MANY-VALUED SIMILARITY MODELLING TRAFFIC SIGNAL CONTROL

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Summary

A fuzzy control system based on a new method called maximal fuzzy similarity, in fact the equivalence relation of Lukasiewicz logic, is introduced to control an isolated pedestrian crossing signals. The main goal in this multi-objective optimization problem is to minimize both pedestrians' and vehicles' delay and make the traffic flow as fluent and safe as possible. Lukasiewicz many-valued logic in known to give solid mathematical foundations to fuzzy reasoning. Besides, simulations made by HUTSIM, a traffic simulation program, show that this method gives better results with respect to total delay than conventional or other fuzzy traffic signal control systems do.

Keywords: Lukasiewicz Logic, Fuzzy Logic, Traffic Signal Control.

1 Introduction

Fuzzy control has been introduced and successfully applied to a wide range of automatic control tasks. Subjective, ambiguous, and vague often characterizes many subjects in transportation engineering. The main benefit of fuzzy set theory is the opportunity to model the ambiguity and the uncertainty of decision-making. Traffic signal control is one of the oldest fields for application of fuzzy logic in transportation engineering [3]. The base idea of fuzzy traffic signal control is to model the control based on human expert knowledge, rather than the modeling of process itself. Fuzzy logic has the ability to comprehend linguistic instructions and to generate control strategies based on priori communication.

In this study we use Lukasiewicz many-valued similarity in comparing actual traffic situations with theoretical ones; we understand fuzzy IF-THEN rules as instances of many-valued equivalence relations rather that generalizations of Modus Ponens rules of inference. This new method was introduced in [4]. Lukasiewicz logic is the only many-valued logic satisfying Gödel style Complete Theorem in the sense of Pavelka [4], therefore, such an approach gives solid logical and mathematical foundations to fuzzy reasoning. Moreover, simulations made by HUTSIM, a traffic simulation program developed at Helsinki University of Technology, showed that this new method gives better results than conventional traffic signal control do, or even better than other fuzzy traffic signal control systems [2], [3] do when counting the sum of pedestrian and vehicle delay.

2 Principles of pedestrian crossings

2.1 General goals of optimization and control

Normally the signals of isolated pedestrian crossings in Finland are working as traffic actuated, and the remaining phase is vehicle green, which is an important safety aspect. Two detectors are located per each lane, one at the stop line and the other 60-100 meters from the stop line. Pedestrian green time is constant (10 seconds) or sometimes even actuated (6-14 seconds) in specific conditions. The pedestrian green time is usually longer for example in situations where there is a lot of children or elderly crossing the road daily.

Basically the problem when controlling a simple traffic signal with a pedestrian crossing should be not very complicated. The only thing the controller has to adjust is the length of the phases, which means the controller has to constantly make the decision of whether terminating or extending the current phase. By adjusting the minimum and maximum values of the extending period it is possible to stress the importance of minimizing either vehicle or pedestrian delay. In most of the traffic signals, minimizing vehicle delay has been put before the minimization of pedestrian delay. This means that after actuating the demand the pedestrian will have to wait for the system to find an appropriate gap in the traffic flow before the green phase of vehicles is terminated and pedestrians allowed to cross the road. Too long pedestrian waiting times encourage people to disobey the signals, thus pedestrian waiting time is another important safety factor. On the other hand, increasing vehicle delay and percentage of stops increases fuel consumption and emissions.

Balancing between different goals makes the optimizing problem of traffic signals complex. The general goal is to minimize delays and make the traffic flow as fluent as possible, i.e. the main goal of fuzzy control is to give pedestrians the opportunity to cross the road safely with a minimum waiting time, but also that the risk of rear-end collisions is minimized by minimizing the number of approaching vehicles at the termination moment of the vehicle green signal. Last but not least, it is important that the traffic control does not encourage pedestrians to cross the road during the pedestrian red phase.

2.2 Rule Formation

Controlling the timing of a traffic signal means making the following evaluation constantly: (1) to terminate the current phase and to change it to the next most appropriate phase, or (2) to continue the current phase. In other words, a controller incrementally evaluates these two options and takes the most appropriate one. The **output** is the decision about the termination (T) or the extension (E) of vehicle signal group (crisp value). The **input** parameters are
- pedestrian waiting time (WT is short/long/very long)
- maximum number of approaching vehicles per lane (A is none/some/many)
- discharging queue indicator, gap between vehicles at stop line (S is low/high)

These parameters are described by fuzzy sets, e.g. for gap between vehicles they are show in Tabel 1. **General rule formulation** is the following:

Table 1: Fuzzy sets for S

$S = x$ [sec]	$\mu_{low}(x)$	$\mu_{high}(x)$
$x \leq 1$	1	0
$x = 1.5$	0.8	0.2
$x = 2$	0.5	0.5
$x = 2.5$	0.2	0.8
$x \geq 3$	0	1

IF	WT is short/long/verylong and A is none/some/many and S is low/high
THEN	termination T/extension E.

For example,

IF	WT is short and A is none and S is low
THEN	T; terminate drivers green.

WT (waiting time) and A (approaching vehicles) were chosen, because they represented the main goals of rule base. The S (gap between vehicles) was chosen, because it is not common to terminate vehicle green while the queue is discharging (method of one stop per intersection). Total number of rules is $18(= 3 \times 3 \times 2)$. There are 9 rules for the extension and 9 rules for the termination decision. The final decision at an actual traffic situation x updated each second is a crisp value T/E and is based on the maximal similarity between x and one of the 18 'ideal' traffic situations as described below. If it should occur that two rules with a different consequence would get the exact same maximal value, the decision is always extension (E).

3 Fuzzy similarity

Fuzzy IF-THEN rules, which are often reported to be some sort of many-valued generalizations of the classical Modus Ponens rule of inference, can be also viewed as instances of many-valued equivalence relation or fuzzy similarity. It is well-known [4] that by fixing a continuous t-norm $t : [0,1]^2 \rightarrow [0,1]$ on the real unit interval one fixes the algebraic structure of some non-classical logic. As proved in [4], the Lukasiewicz t-norm $t(a,b) = \max\{0, a+b-1\}$ (and only it!) has the following properties:
(**A**) Any fuzzy X set with a membership function $\mu : X \rightarrow [0,1]$ generates a *fuzzy similarity relation* S on X, that is, a mapping $S : X \times X \rightarrow [0,1]$ such that, for all elements $x, y, z \in X$,

(i) $S(x,x) = 1$; S is reflexive,

(ii) $S(x,y) = S(y,x)$; S is symmetric,

(iii) $t(S(x,y), S(y,z)) \leq S(x,z)$; S is weakly transitive.
It is easy to see that, by districting on the values 0 and 1, S is a classical equivalence relation on X. In Lukasiewicz logic, the fuzzy similarity is calculated via

$$S(x,y) = 1 - \max\{\mu(x), \mu(y)\} + \min\{\mu(x), \mu(y)\}$$

(**B**) Given n fuzzy similarities $S_1, \cdots, S_n$ on X, the weighted mean, defined by

$$S(x,y) = \frac{1}{M}\Sigma_{i=1}^{n} m_i \cdot S_i(x,y),$$

where $M = \Sigma_{i=1}^{n} m_i$, is again a fuzzy similarity on X. In general, by manipulating the weights m_i we may emphasize those rules that we regard to be the most important ones.

In the traffic signal control we utilize the Lukasiewicz many-valued similarity in the following way.

(1) Each IF-part of the 18 rules correspond to a *theoretical traffic situation* $a_1, \cdots, a_{18}$, i.e. obtains value 1 in some of the above mentioned 8 fuzzy sets, and 0 elsewhere. For example, for a theoretical traffic situation a_1 these values are $\mu_{WT=short}(a_1) = \mu_{A=none}(a_1) = \mu_{S=low}(a_1) = 1$, while $\mu(a_1) = 0$ otherwise.

(2) An actual traffic situation x, the input variable, is compared separately with each a_i, i.e. total fuzzy similarities are calculated. For example, for the theoretical traffic situation a_1,

$$\begin{aligned} S(x, a_1) = \quad & \tfrac{1}{M}\{m_1 \cdot S_{WT=short}(x, a_1) \\ & + m_2 \cdot S_{A=none}(x, a_1) \\ & + m_3 \cdot S_{S=low}(x, a_1)\}. \end{aligned}$$

(3) The THEN-part of such a theoretical traffic situation a_j that

$$S(x, a_j) = \max\{S(x, a_i), i = 1, \cdots, 18\}$$

is the output, and the corresponding signal is fired.

4 Results of pedestrian crossing simulations

The simulation environment was a simple pedestrian crossing with two lines for vehicles, one line in each direction. The simulations were made with HUTSIM, a traffic simulation program developed at Helsinki University of Technology. 30 simulations, each with a different traffic situation, were conducted with every control algorithm. The number of pedestrians per hour varied and was either 15, 50 or 150. Of each of the three cases 10 simulations were made in which the number of vehicles ranged from 200-2000 per hour. The compared control algorithms were a fuzzy control algorithm developed by Niittymäki and Kikuchi [2] referred to in charts as **Fuz**, and two other algorithms which were variants of the above described maximal fuzzy similarity, referred to as **Fsim**(1,1,1) and **Fsim**(3,2,1), where the numbers 1,1,1 and 3,2,1 are the weights m_1, m_2, m_3 of waiting time (WT), number of approaching vehicle (A) and gap between vehicles (S), respectively. Obviously, **Fsim**(1,1,1) gives equal weights, while **Fsim**(3,2,1) emphasizes pedestrian waiting time. As Niittymäki and Kikuchi showed in their earlier study [2], total delays were smaller in **Fuz** compared to a conventional traffic signal control. Still, total delays were even smaller with **Fsim**(1,1,1) and **Fsim**(3,2,1), as can be seen in Figure 1.

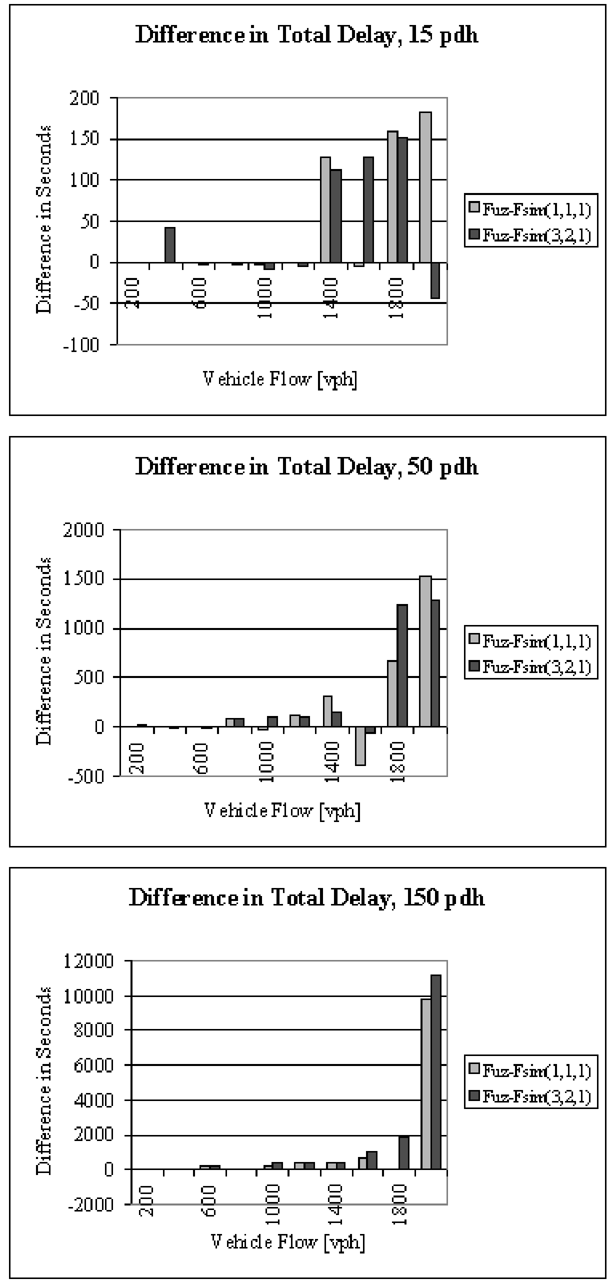

Figure 1: Compared simulation results

The results clearly show that except for the very small negative differences of the first case (15 pedestrians per hour) the algorithms of fuzzy similarity **Fsim**(1,1,1) and **Fsim**(3,2,1) give significantly smaller total delays than the algorithm **Fuz**. According to the simulations, however, **Fuz** is more favorable towards pedestrians than **Fsim**(1,1,1) and **Fsim**(3,2,1) algorithms. An interesting result is that, against intuition, the pedestrian delay of **Fsim**(3,2,1) is slightly bigger than the pedestrian delay of **Fsim**(1,1,1). This is probably due to a combination of factors. First, the linguistic rules and the shape of membership functions play a significant role in the choice between termination or extension. Second, the fact that the weight of the numbers of arriving vehicles is as high as two (over six) has an influence on the output.

5 Summary and conclusions

Optimising the functioning of traffic signal control in pedestrian crossings can sometimes be difficult. Increasing pedestrian waiting time decreases traffic safety while increasing vehicle delay causes environmental problems. To meet the demands of a traffic signal control in pedestrian crossings, fuzzy logic has been introduced. Fuzzy logic suits well for handling complex, inexact situations that often occur in traffic. Fuzzy traffic signal control has already proven to be better in decreasing delays compared to a demand-actuated control. Still, even though the use of fuzzy logic in traffic applications is not a new invention, there are only a few fuzzy traffic signal controllers in use.

As our simulations show, with the correct control algorithm it is possible to decrease both pedestrian and vehicle delay at the same time[1]. However, it seems that the minimisation of the total delay, i.e. the sum of pedestrian and vehicle delay, must be done at the cost of pedestrians. It is natural that since there are usually a lot more vehicles using the road than there are pedestrians crossing it, the total delay is very much affected by the delay caused for vehicles. Minimising vehicle delay is also more favourable towards environment, since increasing pedestrian delay does not increase emissions as increasing vehicle delay does. On the other hand, traffic safety would be better with a minimum pedestrian waiting time, since there would be less reason for walking against a red signal. Therefore, the choice of a control algorithm can, and should, also depend on the location of the crossing. Especially near schools and homes for aged people pedestrian crossings should function on the terms of the pedestrians rather than vehicles. Accordingly, on crowded trunk roads with few pedestrians crossing the road, vehicles should be the first priority. Utilizing fuzzy similarity algorithms this balancing between different goals can be done by varying the corresponding weights.

An important theoretical results is that fuzzy similarity based algorithms give better results in simulations that other fuzzy methods do. This emphasizes the significance of proper mathematical foundations of fuzzy logic.

Fuzzy logic is one of the new intelligent methods of controlling traffic. The use of neural networks in traffic control has also been studied [1]. The continuing growth of traffic has substantial disadvantages on especially traffic safety and environment, and new methods for controlling traffic are an important step towards more environmental friendly transportation. Technology and know-how keep improving and as it seems, intelligent, real time applications are capturing ground also in transportation engineering.

[1] The average vehicle delay is weighted with the number of vehicles as the average pedestrian delay is weighted with the number of pedestrians

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