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A Survey of Fuzzy Set Theory in Intelligent Transportation: State of the art and future trends

Mohsen Davarynejad and Jos Vrancken
Faculty Technology, Policy and Analysis
Delft University of Technology
Delft, the Netherlands
{ M.Davarynejad ; j.l.m.vrancken }@tudelft.nl

***Abstract*— Intelligent transportation systems (ITS) have received increasing attention in academy and in industry. Being able to handle uncertainties and complexity, fuzzy systems are applied in vast areas of real life including intelligent transportation systems. In this paper, a comprehensive survey of the research on the application of fuzzy systems in various traffic control engineering domains and its surroundings is presented. Main issues such as different control levels, different view levels as well as the advantages and disadvantages of fuzzy approaches are reviewed. To conclude, open questions and interesting issues in the field are discussed.**

Keywords—inteligent transportation systems, artifitial inteligence, fuzzy Logic,

I. Introduction

Non-linearity, time variability and nondeterminacy are important features of traffic. With their capability of dealing with complex and nonlinear systems, artificial intelligence is a promising approach that can be used in different layers and divisions of the complex and multi-disciplinary domain of traffic engineering. Fuzzy logic (FL) is an advanced artificial intelligence technique with the capability of handling situations where information cannot be expressed in clear mathematical terms, specially in complex systems were it is difficult to make a precise statement about system behavior or in situations were a kind of linguistic description in the form of *if-then* rules is available. Here, various applications of fuzzy logic at different levels of traffic control are outlined and are taken as example to illustrate fuzzy methods in ITS.

As the goal of traffic control, reducing the total traffic delay (by tuning traffic parameters such as cycle, phase sequence and offsets for urban traffic control) and adjusting the speed and ramp metering in inter-urban networks (according to traffic parameters such as flow and speed) is desired. It may be achieved by having an appropriate monitoring devices, prediction models as well as coordination mechanism between different components including ramp metering, speed limit control, traffic lights, etc. Actually its usability greatly depends on its ability to adapt to changes in traffic patterns.

II. Motivations

So far, in the domain of traffic engineering, fuzzy systems have been applied mainly in the following cases.

A. *Dynamic traffic light control*

Currently, detector data is simply fed into the control algorithm and based on predetermined rules, a control scheme is chosen and the lights are operated accordingly. Besides, several intelligent algorithms have been used in an attempt to find the best control strategy, including FL, reinforcement learning, neural network, evolutionary algorithms, multi-agent, etc. These approaches have the following common features: a) data collection b) control strategy to produce relevant control alternatives c) traffic model to investigate the impact of control alternatives d) an iterative optimization loop to control parameters within the search space to optimize the goal.

In network wide traffic control, coordination between different local control measures plays a critical role. The local control algorithms involved should have several properties to allow efficient coordination. For instance, it should be able to handle constraints (such as maximum and minimum green-time, maximum cycle, offset or queue length), able to handle multi-input, multi-output systems, adaptive to process parameter variables, optimize the object function globally, react based on the current and future conditions (so it has to be predictive).

B. *Ramp metering*

Ramp metering (just like traffic lights) is another effective dynamic traffic measure tool for alleviating congestion. The simplest form of on-ramp-metering is pretimed metering that operates with a constant cycle rate based on regular demand and roadway traffic pattern. In contrast, the traffic responsive meterings such as demandcapacity (DC) approach, occupancy (OCC) strategies [27] as well as the Asservissement Linéaire d'Entrée Autoroutière (ALINEA) strategy [28] in addition to its different variations such as [29] can adaptively respond to real time traffic conditions. They are local ramp-metering strategies that make use of measurements from the vicinity of a single ramp.

Being able to use the measurements from the complete

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network, coordinated ramp metering strategies have the potential to be more efficient than the local ramp metering approaches, specially in the case of restricted ramp metering spaces. It includes conventional methods such as optimal control strategies, multivariable control and HEuristic Ramp-metering coOrdination (HERO) [30].

In terms of sensitivity to small perturbations -that can cause huge impact on the whole network- rural, urban and freeway systems are chaotic. So ramp metering, with its small changes on the main-road, can prevent or delay the breakdown by reducing mainstream congestion. The different types of metering are a kind of traffic shaping that can be used to prevent traffic jam or to postpone it [20]. It has some well known positive effects such as:

- Mainline throughput maximization.
- Average travel speed maximization in upstream and/or downstream of the on-ramp merge.
- Travel time reduction.
- Smoother mainline flow and so accident and auto emission reduction.

C. *Variable speed limits*

In response to the prevailing traffic demand, the Variable Message Signs (VMS) are widely used to display the Variable Speed Limits (VSLs) on motorways. VSLs are recognized as a solution to improve substantial traffic flow efficiency (in the sence of reducing travel time, by both homogenization of speed and prevention of traffic breakdown) and improving safety factors (20-30% reduction in number of accidents [21]).

One of the conventional based recent approaches in speed limit control is SPECIALIST [31] which tries to solve shock wave problem on freeways.

D. *Traffic flow modeling*

The traffic models have the ability to simulate and predict traffic conditions including speeds and flow and as a result, they can predict the travel time by considering the different driving behavior of personal cars and trucks as well as different results in traffic flow because of different percentage of trucks in different situations. The models have the ability to serves as decision support system.

E. *Monitoring*

To improve the traffic conditions on freeways and major roads, it is very important to develop efficient control strategies for which it is vital to have accurate traffic information in space and time using estimation of traffic states. Indeed, monitoring systems are supposed to enhance the level of control service by gathering, completing and correcting the raw data. Most of the current traffic monitoring devices are based on stationary detectors such as loop detectors. With their ability to collect real time data, and because of containing lots of noise, the raw data are used to estimate the state of the traffic.

There is a need to obtain some more information from the raw data including turn-fractions, demand at critical points as well as the probability of traffic breakdown. Moreover, it could be possible to get more information about the free speed distributions, critical density, traffic mix, saturation flows, etc. based on the loop detector data.

F. *Intelligent collision avoidance*

Collision avoidance is a hot topic in different levels of transportation systems, airspace operations, navigation control and autonomous mobile robots. In [3] a fuzzy system is presented that models the intuitive and subjective collision avoidance using some simple fuzzy rules which are applied in automated guided vehicle (AGV) navigation. The simulation results shows the feasibility of the approach while they considered some static obstacles (with no a priori information on the position) as well as moving obstacles (with unknown trajectories).

G. *State determination and classification*

Threshold value logic is still the common way of determining the state of traffic. It means that the state of the traffic may change suddenly even if the change in traffic condition has changed little. The fact is that using threshold value logic, it's not possible to take into account the transitional area between different states.

H. *Prediction*

One of the core subjects in intelligent transportation systems is the prediction of the different traffic properties and trends e.g. travel time, flow and velocity that is in almost all cases, based on observed historical and current measurement data [1]. Robustness and accuracy are two main requirements and are essential for dynamic network management and control. The approaches are sub-classified into four major categories: time series approaches, regression models, pattern matching techniques and AI-based models [2].

III. Fuzzy logic and transportation problems

A. *A brief description of the theory of Fuzzy Logic (FL)*

With its capability in representing qualitative knowledge and ability in non-linear mapping of inputs to outputs, FL is a promising approach in dealing with and controlling complex and high-dimensional problems. It can make some quantitative human like decisions based on simple rules, such as [2]:

If speed is small and flow is small then metering rate is low and speed limit is high (1)

This example is based on the fact that when traffic in freeway is dense, it is crucial to implement on-ramp metering in order to prevent traffic breakdown by adjusting metering rate and keeping the density below the critical value. So by using some expert knowledge in the form of if-then rules, FL is a very suitable tool in dealing with a complex problem[25].

B. *A brief discussion on basic definitions and diferent elements of fuzzy logic*

Instead of two valued logic (true or false logic), FL is multi-valued logic in terms of ability to handle degrees of truth using a set of membership values. Conventional logic tries to describe events in *black and white fashion* and in precise manner, while fuzzy theory deals with approximate reasoning. It blurs the strict cut-off points. It can represent quantities such as about 0, close to 1, much greater than 5 as well as notions such as rather congested, very fast, and so on are defined through their membership functions (MFs) that enables a system to have a precise description and understanding of its inputs and outputs.

A typical fuzzy system, as shown in Figure 1, consists of five basic components. The fuzzification and defuzzification elements are the interfaces to the real world. The fuzzy reasoning is adopted using the remaining parts that handles rule inference, including fuzzy rule base and fuzzy inference engine (that is responsible for combining and evaluating the fuzzy if-then rules) using MFs of knowledge base. This system has many promising properties, e.g. non-linear mapping. The others are addressed in [5] and [6].

There are different defuzzification methods (center of gravity, maximum-membership principle that is also known as the height method [7], center of area, weighted average, smallest of maximum and largest of maximum, to cite a few examples) as well as different fuzzifiers (singleton, Gaussian and triangular) and inference methods (product, minimum, Lukasiewicz, Zadeh, and Dienes-Rescher).

The *center of gravity* and *weighted average* are the most commonly used defuzzification techniques along with the *Gaussian fuzzifiers* and *product inference engine*, which are the main methods most commonly seen in ITS because their usage is easy.

C. *The need of Fuzzy Logic to address various transportation problems*

Due to the *uncertainties* in arrival of traffic at an intersection and in general, because of randomness in the behavior of humans, traditional control methods are not adequate. As a result, the optimisation of either isolated or co-ordinated traffic light setting variables is crucial and to some extent, a complex task.

FL is approximate rather than precise. It is a tool to deal

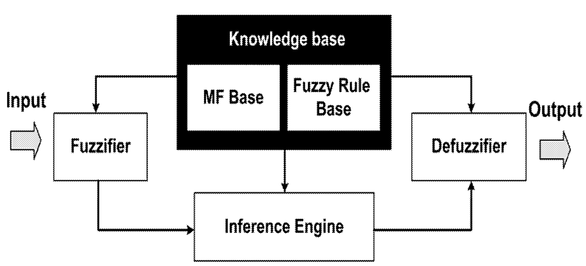

Figure 1. A typical fuzzy system

with reasoning and is derived from fuzzy set theory. It is a mathematical and precise concept of handling inherently *imprecise* and *uncertain* concepts and is very capable in applications were simplicity and transparency is required. This is specially needed in network wide control.

Some of the important features of fuzzy are graduation, granulation and precisiation [32]. It can deal with information in terms of *linguistic variables* and a set of linguistic rules known as fuzzy rules such as (1) that are the most fundamental elements in human knowledge representation which makes it a powerful modeling language and thus *can serves as a means of summarization and information compression through the use of granulation[32]*.

Besides, FL serves as a fundamental tool for natural language computation -that is a kind of computational technique for analyzing and understanding information expresed in natural language [24].

Apart from the features mentioned above, fuzzy systems are well capable in building reliable control systems with acceptable functionality in the presence of uncertainty or ambiguity. So they are very interesting tools specially in the cases were making a precise statements about the behavior of the system is difficult. While traffic controllers have become very advanced, fuzzy has a distinct advantage since it *can represent a complex system with* simple linguistic rules and computational capability.

IV. Fuzzy applications in traffic domain (A Taxonomy of Approaches)

Generally, there are two levels of traffic management and control, the local and the network levels. Nowadays, fuzzy is a popular and common tool in both local and network level of traffic management. At the local level, they are mainly used in designing controllers and at the network level they are mainly used for designing a coordination strategy between different control measures as well as decision support systems. More deeply, we are focusing here on the application of FL in the first two important mentioned domains namely traffic light control and ramp metering.

A. *Traffic Light Control*

Duo to the randomness behavior of road users and short come of traditional fixed time control method to deal with this randomness, lots of control approaches such as TRANSYT [17] and aaSIDRA [15] are presented that are vehicle responsive instead of predefined fixed timing. They are introduced in order to optimize traffic timing at signalized intersections. Based on the green time extension method and the output of the sensors that are installed in each arm of the intersection, signal timings are carried out [18]. In these method, the phase sequence is predefined and is not consequently rearranged and optimized, moreover they are poorly react upon changes in traffic pattern and their performance deteriorates in heavy traffic. To overcome these deficiencies, because of its flexible structure and ability in handling uncertainties or unknown variations, FL is widely used as an alternative approach.

Generally, FL is applied in two different levels of intersection control, namely isolated and co-ordinated levels. The first seminal attempt to use FL in isolated intersection optimization tool was made by Pappis and Mamdani [19] in 1977. The input variables of their system were the passed time of current interval, number of vehicles crossed the green direction, and the length of the queue in the red direction. The output parameter was the extension time of the current green phase. They obtained about 20% improvement in delays.

Sazi Murat et al. [14] proposed a framework for signal control of isolated junctions. They introduce a Fuzzy Logic Multi-phased Signal Control (FLMuSiC) model that is composed of two fuzzy systems. Based on the traffic volumes, one of the systems is used for determining the optimum signal timing by allocation and variations of green time and the other one is designed to arrange the optimal phase sequence. They evaluated their work and compared the result with aaSIDRA [15] and concluded that FLMuSiC outperforms aaSIDRA when the traffic volume is relatively high.

A fuzzy controller for isolated junction with the ability to ensure optimal decision making under both normal and exceptional traffic conditions (such as accident or temporary obstruction) is proposed in [16]. Authors introduced a fuzzy system composed of two sets of fuzzy rules. One with three input parameters called *normal controller* with the amount of changes in green time as the output and the second one called *abnormal controller* with four inputs and the same output as the first one. They concluded that they method outperforms other approaches in the presence of abnormality.

Although it is very logical and strategical to have flexible phase sequence, in most of the cases, the order of the states are predetermined, but in some, the controller can skip a state (if the traffic volume in a certain direction is bellow a certain level) or can move directly to a specific state. The decision, also, is mostly based on predetermined number of rules. The inputs of the controller are quantized arriving and waiting vehicles, expressed in linguistic terms such as few, medium and many. In the case of having predetermined number of rules, although the controller is shown to be more flexible in comparison to the conventional fixed controllers, it might fail if the traffic volume varies. As a result, in some approaches, because of the fact that not all rules can be generated from human expertise nor all rules contribute significantly to the system performance [34], the rule base is adaptively develops, depending on the traffic condition [35].

The tuning of different parameters of MF is another issue that is considered in several papers in wide range of applications including urban traffic flow prediction [37] and isolated traffic light control [38, 41]. The adaptive dynamic programing [39] (that is an advanced control strategy) for optimizing a fuzzy logic controller is proposed in [40] to archive the sub-optimal performance. Authors introduced a controller composed of two inputs (number of vehicles in the green phase and weighted sum of number of vehicles of the other three phases) and one output (either extending the current phase or terminating it). Their study focused on optimizing MFs parameters for traffic signal control and an isolated intersection. Under heavy traffic flow and even sudden flow changes, they reported clearly better performance for their proposed approach compared to actuated control.

There is a strong relationship between the released traffic flow of the upstream intersections and the arrived flow of the neighbor downstream intersection. The intention in introducing coordinated traffic light systems is to synchronize the signals such that the platoon of vehicles could cross the arterial without stopping at red lights while traveling at a certain constant speed. For controlling multiple junctions, in [33], Lee et al. proposed a FL controller with the ability in handling extra information on the upstream and downstream junction sites to maximize the network throughput. In both the light and heavy traffic situation, their approach outperformed a fixed controller. Although for each junction, the controller needed different parameter settings, it could handle changes in traffic flow.

Li et al. [36] proposed an innovative framework for network signal control. Their approach is composed of a fuzzy control level and a fuzzy rules regulation level. They introduced an adaptive fuzzy logic controller in control level to determine the signal timings of an intersection group. By a learning algorithm in regulation level, the controller is capable to produce more suitable fuzzy rules. To describe the interaction among adjacent intersections, the weight coefficient controller (WCC) is being employed. The feasibility and the efficiency of their work is determined via simulation while a comparison is carried out under different traffic conditions. They concluded better performance than actuated controller.

In these controllers, the system mimics human intelligence by gathering information on the status of traffic in each entrance of intersection, and continuously deciding whether to terminate the current phase and should switch to the next step or should stay in the current state by extending the allocate time.

B. *Ramp metering*

In local level for instance in [8], a fuzzy controller is designed to adjust the metering rate and upstream speed limit based on three input variables: flow and speed upstream the on-ramp as well as the ramp queue occupancy. The first two input variables are divided into three classes, e.g. small, medium, high and the queue occupancy is described by the term very high. The three low, medium and high terms are also assigned to the output variables. To ease the calibration process of a fuzzy controller, they applied a genetic algorithm [11] for tuning the fuzzy sets parameters. This approach, in terms of computational demand, because of off-line tuning of parameters, is suitable for real-world application, but since the parameters are fixed during the operation, it is not adaptive to traffic pattern changes. In a simulation context, METANET [26] (a second order macroscopic traffic model) was used to evaluate the effectiveness of the fuzzy controller. The comparison with ALINEA controller reveals that the fine tuned fuzzy controller could control the queue length with much less oscillation and smoother metering rate.

In [9], the authors presented a fuzzy controller just to control the ramp metering rate with three inputs namely number of vehicles at the upstream of main road of freeway, with five triangular MFs: few, a few, comparatively few, medium, many, a great many, the number of transit vehicles waiting at the stop line with four MFs: many, a great many, a few, few and finally the road occupancy rate at the downstream of the main road of freeway with three MFs: large, small, medium. The output is the lengthening red time with three short, medium and long MFs. Compared to the fixed time control approach in terms of queuing delay, they concluded more efficiency while using their propose solution.

Although isolated ramp-metering is developed to maximize the freeway throughput, it is not able to perform adequately. The metering rate at one ramp, in reality, will affect the mainline and hence the merging rate at other ramps, while the isolated ramp-metering solution, considers just the local queue on the ramp and local traffic conditions on the mainline. There are at least two options to have better control, one is coordinated ramp metering that considers a series of ramps with goal of coordinating the response of all ramps, and the other one is hierarchical philosophy that compiles both local and global views into one.

For instance in [10], an adaptive and coordinated control of entrance ramps with FL is developed with the ability to take into account the interdependency of a series of on-ramps. With its adaptation and self optimization capability using neural network [12] and genetic algorithm [11] theory, this approach is used to find the optimal adaptive ramp metering rate. The model called ACCEZZ and has seven inputs including the local speed, flow and occupancy of the mainline right upstream of the on-ramp merge, downstream speed and volume/capacity ratio, queue occupancy of on-ramp, as well as the check-in occupancy. The performance of the approach was performed with a micoscopic traffic flow model. Travel time and ramp delay, queue length etc. are calculated and the result is compared with five different standard algorithms. The rule base was considered flexible in terms of the numbers with assessing a weight to each. The system is capable of learning/optimization while taking into account the interdependency of ramps. The output of the ACCEZZ is just the metering rate and it do not considers the speed limit as an effective actuator.

In [13] a self adaptive coordinated traffic responsive metering fuzzy system is presented. Genetic tuning approach in employed to optimize the total time spent in the network based on 15 minute prediction.

Overall, considering the constraints of links in terms of capacity and density, as well as the feasible range of metering rate, by incorporating human knowledge and ability in handling imprecision, fuzzy ramp metering control is a promising approach in reducing time delay.

V. Advantages and disadvantages of a fuzzy logic approach

Considering its advantages and disadvantages, abandonment of fuzzy logic seems to be impossible. Its merits and drawbacks opens the door to exploration of new directions in searching for more efficient network wide control tools. Among the important technical advantages and disadvantages of fuzzy are the following.

A. *Advantages:*

- Conceptually easy to understand and use, transparent (because they mimic human thinking) and intuitive.
- Powerfull and robust with even only few rules for local control strategies – if the right type of rules are used.
- A powerful modeling language in terms of linguistic variables and if-then rules with wide range of applications by summarizing the information through the granulation aspect.
- Ability in modeling knowledge and experience of a human operator, reasoning and decision making by incorporating quantitative knowledge and expanding incomplete expert knowledge. As a result, high potential in developing real-time (and so adaptive) control of high-dimensional complex traffic processes. For instance the ability of dealing with *What is happening?* and *What may happen?* questions and answers as well as the following statement: "*It is very unlikely that there will be a significant increase in the traffic flow in the near future*".
- A powerful tool in understanding imprecision in natural language or dealing with uncertainty about uncertainty [24].

B. *Disadvantages:*

- Although FL is widely used in the area of traffic control, they are mostly applied on traffic signal control of the isolated intersection and isolated ramp-metering. It is because of the complexity that exists in large-scale systems, such as traffic control, which makes it difficult to describe the whole system using some quantitative knowledge [1].
- Similar to many approaches, curse of dimensionality (CoD) is often the most prohibitive and limiting segment of FSs, although in some cases, it can be handled by introducing different levels of management as introduced in [23] for network wide control.
- Although the influence of the various parameters of FS is usually local, in complex applications it is always vital to tune them and it needs great effort to calibrate the them including the rules and MFs to make it work well in different traffic conditions.
- Although the stability analysis of fuzzy controllers has widely reported, a complete and general methodology is still missing – like lots of traditional non-linear system theories.

Considering the theoretical attractiveness including transparency, practical complexity and wide range of applications, we would rank this methodology as good.

VI. Scope for Future Work

The authors are to incorporate the following provisions to the ongoing research in the future in the area of Amsterdam within the Control for Coordination European project:

- Put the theoretical research into practice, especially the control and modeling approaches.
- Network level traffic management and control using FL and generally soft-computing approaches and investigation on more efficient coordination.
- Use more generic solutions in tuning different parameters of fuzzy systems, for instance supporting vector machines [22].

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