuzzy and VA-methods during morning rush hour and daytime traffic (Niittymäki and Nevala 2000b).

Based on the test results of hypothesis II, it is clear that fuzzy control can be a potential traffic signal control method in isolated control. The application area of fuzzy control seems to be quite large, but the traditional VA control is still competitive, especially if the traffic situation is low-demand or oversaturation conditions. It means that we need at least 2 - 3 different fuzzy control algorithms for daily traffic signal control, but it is still less than usually in traditional VA-control. Unfortunately the SOS-comparison is only trend-setting, because the comparisons are now done against practical control, not against optimized control.

5.3 Hypothesis III - Multilevel, multidimensional and multiobjective control method

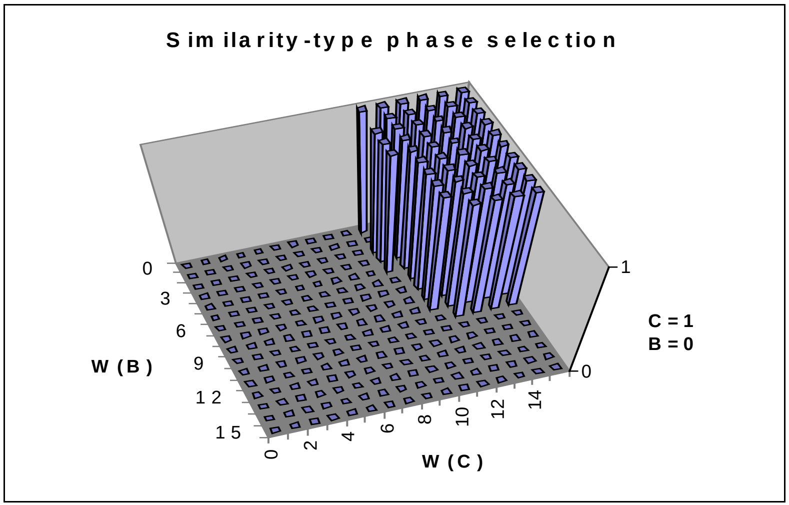
To test hypothesis III a discussion of the characteristics of fuzzy control and a comparison with the traditional VA-control are needed.

It is clear that the fuzzy control developed in this research works at different levels. The phase selector level can also be an example of multi-dimensional, and even, in some cases, of multi-objective, control.

In *Figure 9*, the fuzzy similarity (*Figure 10*) and Mamdani-type (COG) methods are compared using control maps in fuzzy phase selection. The goal is to determine the right phase order in the multi-phase control and to develop the results presented in [P*aper 4*]. The rule-base and results are presented in *Könönen and Niittymäki (2000).*

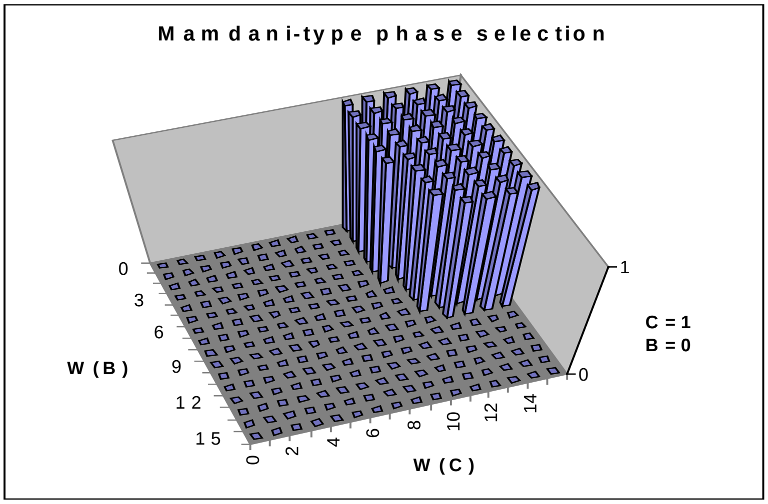
The fact that there is no big difference between the methods indicates in particular that the rules are a more important part of the inference-system than the defuzzification methods or the fuzzification.

The simulation results indicated that there were some improvements using a fuzzy phase selector at multi-phase intersections, although, when traffic volumes were very high and homogeneous, use of the phase selector was of no effect. Moreover, when traffic volumes were small, traditional VA-control gave the best results. This is due to the fact that the rules were not very strict, so every fuzzy controlled signal group got some extra green. Another explanation could be that when traffic volumes were small the situation was not so fuzzy or that other kinds of rules and variable values are needed.



		W(B)															
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
W(C)	0	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	1	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	2	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	3	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	4	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	5	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	6	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	7	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	8	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	9	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	10	C(4)	B(1)	C(3)	C(3)	C(3)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	11	C(4)	C(3)	C(3)	C(3)	C(3)	C(2)	C(2)	C(2)	C(2)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	12	C(4)	C(3)	C(3)	C(3)	C(3)	C(2)	C(2)	C(2)	C(2)	C(2)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	13	C(4)	C(3)	C(3)	C(3)	C(3)	C(2)	C(2)	C(2)	C(2)	C(2)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	14	C(4)	C(3)	C(3)	C(3)	C(3)	C(2)	C(2)	C(2)	C(2)	C(2)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	15	C(4)	C(3)	C(3)	C(3)	C(3)	C(2)	C(2)	C(2)	C(2)	C(2)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)

Figure 9a. Control map comparison of fuzzy phase selecting (Similarity-type phase selection).



		W(B)															
		0	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
W(C)	0	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	1	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	2	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	3	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	4	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	5	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	6	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	7	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	8	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	9	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	10	C(4)	C(3)	C(3)	C(3)	C(3)	C(3)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	11	C(4)	C(3)	C(3)	C(3)	C(3)	C(2)	C(2)	C(2)	C(2)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	12	C(4)	C(3)	C(3)	C(3)	C(3)	C(2)	C(2)	C(2)	C(2)	C(2)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	13	C(4)	C(3)	C(3)	C(3)	C(3)	C(2)	C(2)	C(2)	C(2)	C(2)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	14	C(4)	C(3)	C(3)	C(3)	C(3)	C(2)	C(2)	C(2)	C(2)	C(2)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)
	15	C(4)	C(3)	C(3)	C(3)	C(3)	C(2)	C(2)	C(2)	C(2)	C(2)	B(1)	B(1)	B(1)	B(1)	B(1)	B(1)

Figure 9b. Control map comparison of fuzzy phase selecting (Mamdani-type phase selection).

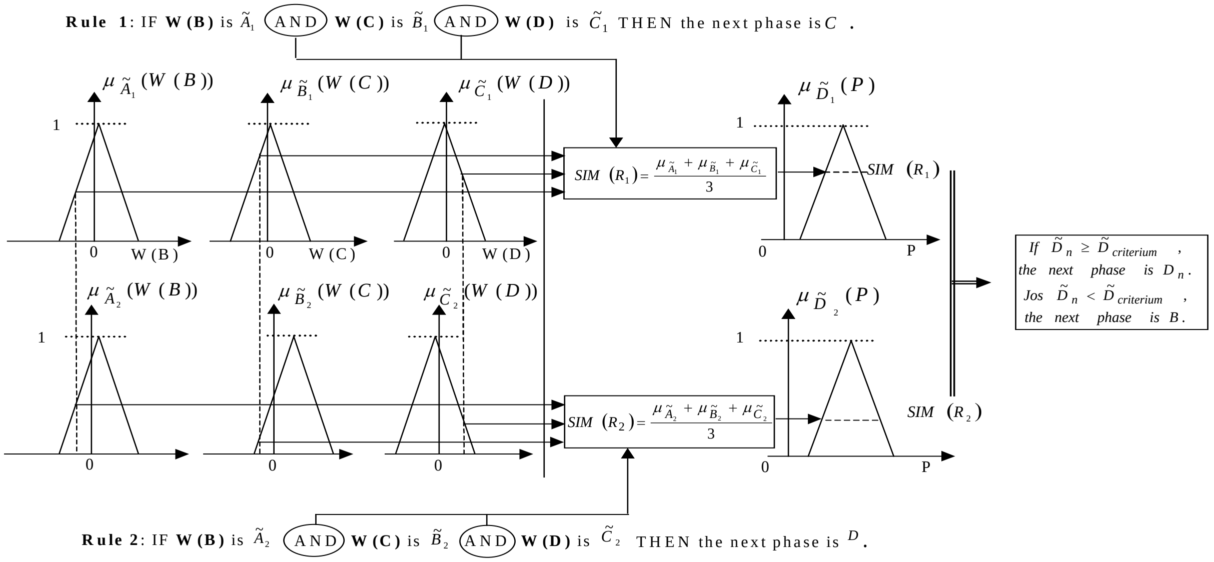


Figure 10. Example of fuzzy similarity inference in phase selecting (Kosonen T 2001).

The multi-dimensionality means that fuzzy control makes decisions based on the data of each signal group or approach (*see Kosonen I 1999 and Figure 11*). *Pursula and Niittymäki (1996)* showed that the traditional extension in VA (using the extension principle) is longer than the extension of the Pappis-Mamdani control, which means that cycle times in the traditional extension principle control are too long to minimize delays (Webster-formula). The traditional extension principle gives extension intervals if requested, but, in fuzzy control, active signal-group green can be terminated if the queue length of the conflicting signal-group is long enough. However, with respect to to safety aspects, the extension principle can be better than fuzzy control because the risk of rear-end collisions is lower (less cycles and less vehicles in the option zone per cycle).

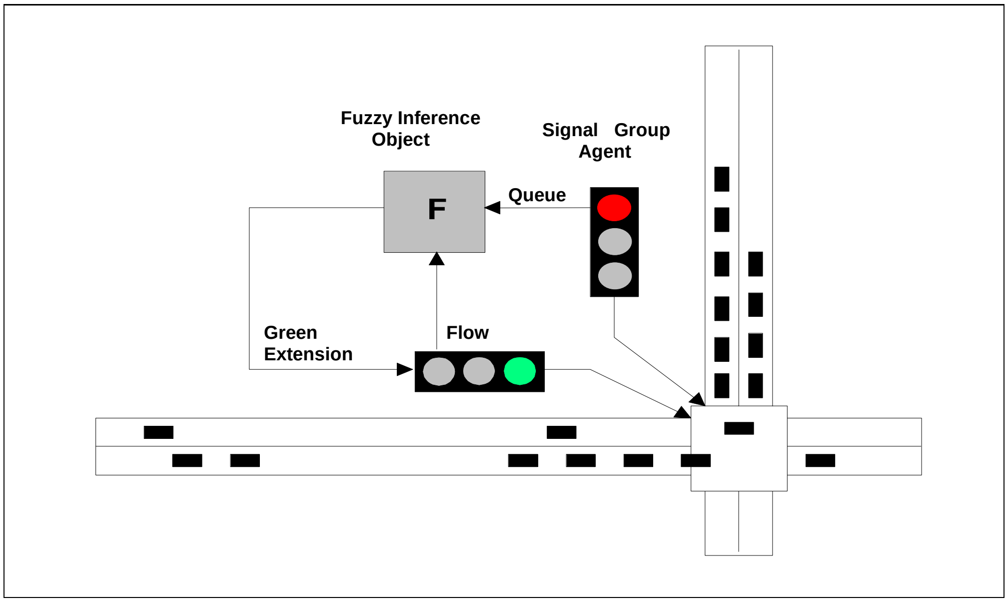


Figure 11. The principle of signal group oriented fuzzy control (Kosonen I and Bång 2001).

The multi-dimensional principles are used on both extension and sequence levels in the FUSICO-applications. For example, *Kosonen T (2001)* has introduced rule-base for the phase-selector in four-phase control. The input of fuzzy inference system is the weight of each phase.

In some cases, multi-dimensional and multi-objective controls are the same things. For example, the goals of signalized pedestrian crossings are to minimize the waiting time of pedestrians and to minimize the delays of vehicles. [*Paper 1*] showed that fuzzy control provides a compromise between the two opposing objectives. This finding is consistent with the characteristics of most other applications of fuzzy control; fuzzy control looks for a compromise in the multi-objective problem environment. The principles of multi-objective algorithms are presented in [P*aper 2*]. *Niittymäki et al. (1997b)* have developed rules, and [*Paper 3*] has shown simulation results of the multi-objective control algorithms. According to the findings, the multi-objective algorithm gives the smallest percentage of stops, which is very important in traffic signal control. The cycle times are at the same level as the cycle times of traditional VA-control, but the delays are shorter. Naturally, the delays of multi-objective algorithm are longer than the delays of the normal (traffic fluency) fuzzy algorithm.

The comparison of extension timing (VA/extension principle vs. Fuzzy/extension level) is shown in *Figure 12*.

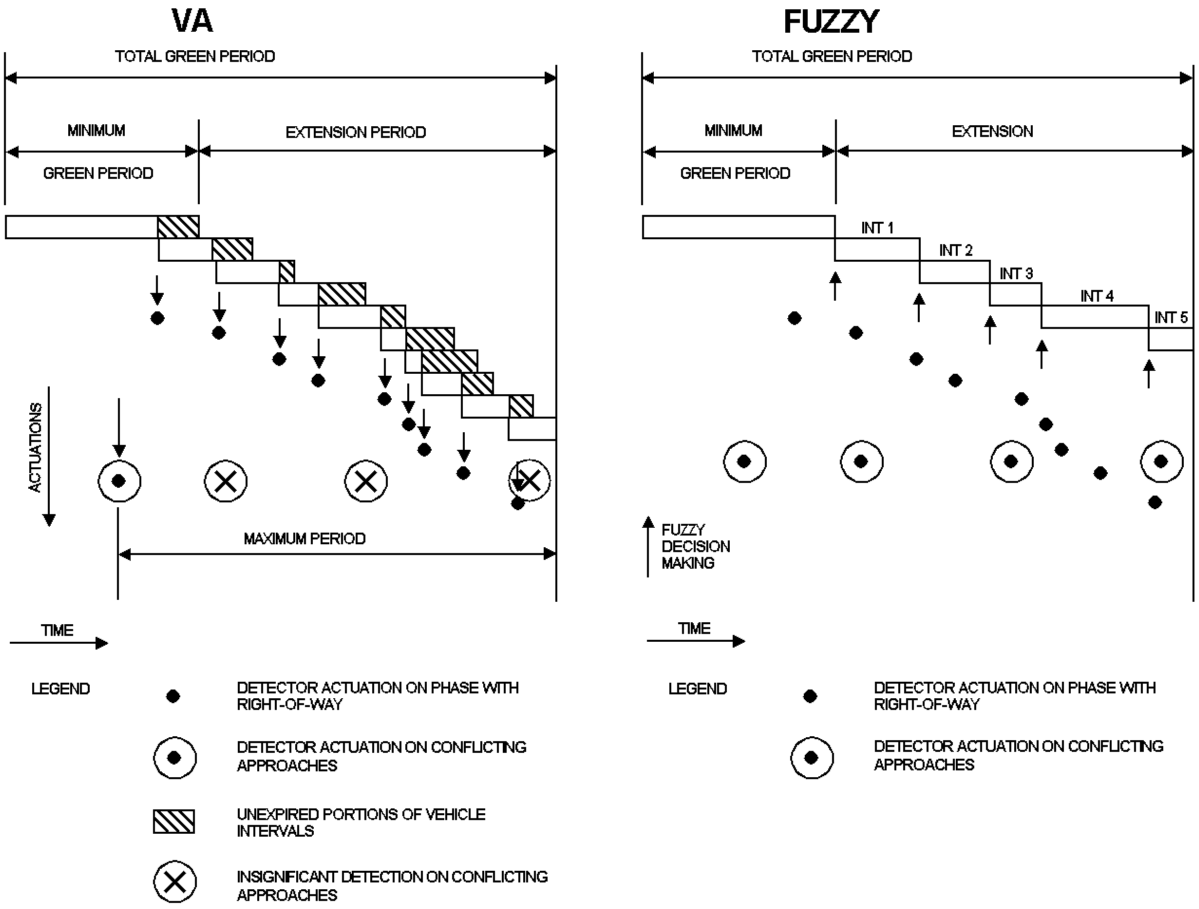


Figure 12. Comparison of the extension principle according to FHWA (1985) and fuzzy extension.

The main difference between the the two control algorithms is that the extension decisions are made in different ways; in the extension principle the decision is based on the detections of phases with right-of-way (green signal group), and in fuzzy extension, it is based on the traffic situation (green signal groups vs. red signal groups). In that way, the fuzzy control algorithm has no maximum green times, but additional rules "if queue is too long" or "if current green is too long" have the same termination meaning. Both control algorithms have minimum green time for queue discharging. In our test cases, the minimum green time was the same in the compared algorithms. The extension interval is constant in the extension principle, and traffic situation dependent in the fuzzy extension. In our test cases, the extension interval inVA was defined by an experienced traffic signal planner. Normally, the main method is that the extension interval equals the time which is needed from the detector to the stop line or to the next detector.

Based on the above analysis hypothesis III can be accepted, that is 1) the multilevel fuzzy control is adaptive, which means that the number of control programs can be smaller than in the traditional VA-control, 2) the extension intervals are defined by using the traffic data of each approach, and 3) the fuzzy inference enables the multi-objective control.

5.4 Hypothesis IV - Realistic control method

To prove hypothesis IV, we have to demonstrate that the developed fuzzy traffic signal control principles can be applied to real intersections as a realistic control method.

In the design of a signal controller, expert knowledge and experience of traffic control is required for the formulation of the linguistic protocol that generates the control input to be applied to the traffic control system (*Evans 1980*). Fuzzy-logic based controllers are designed to capture the key factors for controlling a process without requiring many detailed mathematical functions. Due to this fact, they have many advantages in real time applications. The controllers have a simple computational structure since they do not require many numerical calculations. The "if-then-else" logic of their inference rules does not require a lot of computational time. In addition, 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.

In our application, the controller can be a normal unit, like an FC-2000 or ELC-2 (of Peek Traffic). A normal PC computer with the FUSICO-software was installed beside the controller (*Kosonen I 1999*). The PC-card was an Octagon-systems PC-510 that runs at a speed of 133 MHz. Its operating temperature is from -40 C to +70 C with adequate ventilation. The card had 1 MB on-board memory and a 4 MB optional RAM-chip (required for running the simulation software). Because variations of the temperature and humidity were very high, hard disks were not used. The software was stored on the flash RAM-chip (2 MB). A simple parallel interface was used for detector pulses from the controller to FUSICO, and for control orders from FUSICO to the controller. The system structure is shown in [*Paper 7*]. In this arrangement, the real controller is a “slave” of the FUSICO- control algorithm. (*Könönen 1999, Niittymäki et al 1999a, Könönen and Niittymäki 2000.*)

A picture of the fuzzy controller prototype is shown *in Figure 13.*

Figure 13. Fuzzy signal controlling unit.

The first test intersection in Oulunkylä, Helsinki, was chosen on the basis of the following criteria: isolation of the intersection, high volumes of traffic during peak hours, four approaches, bus-traffic, pedestrian crossings, suburban location and two-phase control. Measurements were carried out during three time periods (each period being 2 – 3 days) between June and August, 1998. [*Paper 3*] reports details of the before-and-after study.

The statistical testing of the field measurements was conducted in two phases. In the first phase, the variances were compared, while in the second phase the means were compared. In addition, in the second phase an appropriate test was chosen on the basis of the result of the first phase. (*Milton and Arnold 1990*.)

1. PHASE: Comparing variances

There are two different ways to compare the means of two normal populations. These are

1. Variances (σ_1^2 and σ_2^2) are unknown and equal, i.e. ($\sigma_1^2 = \sigma_2^2$)
2. Variances (σ_1^2 and σ_2^2) are unknown and unequal, i.e. ($\sigma_1^2 \neq \sigma_2^2$)

Therefore we must have an appropriate test for comparing variances. In this case, the hypotheses are in the following form:

$H_0 : \sigma_1^2 = \sigma_2^2$

$H_1 : \sigma_1^2 \neq \sigma_2^2$

The statistic is $F = \frac{s_1^2}{s_2^2}$ and the comparison is made with F-distribution with appropriate degrees of freedom. Because the test is two-tailed, we can reject the H_0-hypothesis when $F \geq f_{1-\frac{\alpha}{2}}(n_1 - 1, n_2 - 1)$ **[1°]** or $F \leq f_{\frac{\alpha}{2}}(n_1 - 1, n_2 - 1)$ **[2°]**. The results are in *Table 5*. The risk level (alfa) is 0.1, because the sample sizes are different, and this affects to the variances.

Table 5. Variance comparison of Oulunkylä field test delays with risk level α*=0.1.*

Hour	n_1	n_2	s_1^2	s_2^2	**[1°]**	**[2°]**	F	Conclusion
1	79	56	347.6	255.2	1.52	0.67	1.36	Accept H_0
2	64	66	339.2	265.2	1.51	0.66	1.28	Accept H_0
3	71	59	224.0	257.5	1.52	0.66	0.87	Accept H_0
4	85	71	269.7	273.3	1.47	0.69	0.99	Accept H_0
5	81	90	246.8	187.2	1.43	0.70	1.32	Accept H_0
6	94	77	334.1	219.8	1.44	0.70	1.52	Reject H_0
7	114	97	254.8	235.4	1.39	0.72	1.08	Accept H_0
8	47	126	398.9	289.1	1.47	0.65	1.38	Accept H_0
9	23	132	530.5	234.4	1.62	0.55	2.26	Reject H_0

2. PHASE: Comparing means

For comparing two means (μ_1 , μ_2) we can formulate the following hypotheses:

$H_0 : \mu_1 = \mu_2$

$H_1 : \mu_1 > \mu_2$

If the variances are equal, we can find that the following statistic is valid:

$$T = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)_0}{\sqrt{s_p^2(\frac{1}{n_1} + \frac{1}{n_2})}}, \tag{15}$$

where the common population variance s_p^2 is defined as follows:

$$s_p^2 = \frac{(n_1 - 1)s_1^2 + (n_2 - 1)s_2^2}{n_1 + n_2 - 2} \tag{16}$$

and $(\mu_1 - \mu_2)_0 = 0$.

If the variances are unequal the following statistic can be used:

$$T = \frac{(\bar{x}_1 - \bar{x}_2) - (\mu_1 - \mu_2)_0}{\sqrt{(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2})}} \tag{17}$$

This time, the number of degrees of freedom must also be estimated from the data. In this study the *Smith-Satterhwaite* procedure is used for this (*Milton and Arnold 1990*). The estimated number of degrees of freedom is given by (rounded down):

$$\gamma = \frac{\left(\frac{s_1^2}{n_1} + \frac{s_2^2}{n_2}\right)^2}{\frac{\left(\frac{s_1^2}{n_1}\right)^2}{n_1 - 1} + \frac{\left(\frac{s_2^2}{n_2}\right)^2}{n_2 - 1}} \tag{18}$$

The H_0 hypothesis can be rejected if $T \geq t_\alpha(n_1 + n_2 - 2)$. The results are in *Table 6*.

Table 6. Mean (travel time) comparison of Oulunkylä field tests α=0.05 (=cases in which variances are unequal).*

Hour	n_1	n_2	s_1^2	s_2^2	$\bar{x}_1$ - VA	$\bar{x}_2$ - FU	Tα	T	Conclusion
1	79	56	347.6	255.2	65.0	57.4	1.66	2.46	Reject H_0
2	64	66	339.2	265.2	67.5	54.0	1.66	4.44	Reject H_0
3	71	59	224.0	257.5	62.9	58.9	1.66	1.47	Accept H_0
4	85	71	269.7	273.3	67.5	57.4	1.65	3.83	Reject H_0
5	81	90	246.8	187.2	64.4	55.4	1.65	3.97	Reject H_0
6	94	77	334.1	219.8	62.8	56.4	1.65*	2.95	Reject H_0
7	114	97	254.8	235.4	64.4	59.8	1.65	2.55	Reject H_0
8	47	126	398.9	289.1	72.6	63.3	1.66	2.84	Reject H_0
9	23	132	530.5	234.4	83.1	64.2	1.69*	3.79	Reject H_0

The results indicate that the fuzzy algorithm is working well. One important result is that the fuzzy algorithm cycle times are shorter than the cycle times of the traditional vehicle-actuated control algorithm. Basically, this means that the fuzzy control algorithm works in an effective way because the saturation ratio is higher and because there are no extensions in the fuzzy control system for an individual approaching vehicle if the number of queuing vehicles is high.

The results from the field measurements show that the fuzzy control algorithm works better than vehicle-actuated control in most cases. The average travel times $\bar{x}_2$ are approximately 4 - 10 seconds shorter, the percentages of stops are 2 – 12 % lower, the bus delays are shorter in 8/9 cases, and there are good savings in fuel and emissions based on simulation results. All these results show that the fuzzy control algorithm can be successfully used to control traffic at real intersections. However, better traffic fluency is only one advantage. Pedestrians can also benefit, because the cycle times are on average 8 seconds shorter, which means shorter waiting times based on shorter green times of conflicting signal groups. The pedestrian signal groups were requested secondarily in our experiment.

In the case of fuzzy public transport priority, three different test intersections were selected. *Mäenpää (2000)* has studied these simulation and field measurement results more carefully and made statistical tests. The results of the before-and-after-study indicated that average delays of buses decreased at all intersections and in almost all traffic situations when compared to the traditional VA-control without public transport priorities. When studying the results, it can be noticed that the average delays of all vehicles decreased in one third of all traffic situations. Delays increased in two thirds of situations. These changes were small, mostly under 5 seconds. The changes of average delays of buses were smaller. The best results were achieved in daytime traffic. [*See also paper 8*.]

The results and experiences of fuzzy control at all real intersections have proved that the developed fuzzy controller works also in reality. The main result is that the advantages and the application areas shown by simulations can be transferred to real intersections. However, the developed fuzzy controller needs many small changes and improvements before it is a real product. So far, it is more or less a prototype.

6 DISCUSSION AND CONCLUSIONS

In the real world traffic conditions are changing all the time, and therefore a dynamic signal control that responds to actual traffic conditions is needed. The task is to develop an effective control process for traffic signal timings, and to develop an on-line traffic model that represents the dynamic traffic conditions accurately. The subject of the FUSICO-project was the application of fuzzy control to traffic signal control at an isolated intersection level. This thesis has four hypotheses. The hypotheses are I) generality of fuzzy control, II) competitiveness of fuzzy control III) multilevelity, -dimensionality and -objectiveness and IV) realisticity in real traffic signal control.

The three main methods used to test the hypotheses are rule derivation, simulation, and field tests of a fuzzy controller using on-line simulation and before-and-after measurements. The methods have proved to be valid for this kind of study.

This thesis had six detailed objectives: 1) to present fuzzy logic as a control method in adaptive traffic signal control, 2) to present systematics for isolated traffic signals and signal group control, 3) to derive and introduce a general rule base for isolated traffic signals in different cases, 4) to discuss fuzzification and defuzzification in the control process, 5) to test the efficiency of fuzzy signal control using simulation and field tests and 6) to introduce and test in practice a prototype fuzzy controller (FSC). We have worked quite a lot with objectives 1 and 3, and achieved these objectives quite well. The results concerning objectives 2, 5 and 6 are presented in this thesis and publications. Objective 4 was more complicated than expected. The main results, findings and disappointments are discussed below.

The increasing traffic demand in urban road networks has already promoted many traffic actuated control concepts during the last twenty years. By developing a general fuzzy approach for traffic signal control planning this study promotes a more efficient and goal-driven signal control planning method; in general, the results can also be used in the day-to-day planning and design of signal control in practice as well. The first important finding is, that the rule base is an important part of the fuzzy control process and the development of rules is time-consuming. The entire knowledge of the traffic signal control designer is stored as rules in the knowledge base. In this study, the aim was to model the actions of an experienced policeman represented by knowledge of an experienced signal control planner. The used method is a combination of the suggested ways by *Sugeno and Nishida (1985).* The use of control maps has opened some new possibilities to analyse or even to develop and test rules. According to the results the control parameters of fuzzy traffic signal control can be divided into three different groups: traffic volume, capacity, and level of service parameters. The fuzzy control algorithm of isolated traffic signal control can be derived based on these parameters.

The fuzzy inference is perhaps the most important part of fuzzy control, but also the methods of fuzzification and defuzzification have to be discussed. As far as theory is concerned, we have also introduced a new fuzzy IF-THEN control algorithm based on the Lukasiewicz equivalence, called fuzzy similarity. This algorithm looks for the IF-part nearest in value to the real input value; the THEN-part of this value is then fired. Although the main advantage of this kind of defuzzification method rests on its stronger mathematical background, the results have nevertheless been promising.

One important methodological finding is that without simulation it is not fully possible to develop new control strategies. Simulation has given new possibilities to test and evaluate strategies of signal control, and it 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. In our case, the existence of the HUTSIM simulation model and the simultaneous development of its capabilities has been a starting point for the success of this thesis. We tested several different control strategies in different isolated control environments:

1) The results of a signalized pedestrian crossing indicated that the fuzzy control provides pedestrian friendly control keeping vehicle delay smaller than in the conventional control. In other words, the fuzzy controller provided a compromise between the two opposing objectives, minimum pedestrian delay and minimum vehicle delay, in accordance with the level of the pedestrian and vehicular volumes. This finding is consistent with the characteristics of most other applications of fuzzy control.

2) The results of the comparison of the Pappis-Mamdani fuzzy control algorithm with traditional vehicle-actuated control indicated that fuzzy control could be suitable for traffic signal control. The long cycle times of the traditional extension principle indicate the weakness of a gap seeking control. On the other hand, the number of stopped vehicles of the Pappis-Mamdani control was higher than with traditional vehicle-actuated control. Based on these experiences, we developed our own control algorithm for two-phase vehicle control. The difference between our FUSICO-control algorithm and the Pappis-Mamdani control algorithm is the fact that our FUSICO-control algorithm gives a smaller number of stops than the traditional extension principle or the Pappis-Mamdani control. Basically, this means that the FUSICO-algorithm should also result in less fuel consumption and better traffic safety than the traditional vehicle-actuated control algorithms or the Pappis-Mamdani control algorithm. According to the statistical tests, the application area of fuzzy control is wide.

3) The results of multi-phase control indicate that the traditional extension principle is a functional traffic signal control mode in the area of very low traffic volumes. However, the results also indicate that an application area of fuzzy control is available. If the major traffic flow is more than 500 veh/h, the results of fuzzy control are at least as good as the results of traditional control.

4) The results of fuzzy public transport priorities are at least promising, and city planners are satisfied with the results of fuzzy control. Public transport priority is a typical multi-objective control problem, which seems suitable for being solved by fuzzy logic.

5) The results of fuzzy signal control on major arterials are also promising. In his Master's thesis *Kosonen T (2001)* studied fuzzy control on major arterials and tested the phase selection level at real intersections in this application.

The multilevel (traffic situation, phase selection and extension inference) fuzzy control makes adaptiveness possible. This also means that the number of control programs can be smaller than in the traditional VA-control. The most significant difference between traditional and fuzzy control methods is that the extension principle in VA-control looks at only the green signal groups, but the fuzzy control analyzes also the queues behind the red signal groups. This kind of multi-dimensionality, the opposite input-parameters, and the free rule-base development enable the multi-objective control.

Dynamic traffic control relies on the veracity of on-line traffic data to provide traffic actuated control commands. The problems in traffic signal control in its present state of development lie in the great need of input (detector) data for on-line mathematical optimization, in the identification of the overall traffic situation through detector inputs, in the vagueness of defining and treating the multiple and partly conflicting goals of optimization, and in the problems of using system-wide priority measures for public transport or pedestrians. One very important sub goal was to develop a real fuzzy controller and test it at real intersections. The proposed controller consists of traffic and control models, and it is justified that this kind of traffic control system with an embedded on-line simulation model is a working method. The results of field tests in Helsinki, Vantaa, Lahti and Jyväskylä have been good, and according to the statistical tests, the fuzzy control has proven to be a potential control method in real isolated traffic signal control. However, the experience has shown that while the traffic model is rather complicated and even though accurate, the control model is still less than perfect for fuzzy traffic control. The development of the fuzzy signal controller continues with many small changes and improvements.

As a summary, the main findings of this thesis are
- the fuzzy inference is perhaps the most important part of fuzzy control,
- the fuzzy control algorithm of isolated traffic signal control can be derived based on human thinking,
- the fuzzy similarity is a promising defuzzification method,
- the use of control maps is very helpful in the analysis and development of rule base,
- the multi-dimensionality, the opposite input-parameters and the free rule-base development enable multi-objective control,
- the simulation is capable and important research method in traffic signal control,

- the simulations indicate that fuzzy isolated signal control can be a competitive control method,
- the fuzzy control is a potential control method in real isolated traffic signal control.

The results in general have been promising. So far, only limited comparisons between fuzzy methods and mathematical optimization methods, for example Miller's traditional optimization algorithm have been made. However, all results in the thesis are valid because we have compared them against practical traffic signal timings in Finland. We have also shown some general aspects or findings for traffic signal control, like multi-dimensional control, multi-level control, the number of detectors and their locations, advantages of traffic situation modeling and on-line simulation, and features of soft public transport priority. However, we have not achieved all expected results. The disappointments of this study are

- the developed algorithms are not working well if the traffic situation is low-demandad,
- it is not possible to give any recommendations for defuzzification method,
- the results of the membership calibration studies are not as good as expected,
- a thorough theoretical analysis of the control is still missing.

Some disappointments can be solved doing some efforts, for example developing specific rule-base for low-demand situations, and it seems that the membership functions are not such an important part of fuzzy inference systems than the fuzzy rules. It is also clear that it is not possible to give clear recommendations for defuzzification method, because it is not possible to define exactly correct output for the signal-group extension in traffic signal control. However, we have compared different methods using simulation.

The post-study strives to create a systematic methodological framework for traffic signal control from isolated signals to coordinated and area (urban) traffic control systems (*Kosonen I and Bargiela (2000), Kosonen I and Bång 2001, Niittymäki 1999, Niittymäki and Nevala 1999, 2000a, Nevala et al 2000*). In striving to do this, we hope to develop a systematic approach to the goals, problems and methods of signal control. The analysis of the needs of input data, the formulation of goals and objectives in general, the discussion of different control strategies and of the consequences of alternative decisions, all give new inputs to the overall design and analysis of signal control systems. For example, *Kosonen T (2001*) proposes to introduce the on-line traffic model with many detectors in each lane (distributed model) and to use different control principles and membership functions for minor- and major-approaches, respectively. The post studies will form the basis on which to formulate and test a new fuzzy control system framework, and increase the theoretical knowledge, and the level of practical know-how in the area of traffic signal control.

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