Development of Ramp Metering Using Fuzzy Logic Control Algorithm on Freeway

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Abstract: Ramp metering can effect on mitigating the traffic congestion on freeway. In Taiwan, the conventional Local Traffic Responsive (LTR) ramp metering model based on the capacity and demand algorithm has been adopted for freeway ramp control since long time. For enhancing the ramp metering technology, this paper aimed at developing a new Fuzzy Logic Control (FLC) algorithm based on the real traffic situation for ramp metering control on the highway tunnel, by taking Freeway No.5 as the case, which is a freeway with the longest tunnel of 12.9km, in order to enhance the ramp metering performance on relieving traffic congestion. Through the comparative analysis using microscopic simulation, the FLC ramp metering results in higher performance on mitigating the congestion than the LTR control and no control.

Keywords: Ramp Metering, Fuzzy Logic Control, Freeway, Traffic Simulation

1. INTRODUCTION

Recurrent congestion occurs frequently at some bottleneck locations on freeway in Taiwan. In order to mitigate freeway traffic congestion, many ramp metering algorithms had been applied for optimal utilization of the freeway capacity (FHWA 2006). The original ramp metering controllers used artificial operation or pre-timed ramp metering and now modern ramp metering algorithms are traffic responsive ramp metering (Banks, 1996). The metering rate generating technology of traffic responsive metering can basically be divided into mathematical programming method and logical decision making method (Papageorgiou, 1991, 1995). Logical decision making method is usually used to ensure getting feasible solutions in practice. In Taiwan, ramp metering was first officially implemented in 1998. It is the pre-timed ramp metering and is used for daily freeway traffic control from 7 am to 7 pm. Since 2003, the traffic responsive metering, namely Local Traffic Responsive (LTR), has been used to control the traffic flow allowable into freeway in real-time. LTR has dynamic demand-capacity logic (Arnold, 1998). The LTR logic adopted in Taiwan is shown in Figure 1. In the logic, firstly, is to check if the sum of upstream flow is less than downstream capacity and accordingly, the ramp metering rate can be calculated by the downstream capacity minus the upstream flow. Otherwise, if the traffic has congestion warning, the ramp metering rate should be adopted minimum metering rate. Second, if the metering rate is more than maximum metering rate, it means the traffic loading on the mainstream of freeway is low, and then the ramp meter could be turned off. For the situation of metering rate less than maximum metering rate, the ramp meter should be considered to turn on depending on stable demand. However, LTR has starting late problems and response late problems especially for long highway tunnel. Hence, this research motivation is developing a novel ramp metering algorithm which can practice at long highway tunnel.

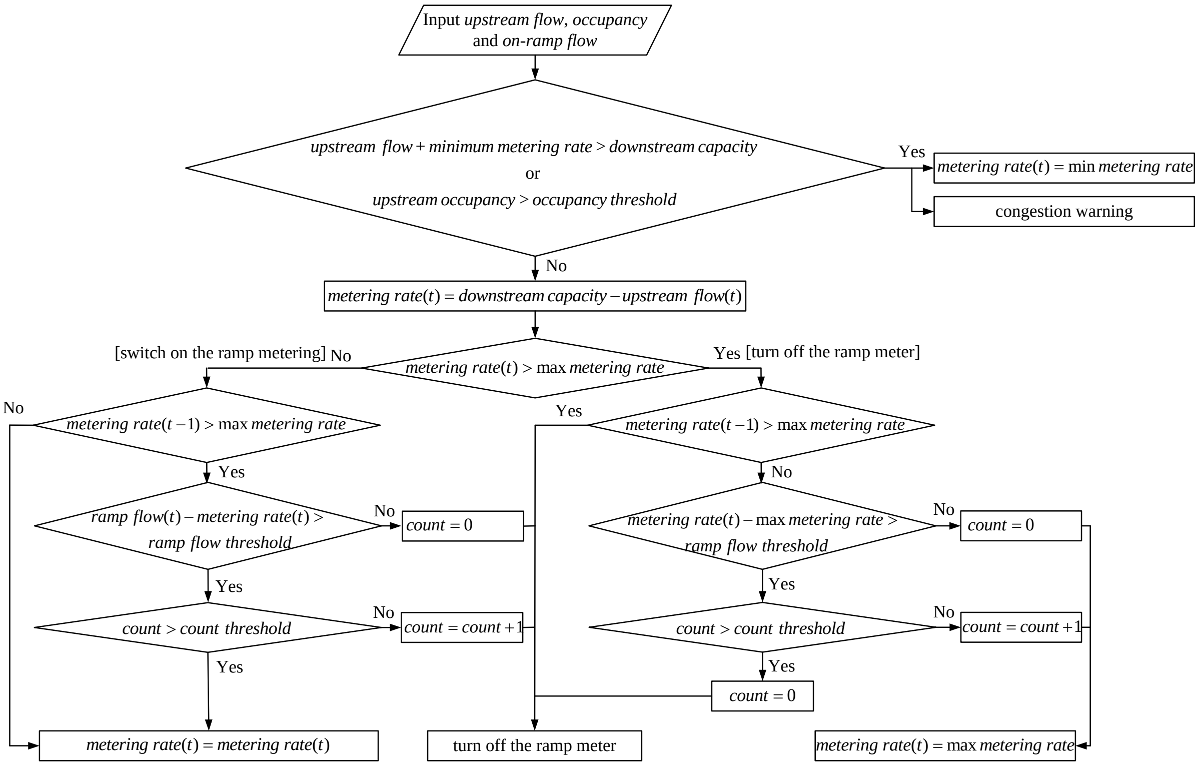

Figure 1**.** The control logic of the LTR metering model adopted in Taiwan's freeway

Bogenberger et al. described 17 different ramp metering approaches, and depicted that Fuzzy Logic Control (FLC) metering model could be an effective approach to control on-ramp traffic (Bogenberger etc. 1999). Fuzzy logic algorithm can handle missing or imprecise traffic data, and can compromise conflicting objectives (Taylor etc., 1998). The parameters of the FLC controller need to be calibrated in order to reach the premium performance

Traffic data collected by detector frequently contain errors due to noise, mechanical failure of detectors and transmission errors. Unfortunately, most ramp-metering algorithms are sensitive to detector data error because they calculate the metering rates directly from detected traffic raw data. Regarding this point, the FLC control has the advantage to be able to utilize partial or imprecise information and reduce the sensitivity to traffic data errors (Chen and May etc., 1990; Bogenberger, 2000). On the other hand, a number of hybrid rules of FLC control can be combined to produce metering rate. This mechanism can be useful for reducing the dependence just on the traffic data by single detector. Therefore, the FLC algorithm has the advantage and is selected in this research.

2. TRAFFIC CHARACTERISTICS ANALYSIS

2.1 Freeway No. 5

In this paper, the Freeway No. 5 is selected as the case to test the performance of the developed ramp metering model using Fuzzy Logic Control. As shown in Figure 2, National Freeway No.5 is a freeway in northern Taiwan which links Taipei and Yilan, consisting of 7 interchanges and 5 tunnels. One of these tunnels has 12.9km long is Hsueh-shan Tunnel which also is fifth-long highway tunnel in the world. After beginning operation on June 16th, 2006, National Freeway No.5 has attracted a lot of potential tourism trips. Therefore, the recurrent congestion occurs regularly during holiday and weekend.

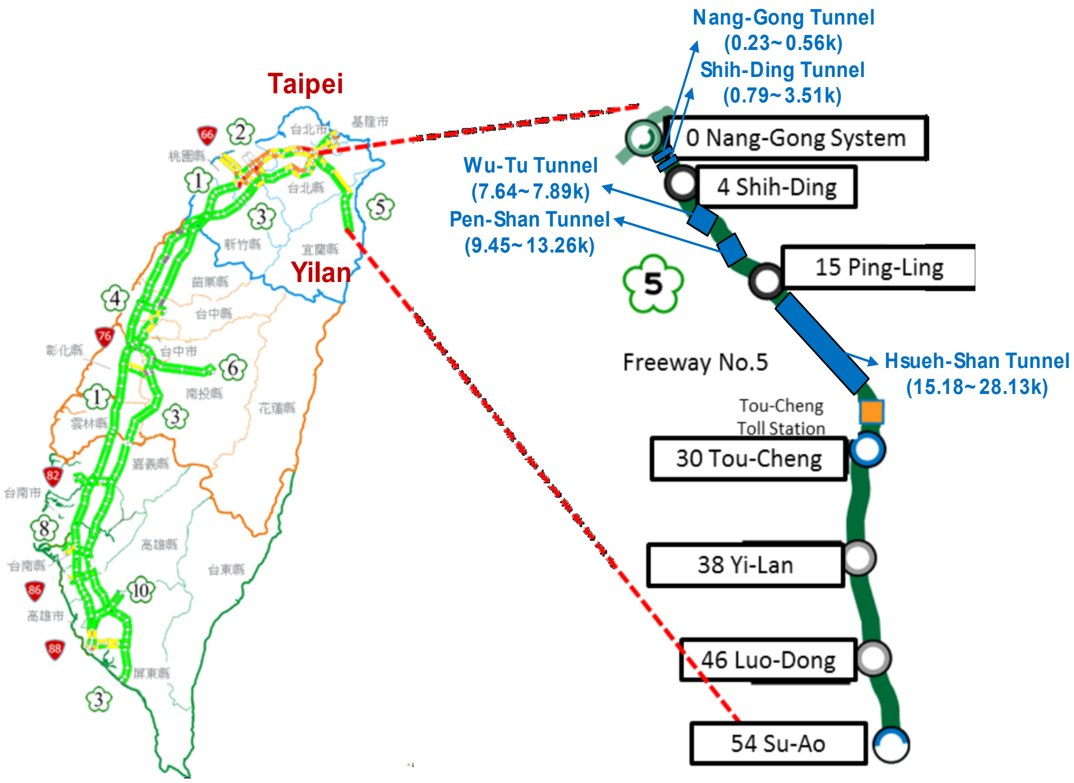

Figure 2. Location of National Freeway No.5

2.2 Traffic Flow Analyses

After collecting one month of traffic flow data on Freeway No.5, we found the average speed is over 70kph on weekdays whether southbound or northbound, but on weekend there occurred regularly congestion and average speed less than 40kph. The southbound recurrent congestion usually happens from 9 a.m. to 12 p.m. on Saturdays. The northbound recurrent congestion is more serious and usually happens in front of the Hsueh-Shan tunnel from noon to midnight on Sundays. The bottleneck capacity is 1,600 vehicles per hour per lane which is less than normal freeway capacity. For instance, as shown in Figure 3, the time-space distribution of speed under congestion situation on one Sunday is plotted to grasp the overall traffic congestion situation at National Freeway No.5. The congestion could be found from about 35k to 20k in front of long tunnel Hsueh-Shan Tunnel. Transition time from non-congestion to congestion situation is very short. The traffic flow has the catastrophe phenomenon significantly during congestion period. The speed changed rapidly in the steepness slope of space-time diagram of speed. Within just a few minutes, speed dropped from 70kph (non-congestion) down to less than 30kph (congestion).

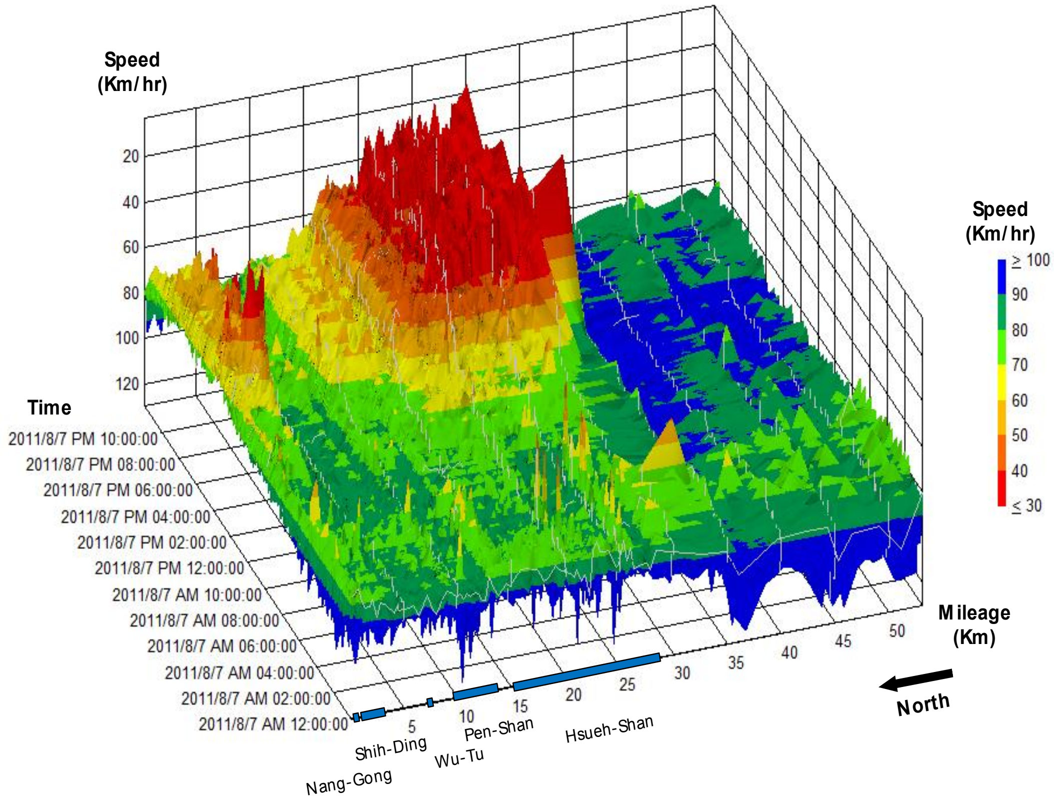

Figure 3. Time-space distribution of speed on National Freeway No.5

There are four interchanges before the congestion bottleneck in front of the Hsueh-Shan long tunnel. All the entrance traffic on-ramp will pass through the Hsueh-Shan Tunnel towards Taipei Capital City communicatively. For mitigating the congestion approaching to tunnel, one of the strategies is to control the four on-ramps coordinately with more effective metering method. Therefore, in this paper, a ramp metering model using Fuzzy Logic Control is developed and compare with performance using the conventional traffic response model adopted in the past in this area.

3. MODEL OF FUZZY LOGIC CONTROL

3.1 Linguistic Variables Fuzzification

There are 7 input variables for FLC control logic selected to create ramp metering rate (MR) in terms of the traffic flow characteristics, which are upstream speed (US), upstream occupancy (UO), local speed (LS), local occupancy (LO), downstream speed (DS), downstream occupancy (DO) and on-ramp occupancy (OO). Figure 4 shows the layout of detector locations.

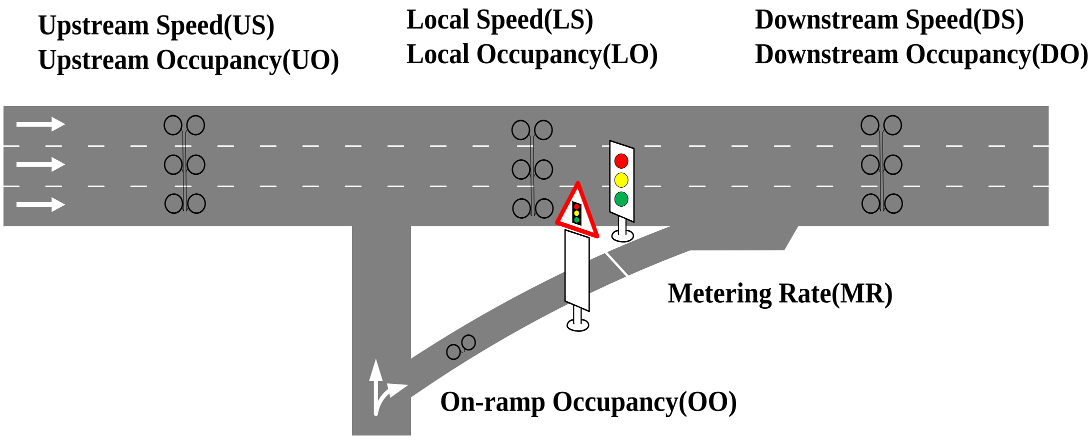

Figure 4. Layout of detector locations for FLC ramp metering model

Membership function usually is defined as triangles, trapezoids or bell-shaped curves. Triangles fuzzy number is used in this paper. Figure 5 illustrates the preset fuzzy membership function for translating each variable into a set of fuzzy classes, which are very low (VL), low (L), medium (M), high (H) and very high (VH). The range of each class is determined by real traffic data distribution. The degree of activation indicates how true that class is on a scale between 0 and 1 like a probability distribution. IF the fuzzy class is VL, membership can be calculated by Eq. (1). If the fuzzy class is L, M or H, membership can be calculated by Eq. (2). Similarly, if the fuzzy class is VH, membership can be calculated by Eq. (3).

$$f_i(x)=\begin{cases}1 & \text{for } x<0\\ -\dfrac{1}{\beta_i}\left[x-\beta_i\right] & \text{for } 0<x<\beta_i\\ 0 & \text{else}\end{cases} \tag{1}$$

$$f_i(x)=\begin{cases}1 & \text{for } x=C_i\\ \dfrac{1}{\beta_i}\left[x-\left(C_i-\beta_i\right)\right] & \text{for } C_i-\beta_i<x<C_i\\ -\dfrac{1}{\beta_i}\left[x-\left(C_i+\beta_i\right)\right] & \text{for } C_i<x<C_i+\beta_i\\ 0 & \text{else}\end{cases} \tag{2}$$

$$f_i(x)=\begin{cases}1 & \text{for } x<0\\ \dfrac{1}{\beta_i}\left[x-\left(1-\beta_i\right)\right] & \text{for } 1\text{-}\beta_i<x<1\\ 0 & \text{else}\end{cases} \tag{3}$$

Where,

x :the variable value,

C_i :the centroid of i^{th} fuzzy class, and

β_i :the base width of i^{th} fuzzy class.

For instance, if the upstream speed were 45 kph, the VL class would be activated to a degree of 0.2, and the L class would be activated to a degree of 0. Besides, the range of the each class can be different. The best percentage of overlap between classes specifies application class. The threshold percentage recommended is between 25 percent overlap and 75 percent overlap (Taylor, 1998).

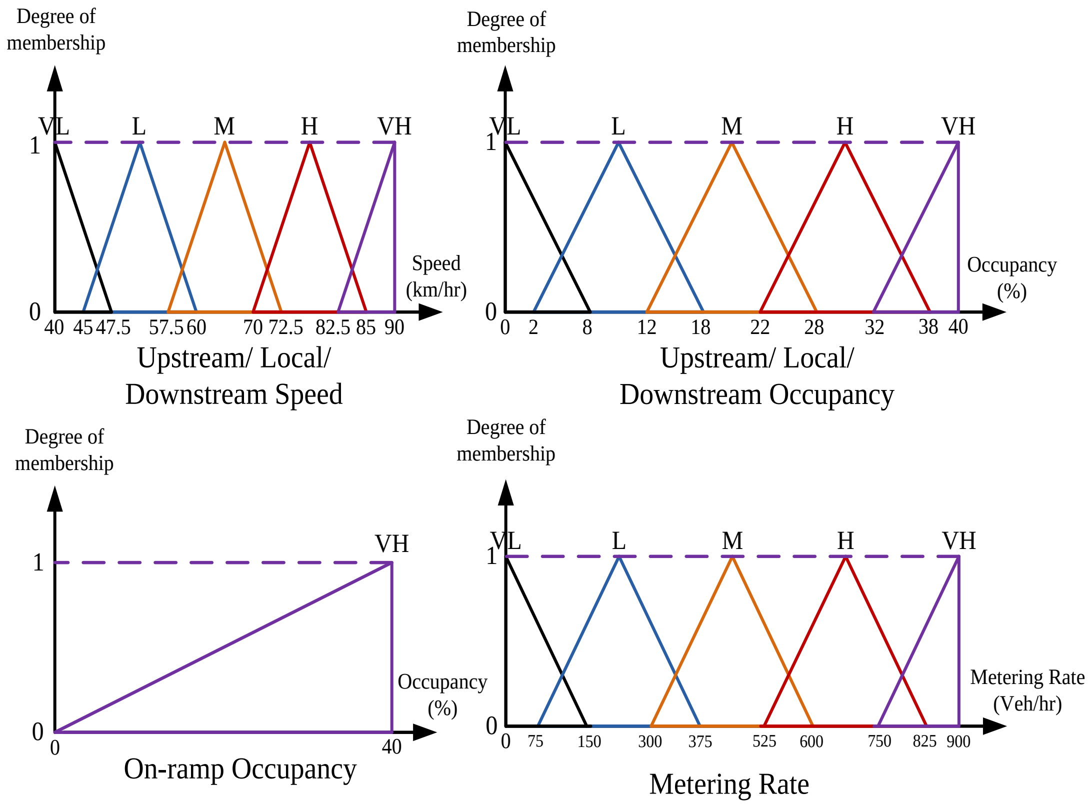

Figure 5. The membership functions of traffic variables for FLC model

3.2 Rule Base

The rules are expressed in the form of IF variable IS property THEN action. The operators are used to connect the relationship of different variables. The operators are AND, OR, and NOT. The operators are usually defined as the minimum, maximum, and complement. Their formulas are as follows:

$$\mu_{A\cap B}(y)=\min\{\mu_{A}(x_1),\ \mu_{B}(x_2)\}$$

(4)

$$\mu_{A\cup B}(y)=\max\{\mu_{A}(x_1),\ \mu_{B}(x_2)\}$$

(5)

$$\mu_{A}c(y)=1-\mu_{A}(y)$$

(6)

The rule base is the core of the FLC metering model. There are 18 reasonable rules generated in this paper, as shown in Table 1. For example, from Rule 9 to Rule 17 are set for preventing increase of traffic volume at downstream bottleneck. Rule 18 is designed to prevent queue formation under considering the fair between main lane and on-ramp.

Table 1 Rule base for FLC metering control

Rule	Premise	Outcome
1	IF US is M AND UO is M	THEN MR is M
2	IF US is H AND UO is L	THEN MR is H
3	IF US is VH AND UO is VL	THEN MR is VH
4	IF LS is VL AND LO is VH	THEN MR is VL
5	IF LS is L AND LO is H	THEN MR is L
6	IF LS is M AND LO is M	THEN MR is M
7	IF LS is H AND LO is L	THEN MR is H
8	IF LS is VH AND LO is VL	THEN MR is VH
9	IF DS is M	THEN MR is M
10	IF DS is L	THEN MR is L
11	IF DS is VL	THEN MR is VL
12	IF DO is M	THEN MR is M
13	IF DO is H	THEN MR is L
14	IF DO is VH	THEN MR is VL
15	IF DS is VL AND DO is VH	THEN MR is VL
16	IF DS is L AND DO is H	THEN MR is L
17	IF DS is M AND DO is M	THEN MR is M
18	IF OO is VH	THEN MR is VH

For instance, if the downstream speed is 13 kph and downstream occupancy is 46 percent. The rule 10 and 11 are used to create metering rate, as shown in Figure 6. In Figure 6, green line represents the activation degree of the downstream speed and blue line represents the activation degree of the downstream occupancy. Aimed at rule 15, green solid line is selected due to the AND operator and activates red area for VL class. In the same way, blue dotted line is selected by rule 10 and activates yellow area for L class. Finally, the metering rate can be computed by defuzzification process.

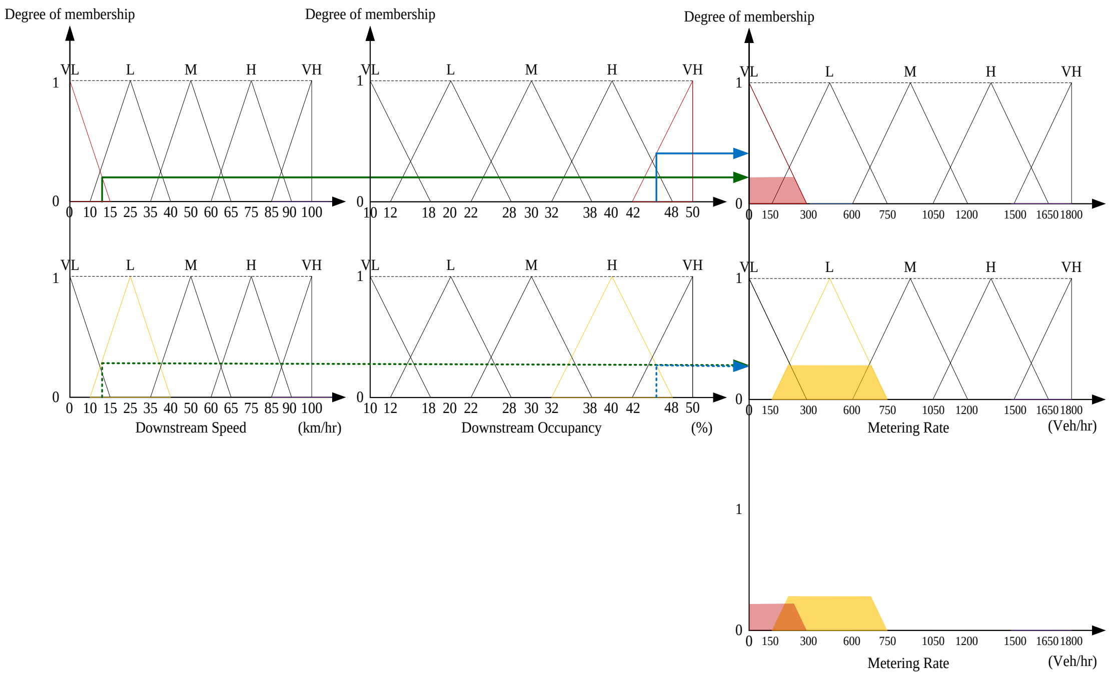

Figure 6. Rules for creating metering rate

3.3 Metering Rate Deffuzzification

Numerical metering rate is produced from all of rule outcomes in the last step of FLC metering control. The reverse process from a set of linguistic variables to a single metering rate has different methods, such as maximum-membership method, weighted average method, center of gravity method and area method. The area method is used in this paper, and the formula is as following:

$$Metering\ Rate = \frac{\sum_{i=1}^{N} C_i \times I_i}{\sum_{i=1}^{N} I_i} \tag{7}$$

Where,

C_i :the medium of the i^{th} class, and

I_i :the implicated area of the i^{th} class.

IF the fuzzy class is VL, the implicated area can be calculated by Eq. (8). If the fuzzy class is L, M or H, the implicated area can be calculated by Eq. (9). Similarly, if the fuzzy class is VH, the implicated area can be calculated by Eq. (10).

$$I_i = D_{i2} \times f_i + \frac{(\beta_i - D_{i2}) \times f_i}{2} \tag{8}$$
$$D_{i2} = f_i \times -\beta_i + \beta_i$$

$$I_i = \frac{\left[\left(D_{i2} - D_{i1}\right) + 2\beta_i\right] \times f_i}{2}$$
$$D_{i1} = f_i \times \beta_i + (C_i - \beta_i)$$
$$D_{i2} = f_i \times -\beta_i + (C_i + \beta_i) \tag{9}$$

$$I_i = (1 - D_{i1}) \times f_i + \frac{\left(D_{i1} - (1 - \beta_i)\right) \times f_{ii}}{2}$$
$$D_{i1} = f_i \times \beta_i + (1 - \beta_i) \tag{10}$$

Where,

D_i :the upper base of the implicated area,

f_i :clear value,

C_i :the centroid of i^{th} fuzzy class, and

β_i :the base width of i^{th} fuzzy class.

4. COMPARATIVE ANALYSIS USING SIMULATION

4.1 Design of Simulation

The simulation software, VISSIM, is utilized to conduct the simulation network including of 7 interchanges from Suao to Nangang on the northbound Freeway No.5. The data from northbound vehicle detectors were adapted from 11 a.m. to 3 p.m. on August 7th, 2011. Some simulation input data can be obtained from these vehicle detectors including of vehicle input per 5 minutes, the ratio of straight to off-ramp per 5 minutes and desired speed for different sections. Besides, according to the user manual of VISSIM, the suitable parameters for driving behavior model of Wiedemann 99 are chosen to simulate the traffic flow on freeway traffic through a validation procedure. Others parameters are selected from the default value. In the end, VisVAP software is used to set up ramp metering controllers for different ramp metering algorithms at the end of the on-ramp.

After conducting the simulation, the flow rates of different locations are validated between the actual value and simulation value. The results show the MAPE are all less than 10%. Hence, the simulation network is trusted to be able to simulate the real traffic situation.

4.2 Performance Comparative Evaluation

The simulation time is 7200 seconds, including warm-up time of 3600 seconds. The resulted data is the average by running 3 times using various random seeds. The variation of results under different random number seeds is proven very small, and that means the simulation reliability is enough acceptable.

The bottleneck, Hsueh-Shan tunnel, is after Toucheng interchange on the northbound Freeway No.5. These four interchanges are expected to relieve the congestion including of

Toucheng, Yilan, Luodong and Suao. As shown in Table 2, the throughputs of different sections under the LTR control have not much change comparing with no control. On the contrary, under the FLC control, the metering rates of Toucheng and Yilan interchanges are lower, and the metering rates of Luodong and Suao interchanges are relaxed. Although the total throughputs are similar, the FLC control logics are going to create better traffic performances, as shown in Table 3 and Table 4. Using LTR, the average speed and average travel time have not different with the performances of no control. On the other hand, under the FLC control, average speed is increasing and average travel time is decreasing on the entire freeway sections, except the last section closing the Hsueh-Shan Tunnel from Toucheng to Pingling, due to the tightened metering rate at this ramp for preventing the congestion cumulating at the point and releasing more metering rates for upstream ramps to get higher traffic performance of entire freeway section. Figure 7 presents the overall traffic condition under different control by time-space diagram of speed. As shown in this figure, the FLC can obviously reduce congestion area and can improve the traffic performance approaching the tunnel.

In fact, LTR control uses upstream flow to calculate the metering rate is not sensitive when the bottleneck is at the downstream. It is worth mentioning, FLC control can exchange part metering rate between different ramps for getting better traffic performance of whole network and allocate these metering rates on different on-ramps suitably.

Table 2 Comparison of throughput under different controls

Throughput (veh/hr)	Suao to Pingling	Luodong to Pingling	Yilan to Pingling	Toucheng to Pingling
No control	291	605	602	683
LTR	288 (-1.0%)	600 (-0.8%)	602 (0.0%)	681 (-0.3%)
FLC	358 (23.0%)	749 (23.8%)	515 (-14.5%)	463 (-32.2%)

Table 3 Comparison of average speed under different controls

Average speed (km/hr)	Suao to Pingling	Luodong to Pingling	Yilan to Pingling	Toucheng to Pingling
No control	63.7	56.9	47.9	41.2
LTR	64.0 (0.5%)	56.9 (0.0%)	48.0 (0.2%)	40.6 (-1.5%)
FLC	71.4 (12.1%)	64.3 (13.2%)	51.2 (6.8%)	40.1 (-2.6%)

Table 4 Comparison of average travel time under different controls

Average travel time (sec/km/veh)	Suao to Pingling	Luodong to Pingling	Yilan to Pingling	Toucheng to Pingling
No control	56.5	63.3	75.1	87.4
LTR	56.2 (-0.5%)	63.3 (0.0%)	74.9 (-0.2%)	88.7 (1.5%)
FLC	50.4 (-10.8%)	55.9 (-11.6%)	70.3 (-6.4%)	89.7 (2.7%)

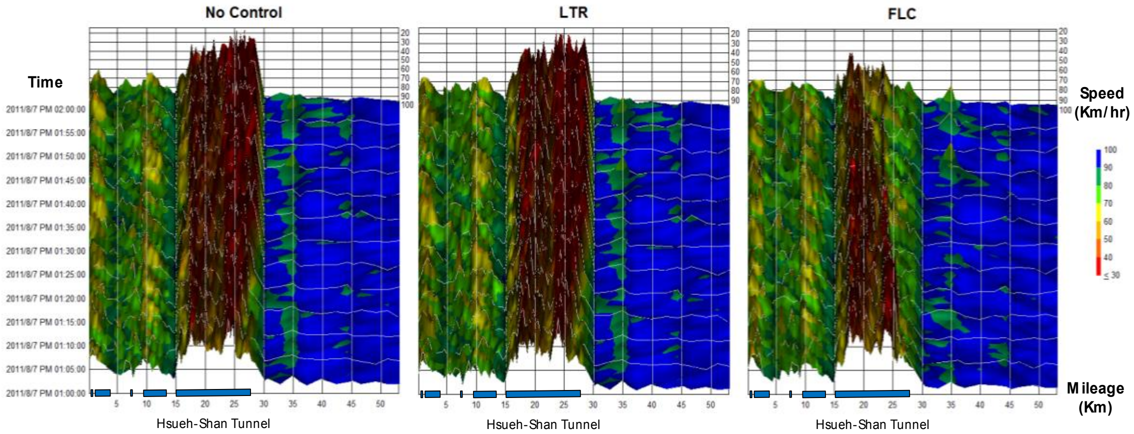

Figure 7. Speed time-space distributions under different ramp metering controls

5. CONCLUSION AND SUGGESTION

In this paper, fuzzy logical algorithm is adopted to establish FLC ramp metering control model. Through application using the real case of freeway and by comparing the performance, we can assure that the FLC model can really mitigate the traffic congestion near interchange and has better performance than the no control and LTR control. This FLC ramp metering model is then expected to be implemented in practice in the near future.

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