

Simulation Research of Fuzzy Control in Entrance Ramp of Freeway

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Abstract: A fuzzy logic approach was proposed to regulate the number of vehicles entering a freeway entrance point during rush traffic times. The basic structure of a fuzzy logic controller was analyzed and the fuzzy control algorithm was formulated. The membership functions were developed and the fuzzy logic entrance ramp controller was designed based on such traffic information as the flow, speed, occupancy, and ramp queue length. These variables were each measured by several sensors built into the upstream, downstream, and entrance ramp portion of the freeway. Simulation research was carried out by taking full advantage of a computer. Simulation results show that such an approach is practical and effective. It can avoid traffic jams and congestion on the mainline, improve the passing capability, and make the vehicles travel more efficiently and safely.

1. Introduction

The fuzzy logic control techniques were originally introduced by Zadeh [1][2] as a means of both collecting human knowledge or experience and dealing with uncertainties in the control process. Since then, the fuzzy logic control has attracted a great deal of attention and a lot of works have been published in the field. The fuzzy logic control has proved to be a successful control approach to many complex nonlinear systems or even nonanalytic systems [3].

However, it is difficult to infer the proper control input for a multi-variable system since the dimension of its relation matrix is very large. The high dimensionality of the relation matrix might lead to not only computational difficulties but also memory overload when the physical control system is implemented on a computer. To solve this problem, Gupta proposed a fuzzy control algorithm by which the multi-variable fuzzy system is decomposed into a set of one-dimensional systems [4]. The decomposition of control rules is preferable since it alleviates the complexity of the problem.

Freeway traffic system is a complex system including drivers, vehicles, and roads. The complexity, nonlinear character, stochastic behavior, and uncertainty of the system make obtaining an exact mathematical model difficult and time-consuming. Therefore the traditional control theory based on an exact mathematical model is less effective to traffic control.

The widespread application of computers allows artificial intelligence to develop quickly. The advanced technologies of artificial intelligence such as expert system, fuzzy logic, artificial neural network, and genetic algorithm are applied to the field of traffic engineering in contrast to the drawbacks of traditional control technologies. Fuzzy logic does not rely on an accurate mathematical model and can handle linguistic information as well as data information, so it is especially suitable for ambiguous and qualitative knowledge. Because fuzzy logic is similar to some features of the mode of human thinking, it has good results embedded in the inference process.

Fuzzy logic is an effective tool to handle the complexity, nonlinear character, and uncertainty of traffic system. Fuzzy control plays an important role in the field of traffic control and fuzzy control approach has shown its superiority [5].

There are four control approaches in developing freeway control strategies: entrance ramp control, mainline control, corridor control, and charge control. An entrance ramp control system is considered

as an important component of freeway traffic control and intelligent transport systems. The entrance ramp meter is a traffic signal placed at the freeway entrance and is controlled by a traffic strategy. A ramp meter operates to discharge vehicles at a measured rate based on real-time traffic conditions. It protects the sensitive demand-capacity balance at the ramp merge or at a downstream bottleneck. As long as the mainline traffic demand does not exceed capacity, throughput is maximized, speed remains more uniform, and congestion related accidents are reduced. Smoother flow on the freeway by preventing the occurrence of bottlenecks through ramp control can lead to the improvement in traffic safety, reduction in fuel consumption and air pollutants. On the other hand, when vehicles attempt to force their way into the mainline turbulence on the mainline flow is created. This turbulence can cause the mainline traffic to break down [6]. Reduced turbulence in the merge zone can lead to reduced sideswipe and rear-end accidents.

The basic structure of a fuzzy logic controller is analyzed and the fuzzy control algorithm is formulated. The membership functions are developed and the fuzzy logic entrance ramp controller of the freeway is designed. Simulation research is carried out by taking full advantage of a computer. Simulation results show that such an approach is promising.

2. The Basic Structure of a Fuzzy Logic Controller and the Fuzzy Control Algorithm

The basic structure of a fuzzy logic controller is shown in Figure 1. There are four components in a fuzzy logic controller, namely: fuzzification interface, knowledge base, fuzzy inference, and defuzzification interface.

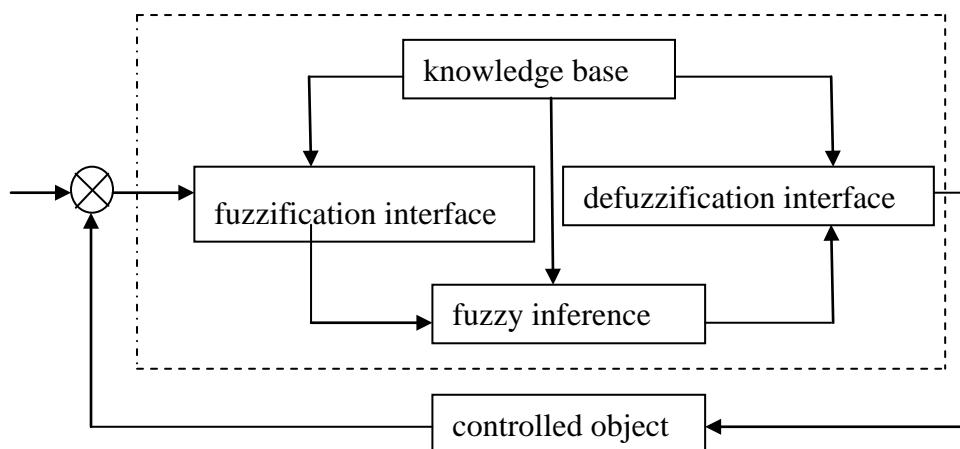


Figure 1 Basic structure of fuzzy logic controller

Fuzzification translates each numerical input into a set of fuzzy classes. A fuzzy class represents a fuzzy subset of a universe of discourse and has a defined membership function. The main functions of the fuzzification interface are to measure the values of input variables, to perform a scale mapping that transfers the range of values of input variables into corresponding universes of discourse, and to perform the fuzzification that converts input data into suitable linguistic values. Not only the input variables have to be fuzzified but also the output variables[7][8].

The knowledge base, also called fuzzy rule, is the heart of a fuzzy logic controller. The fuzzy rules are based on expert opinions, operator experience, and system knowledge. The rules have the following form:

IF < premise 1 > AND/OR < premise 2 > THEN < consequent > .

Each rule is assigned a weight indicating its importance. If a rule is more important or more reliable than other rules, it has a greater weight. A fuzzy system that is composed of a set of fuzzy rules can show the mapping from input variables to output ones.

The fuzzy inference has the capability of simulating human decision-making based on fuzzy concepts. It evaluates a set of conditions of inputs in a comprehensive way, based on fuzzy rules, to

get a linguistic output variable. Because a fuzzy rule based system consists of a set of fuzzy rules with partially overlapping conditions, a particular input to the system often “triggers” multiple fuzzy rules. For example, more than one rule will match the input to a nonzero degree. Therefore a method is needed to combine the inference results of these rules. This is accomplished typically by superimposing all fuzzy conclusions about a variable. Mamdani type inference, i.e. Max-Min inference, is often chosen. The inference process is as follows.

Assume there are fuzzy rules $r_1, r_2 \dots r_n$.

r_1 : IF x is A_1 AND y is B_1 THEN z is C_1

r_2 : IF x is A_2 AND y is B_2 THEN z is C_2

...

r_n : IF x is A_n AND y is B_n THEN z is C_n

Then for the antecedent of fuzzy control rules there are inference intensity $\alpha_1, \alpha_2 \dots \alpha_n$.

$$\alpha_1 = u_{A_1}(x) \wedge u_{B_1}(y) \quad (1)$$

$$\alpha_2 = u_{A_2}(x) \wedge u_{B_2}(y) \quad (2)$$

...

$$\alpha_n = u_{A_n}(x) \wedge u_{B_n}(y) \quad (3)$$

Where u_{A_i} and $u_{B_i}, i=1,2,\dots,n$, are the membership functions of A_i and B_i , respectively.

For the i^{th} fuzzy rule r_i , the amount of fuzzy control is C_i' . The membership functions of C_i' , $i=1,2,\dots,n$, are $u_{C_i'}(z)$,

$$u_{C_i'}(z) = \alpha_i \wedge u_{C_i}(z) \quad (4)$$

Where $u_{C_i}, i=1,2,\dots,n$, are the membership function C_i .

For a fuzzy logic controller, all the fuzzy rules need to be combined to get the final amount of fuzzy control. The final amount of fuzzy control is C and its membership function is $u_C(z)$.

$$u_C(z) = V_i u_{C_i}(z) = V_i (\alpha_i \wedge u_{C_i}(z)) \quad (5)$$

Where “ \vee ” and “ \wedge ” are maximum operator and minimum operator, respectively.

The main functions of the defuzzification interface are to perform a scale mapping that converts the range of values of output variables into corresponding universes of discourse, and to perform the defuzzification that produces a clear decision output. Defuzzification is a step that converts the final combined fuzzy conclusion into a crisp one. The defuzzification approaches in common use are the maximum membership function approach, weighted average approach, and gravitational center approach. For the defuzzification process in a ramp metering algorithm the gravitational center approach is used, this helps to suppress parameter variations and stochastic disturbances. The crisp output of the controller is the metering rate of a controlled entrance ramp.

3. Fuzzy Entrance Ramp Metering Controller

Sensors such as inductive loop detectors and ultra-audio wave detectors are built into the upstream, downstream, and on-ramp in a freeway section. The upstream occupancy, upstream speed, upstream flow, downstream occupancy, downstream speed, downstream flow, ramp occupancy, and ramp queue length are measured by the sensors. Overall there are eight inputs mentioned above into the fuzzy logic entrance ramp controller[9].

The output of the controller is the metering rate of the controlled entrance ramp. The aim is to protect the sensitive demand capacity balance at the ramp merge or at a downstream bottleneck, so

that throughput is higher, speed remains more uniform, and congestion related accidents are reduced. The fuzzy rules are laid down on the basis of expert opinions, operator experience, and system knowledge to realize the aim. The output values are calculated by using the fuzzy control algorithm. The range of UO (Upstream Occupancy) is from zero to one hundred percent. UO is described by the terms “VS (Very Small)”, “S (Small)”, “SE (Smaller)”, “M (Medium)”, “HE (Higher)”, “H (High)”, and “VH (Very High)”. Gaussian curves are assumed for the membership functions of UO, as seen in Figure 2.

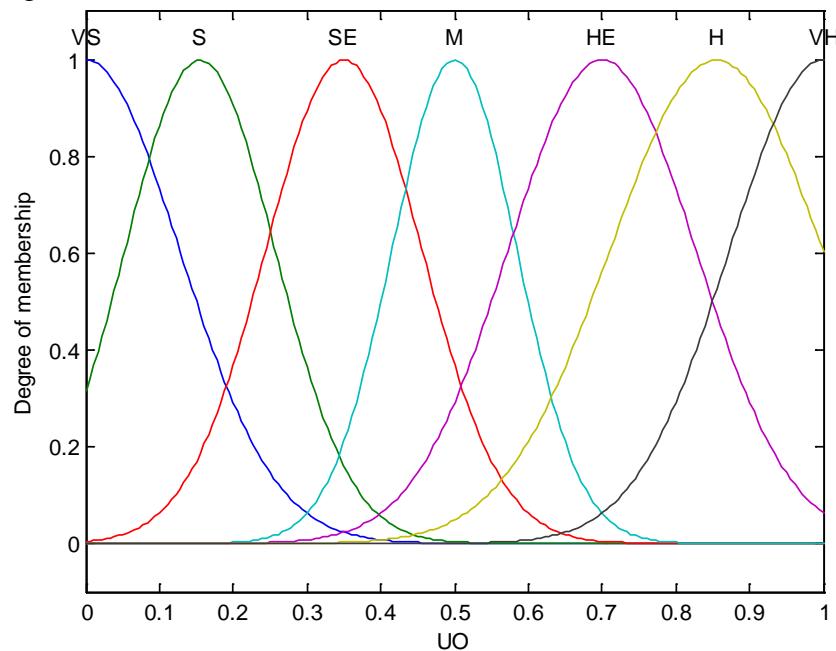


Figure 2 The membership functions of UO

The range of US (Upstream Speed) or DS (Downstream Speed) is from zero to 150 km/hour. The range of UF (Upstream Flow) or DF (Downstream Flow) is from zero to 3600 vehicles/hour. The range of QL (Ramp Queue Length) is from zero to 60veh. The range of DO (Downstream Occupancy), RO (Ramp Occupancy), or MR (Metering Rate) is from zero to one hundred percent. US, UF, DO, DS, DF, RO, QL or MR is also described by the terms “VS”, “S”, “SE”, “M”, “HE”, “H”, and “VH”. Gaussian curves are also assumed for their membership functions.

The fuzzy rules and their weights are based on expert opinions, operator experience, and system knowledge. All of the rules are listed below:

- 1), IF (UO is VS) THEN (MR is VH) [weight 0.5];
- 2), IF (UO is S) THEN (MR is H) [weight 0.5];
- 3), IF (UO is SE) THEN (MR is HE) [weight 0.5];
- 4), IF (UO is M) THEN (MR is M) [weight 0.5];
- 5), IF (UO is HE) THEN (MR is SE) [weight 0.5];
- 6), IF (UO is H) THEN (MR is S) [weight 0.5];
- 7), IF (UO is VH) THEN (MR is VS) [weight 0.6667];
- 8), IF (DO is VS) THEN (MR is VH) [weight 0.5];
- 9), IF (DO is VH) THEN (MR is VS) [weight 1.0];
- 10), IF (US is VS) AND (UO is VH) THEN (MR is VS) [weight 0.6667];
- 11), IF (US is S) AND (UO is VH) THEN (MR is S) [weight 0.6667];
- 12), IF (US is VS) AND (UO is H) THEN (MR is VS) [weight 0.6667];
- 13), IF (US is S) AND (UO is H) THEN (MR is S) [weight 0.5];
- 14), IF (US is VH) AND (UO is VS) THEN (MR is VH) [weight 0.3333];
- 15), IF (US is H) AND (UO is VS) THEN (MR is H) [weight 0.3333];
- 16), IF (US is VH) AND (UO is S) THEN (MR is VH) [weight 0.3333];
- 17), IF (US is H) AND (UO is S) THEN (MR is H) [weight 0.3333];

- 18), IF (US is SE) AND (UF is H) THEN (MR is SE) [weight 0.3333];
- 19), IF (US is SE) AND (UF is VH) THEN (MR is SE) [weight 0.3333];
- 20), IF (US is M) AND (UF is H) THEN (MR is M) [weight 0.3333];
- 21), IF (US is M) AND (UF is VH) THEN (MR is SE) [weight 0.3333];
- 22), IF (US is HE) AND (UF is H) THEN (MR is HE) [weight 0.3333];
- 23), IF (US is HE) AND (UF is VH) THEN (MR is M) [weight 0.3333];
- 24), IF (US is H) AND (UF is S) THEN (MR is H) [weight 0.3333];
- 25), IF (US is H) AND (UF is VS) THEN (MR is H) [weight 0.3333];
- 26), IF (US is VH) AND (UF is S) THEN (MR is VH) [weight 0.3333];
- 27), IF (US is VH) AND (UF is VS) THEN (MR is VH) [weight 0.3333];
- 28), IF (DS is VS) AND (DF is VH) THEN (MR is VS) [weight 1.0];
- 29), IF (DS is VS) AND (DF is H) THEN (MR is VS) [weight 1.0];
- 30), IF (DS is S) AND (DF is VH) THEN (MR is VS) [weight 0.6667];
- 31), IF (DS is S) AND (DF is H) THEN (MR is S) [weight 0.6667];
- 32), IF (RO is H) THEN (MR is H) [weight 0.6667];
- 33), IF (RO is VH) THEN (MR is VH) [weight 1.0];
- 34), IF (QL is H) THEN (MR is H) [weight 0.6667];
- 35), IF (QL is VH) THEN (MR is VH) [weight 1.0].

The rules No.1-7 adjust the metering rate according to the upstream occupancy. The rules No.8-9 adjust the metering rate according to the downstream occupancy. The rules No.10-17 adjust the metering rate according to the upstream speed and upstream occupancy. The rules No.18-27 adjust the metering rate according to the upstream speed and upstream flow. The rules No.28-31 adjust the metering rate according to the downstream speed and downstream flow. The rules No.32-35 adjust the metering rate according to the ramp occupancy or ramp queue length.

Notice that our rule base does not individually consider all of the possible input combinations. If the rule base were incomplete, it is possible that no rule would be activated for certain inputs. This problem is solved by completing the rule base with the upstream occupancy rules No.1-7. Because the entire range of upstream occupancy inputs is considered, at least one of these seven rules will fire all the times. The rules No.10-31 adjust the metering rate according to speed coupled with either occupancy or flow. The fundamental relationship between speed and occupancy (or between speed and flow) is used to get a more specific congestion index. The rules No.7, 9, 10-12, 28-31 have relatively higher weights. The reason for this is to restrict the metering rate when the vehicles are unable to merge onto the mainline of freeway. The objective of rules No.28-31 is to mitigate the formation of a downstream bottleneck. The rules No.32-35 are designed to prevent excessive queue formation on the ramp.

4. Simulation

Based on the membership functions of eight input variables and one output variable that are defined, and based on the fuzzy rules, the mapping that transfers the values of input variables into corresponding ramp metering rate can be obtained. As long as a set of input values measured by the sensors are fed into the controller, the ramp metering rate can be sent out. Simulation results are shown in Table 1.

Case 1 indicates that the ramp metering rate is very high when the traffic flow in the upstream and downstream is very smooth, and when there is a long queue of vehicles on the ramp. Case 2 indicates that the ramp metering rate is relatively higher when the traffic flow in the upstream and downstream is smooth, and when the ramp occupancy is high. Cases 3 to 6 indicate that the ramp metering rate is getting smaller and smaller when the mainline traffic is becoming more and more congested.

Tab.1 Simulation result

	Case 1	Case 2	Case 3	Case 4	Case 5	Case 6
UO	0.03	0.30	0.38	0.70	0.85	0.98
US	150	120	110	90	50	10
UF	150	2500	3000	2500	1200	120
DO	0.03	0.30	0.38	0.70	0.85	0.98
DS	150	120	110	90	50	10
DF	150	2500	3000	2500	1200	120
RO	0.98	0.80	0.40	0.40	0.40	0.40
QL	60	45	30	30	30	30
MR	0.9202	0.7547	0.6271	0.3514	0.1751	0.1094

5. Conclusions

The fuzzy logic is ideal for controlling nonlinear, complex systems. A typical fuzzy control system consists of a rule base, membership functions, and an inference process. Since rules are easy to define, alter or eliminate, fuzzy logic allows simple development and modification.

The fuzzy logic entrance ramp controller is designed based on the traffic information measured by several sensors built into the mainline of freeway and entrance ramp. Simulation research is carried out by taking full advantage of a computer. Simulation results show that such an approach is practical and effective. The fuzzy logic approach is of great significance for improving the safety and efficiency on freeway. Simulation results are proved to illustrate the effectiveness of the proposed method.

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