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Fuzzy Logic Based Adaptive Cruise Control with Guaranteed String Stability

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Abstract: Recently, many topics in intelligent transportation system (ITS) are researched. One of the topics is adaptive cruise control (ACC). The adaptive cruise control systems should be designed such that string stability can be guaranteed in addition to that every vehicle in a string of ACC vehicles which use the same control law must track any bounded acceleration and velocity of its preceding vehicle with a bounded spacing and velocity error. The purpose of this paper is to design fuzzy logic based ACC which guarantees string stability. The feature of this controller is adaptation to a target speed and speed reduction to keep a safe distance from preceding vehicle and also guarantees string stability. This controller controls throttle angle and brake pressure. The performance of this controller has been investigated through computer simulation using Carsim of Mechanical Simulation Corporation. The results show that the proposed controller can guarantee safe time gap and string stability satisfactorily.

Keywords: Adaptive Cruise Control, Fuzzy Control, Intelligent Transportation System (ITS), Longitudinal Control

1. INTRODUCTION

Adaptive cruise control (ACC) has been introduced to provide significantly enhanced driver convenience and reduced workload as a driver assistance system. When there is not a preceding vehicle is in sight, ACC system controls velocity of the vehicle to follow target velocity. When there is a preceding vehicle in sight, ACC system reduces the velocity and keeps a safe distance from preceding vehicle. So this is the reason that it is called ‘adaptive’. Fuzzy controllers are expert systems based on if – then rules. So, fuzzy controller can be useful to design ACC system. There are several researches about fuzzy logic based ACC. R. Holve and P. Protzel researched about acceleration control of ACC using fuzzy logic [2]. José E. Naranjo, Carlos González, Jesús Reviejo, Ricardo García, and Teresa de Pedro proposed go and stop ACC based on throttle and brake fuzzy control [5][7]. H.M. Kim, Julie Dickerson and Bart Kosko also proposed fuzzy logic based throttle and brake controller for platoons [3].

When the preceding vehicle accelerates or decelerates the range error is expected to be non-zero. The range error would propagate from vehicle to vehicle in a string of ACC vehicles which use the same control law. Thus, string stability is guaranteed. String stability of a string of ACC vehicles refers to a property in which range errors are guaranteed not to amplify as they propagate towards the tail of the string. Therefore, string stability should be considered importantly. So, string stability problem is important subject of research about ACC. There are several researches about string stability. Caudill, R. J. and Garrard, W. L. has been studied about string stability problem as early as 1977 [1]. Chi-Ying Liang and Huei Peng, studied ‘optimal adaptive cruise control with guaranteed string stability [4]. Jing Zhou and Huei Peng, studied about flow stability and string stability [6]. Despite there were several researches about string stability, many of the prototype ACC vehicles were still designed without considering string stability. And, although there have been researches about fuzzy logic based ACC, researches about string stability of fuzzy logic based ACC have been not conducted. This paper proposes fuzzy logic based ACC with guaranteed string stability and evaluates ACC using Carsim of Mechanical Simulation Corporation

2. FUZZY LOGIC BASED ACC DESIGN

2-1 Fuzzy ACC System

Range policy for proposed fuzzy logic based ACC is adopted as a constant time headway policy. The desired inter-vehicular range by constant time headway is as follows.

$$R_{Desired} = A + T \cdot V \tag{1}$$

A : The separation distance
T : The time head way
V : The host vehicle speed(Pursuing vehicle speed)

The proposed ACC design is divided into two. These are ACC controller design and throttle/brake controller. The ACC controller is based on fuzzy logic and determines desired acceleration for host vehicle. The throttle/brake controller determines throttle input

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and brake input corresponding desired acceleration for host vehicle obtained ACC controller. The separation distance is set as 2m and the time head way is set 2 second for this research.

The proposed ACC system is as follows.

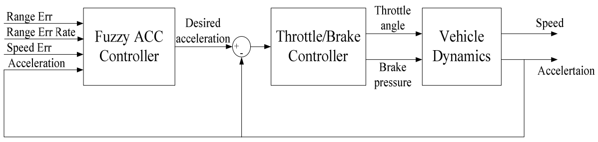

Fig. 1 Fuzzy logic based ACC system

Considering condition of real driving, brake controller and throttle controller are designed not to work simultaneously, because brake and throttle do not work actually at the same time.

Input variables for fuzzy ACC controller are range error, range error rate, speed error and acceleration. The output is desired acceleration. Range error and range error rate are as follows.

$$e_i = x_{i-1} - x_i - R_{i\_desired} \quad \text{(Range Error)} \qquad (2)$$

$$\dot{e}_i = V_{i-1} - V_i \quad \text{(Range Error Rate)} \qquad (3)$$

2-2 Fuzzy Rule Base for ACC

There are 14 rules for the proposed fuzzy logic based ACC controller. The rules are as follows.

RULE1: IF *Range_Err* **is** *Negative* **and** *Range Err Rate* **is** *Negative* **and** *Speed_Err* **is** *Negative,*
THAN *Desired Acceleration* **is** *Negative Big*
RULE2: IF *Range_Err* **is** *Zero* **and** *Range Err Rate* **is** *Negative* **and** *Speed_Err* **is** *Negative,*
THAN *Desired Acceleration* **is** *Negative Small*
RULE3: IF *Range_Err* **is** *Negative* **and** *Range Err Rate* **is** *Zero* **and** *Speed_Err* **is** *Negative,*
THAN *Desired Acceleration* **is** *Negative Small*
RULE4: IF *Range_Err* **is** *Zero* **and** *Range Err Rate* **is** *Zero* **and** *Speed_Err* **is** *Negative,*
THAN *Desired Acceleration* **is** *Zero*
RULE5: IF *Range_Err* **is** *Positive* **and** *Range Err Rate* **is** *Zero* **and** *Speed_Err* **is** *Negative,*
THAN *Desired Acceleration* **is** *Positive Small*
RULE6: IF *Range_Err* **is** *Zero* **and** *Range Err Rate* **is** *Positive* **and** *Speed_Err* **is** *Negative,*
THAN *Desired Acceleration* **is** *Positive Small*
RULE7: IF *Range_Err* **is** *Positive* **and** *Range Err Rate* **is** *Negative* **and** *Speed_Err* **is** *Negative,*
THAN *Desired Acceleration* **is** *Positive Big*
RULE8: IF *Speed_Err* **is** *Positive,*
THAN *Desired Acceleration* **is** *Negative Small*
RULE9: IF *Speed_Err* **is** *Positive* **and** *Range Err* **is** *Positive,*
THAN *Desired Acceleration* **is** *Positive Small*
RULE10: IF *Acceleration* **is** *Negative Big,*
THAN *Desired Acceleration* **is** *Positive Big*
RULE11: IF *Acceleration* **is** *Negative Small,*
THAN *Desired Acceleration* **is** *Positive Small*
RULE12: IF *Acceleration* **is** *Zero,*
THAN *Desired Acceleration* **is** *Zero*
RULE13: IF *Acceleration* **is** *Positive Small,*
THAN *Desired Acceleration* **is** *Negative Small*
RULE14: IF *Acceleration* **is** *Positive Big,*
THAN *Desired Acceleration* **is** *Negative Big*

The rules from Rule1 to Rule7 are used for adaptive cruise control mode. Rule8 and Rule9 are used for cruise control mode. The rules from Rule10 to Rule14 are used for reducing oscillations of throttle and brake inputs.

Membership functions for input variables and output variable for fuzzy ACC controller are as follows.

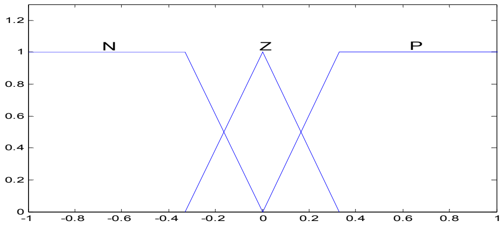

Fig. 2 Membership functions for Range Error

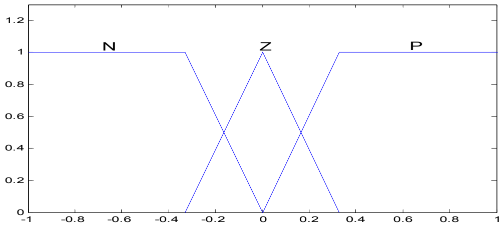

Fig. 3 Membership functions for Range Error Rate

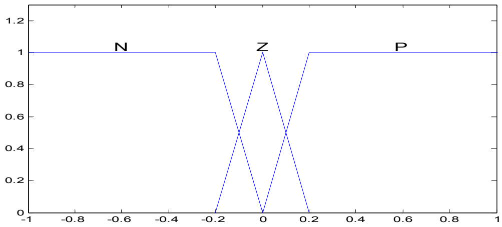

Fig. 4 Membership functions for Speed Error

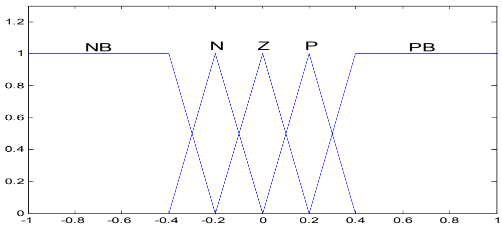

Fig. 5 Membership functions for Acceleration

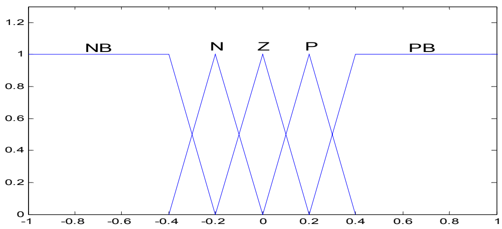

Fig. 6 Membership functions for Desired Acceleration

3. STRING STABILITY

When the preceding vehicle moves at constant velocity, the range error should converge to zero. But, the range error is expected to be non-zero during acceleration or deceleration of the preceding vehicle. The string stability of a string of ACC vehicles refers to a property in which range errors are guaranteed not to amplify as they propagate towards the tail of the string. The following figure shows string of ACC.

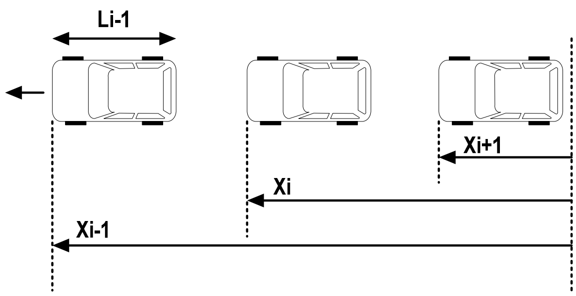

Fig. 7 String of adaptive cruise control vehicles

String stability has to be guaranteed for safe driving in the ACC control. The string stability problem has been studied since the late 1970s. This property ensures that the variation of preceding vehicle speed will not result in amplified fluctuations in the following vehicle speed. Generally, to analyze string stability, a propagation transfer function is used. The propagation transfer function is defined as follows.

$$G(s) = \frac{e_i}{e_{i-1}} \tag{4}$$

e_i is range error of i_th vehicle in the string.

e_{i-1} is range error of i-1_th vehicle in the string.

If the magnitude inequality $\|G(s)\| < 1$ must hold for all frequencies, string stability is ensured. This means that range error is reduced. In this research, string stability is analyzed through simulation about the string of five vehicles.

4. SIMULATION RESULTS

For this research, simulations using Carsim were conducted. First of all, simulations for adaptive cruise control and cruise control mode were conducted in the condition containing 'go and stop' situation. Next, to analyze string stability the string of five vehicles were simulated.

4-1 Simulations for ACC and CC

Simulations about two vehicles were conducted to evaluate whether following vehicle can follow preceding vehicle satisfactorily. Preceding vehicle speed is as follows.

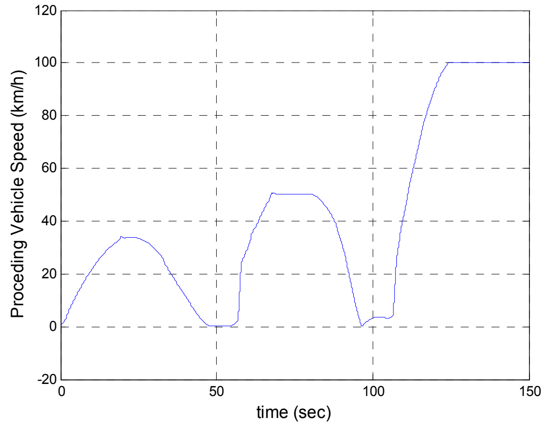

Fig. 8 Preceding Vehicle Speed

The preceding vehicle is driven in 'stop and go' situation until near 100 second. After 100 second, the preceding vehicle is accelerated to 100km/h. It is expected that first, the following vehicle is driven in adaptive cruise control mode and is converted into cruise control mode when the preceding vehicle speed exceeds target speed for cruise control. This is appropriate simulation scenario to evaluate a performance of ACC and CC.

Following figure shows the following vehicle speed as simulation result of the simulation scenario.

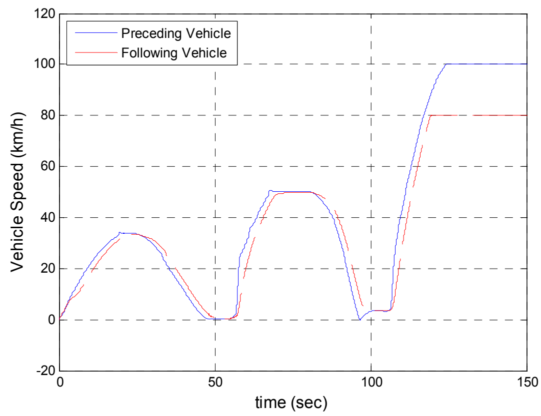

Fig. 9 Following Vehicle and Preceding Vehicle Speed

Above figure shows that the proposed fuzzy controller works satisfactorily for adaptive cruise control and cruise control. First, the following vehicle follows the preceding vehicle well through range adaptation by ACC controller. Also, above figure shows that ACC mode is converted into CC mode at about 120 second.

Following figure shows range error of the following vehicle in the simulation scenario.

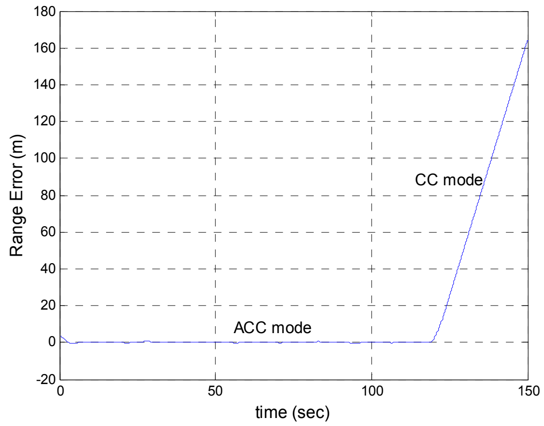

Fig. 10 Range error of following vehicle

Range error is held near almost zero in ACC mode. After about 120 second, range error is increased. This means that after about 120 second, ACC mode is converted into CC mode.

Throttle and brake input by proposed fuzzy ACC controller and acceleration of following vehicle are as follows.

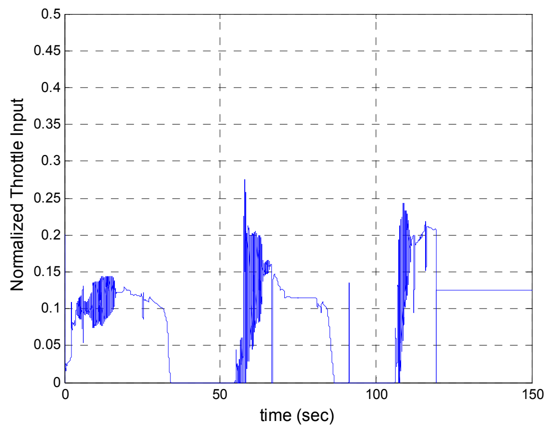

Fig. 11 Normalized throttle input of following vehicle

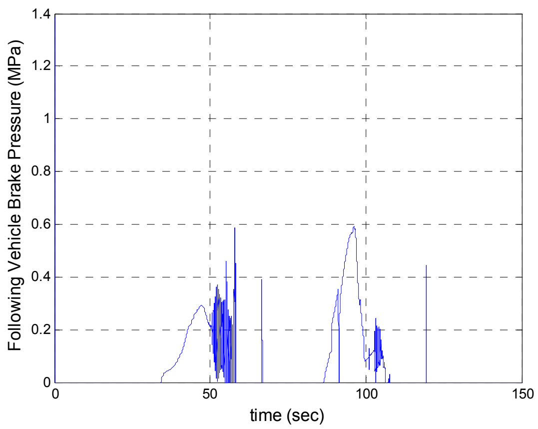

Fig. 12 Brake pressure of following vehicle

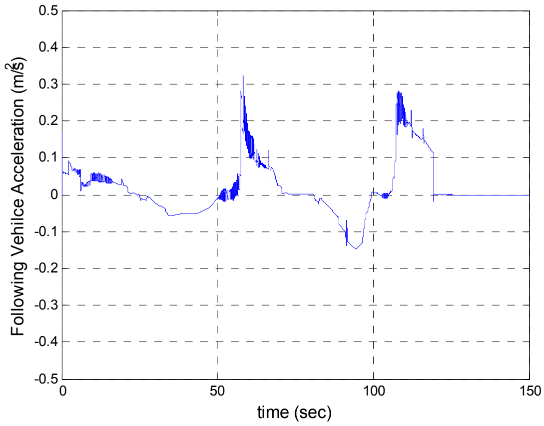

Fig. 13 Acceleration of following vehicle

Throttle input, brake input and acceleration of following vehicle have some oscillations. It is acceptable because of slow response characteristic of a vehicle. But improvement for these oscillations is demanded.

4-2 Simulations for string stability analysis

The string of five vehicles was simulated for string stability analysis. And keeping safe range of five vehicles is considered. Following figure shows speed of vehicles in the string as simulation results.

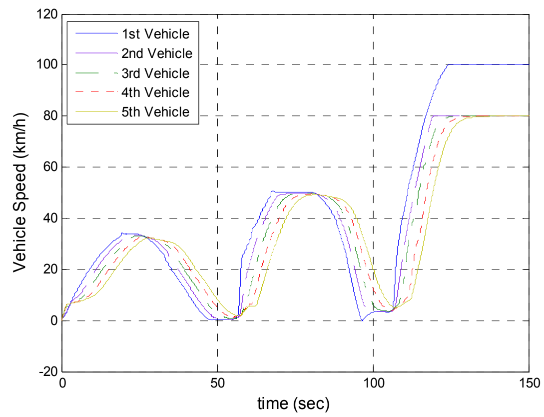

Fig. 14 Speed of five vehicles string

Above figure shows that five vehicles follow a preceding vehicle nicely. All vehicles are driven as ACC mode in go and stop situation and are also driven as CC mode when a preceding vehicle speed exceeds target speed for cruise control. It means guarantee of string stability, indirectly. Also, position of five vehicles is considered as well as speed.

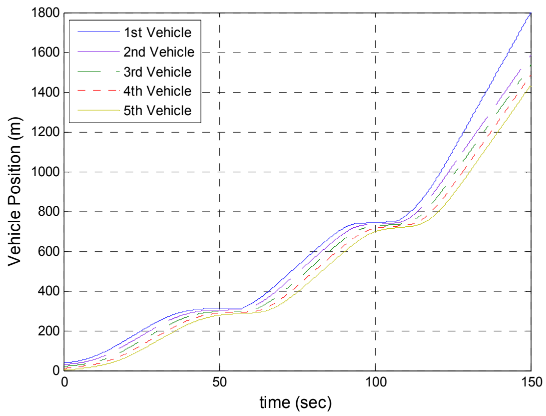

Fig. 15 Position of five vehicles string

Through above figure, it is known that five vehicles follow preceding vehicle by keeping safe range. Above figure shows that i-1_th vehicle always precedes i_th vehicle.

Through these analyses, it is supposed that the proposed fuzzy ACC controller guarantees string stability. Consideration of range error of five vehicles in the string makes analysis about string stability more surely.

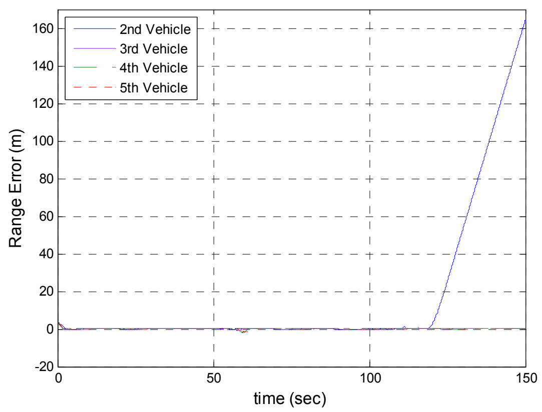

Fig. 16 Range error of 5 vehicles string

Above figure shows that range error of all vehicles is kept near zero. This means that all vehicles in the string are driven nicely for adaptive cruise control and cruise control under control of proposed fuzzy ACC controller. These simulation results explain guarantee of string stability.

The propagation transfer function is defined as range error of preceding vehicle over range error of host vehicle, namely e_i / e_{i-1}. If the magnitude of the propagation transfer function is smaller than 1, string stability is ensured. It means that range error of following vehicle must be always smaller than range error of preceding vehicles. Therefore, plots of range error about all vehicles are considered. Following figure is the plot of range error.

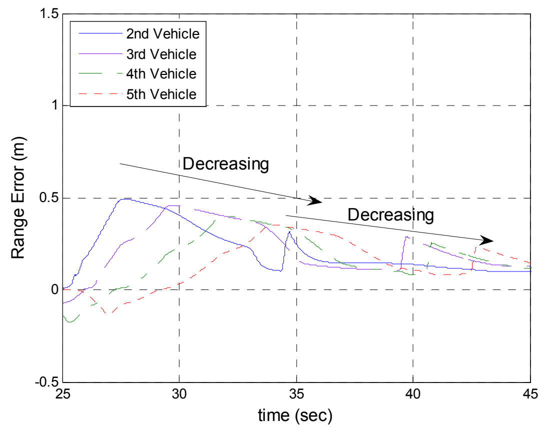

Fig. 17 Range Error of 5 vehicles

Range error of second vehicle, which is first vehicle controlled by ACC controller, is propagated to range error of third vehicle. And range error of third vehicle is propagated to fourth vehicle, again. This procedure is repeated. Consequently, range error of a vehicle effects range error of all vehicles behind. Through Fig. 17, range error can be considered. Because range error grows smaller and smaller, it can be thought that string stability is guaranteed. In other words, range error of following vehicle is always smaller than range error of preceding vehicle and it shows that string stability is guaranteed.

5. CONCLUSION

This paper proposes fuzzy controller for adaptive cruise control and its performance is evaluated by simulations using Carsim. Simulations are conducted in the driving condition containing ‘go and stop’ situations and high speed driving to evaluate adaptive cruise control and cruise control. Simulation results show that a following vehicle follows a preceding vehicle nicely by keeping safe range in ACC driving mode. It means that proposed ACC controller works as ACC controller satisfactorily. Also, the vehicle controlled by proposed fuzzy ACC controller keeps target speed very well in CC driving mode. It is found that throttle and brake input by the proposed fuzzy logic based adaptive cruise controller fluctuate in the some area, as simulation results. Although it is acceptable because of slow response characteristic of a vehicle, improvement for oscillations of throttle and brake input is demanded as future works.

Also string stability is analyzed by simulation about the string of five vehicles. Simulation results show that all vehicles in the string are controlled by proposed fuzzy ACC controller, nicely. And through consideration of the magnitude of range error of preceding vehicle and range error of following vehicle, string stability is analyzed. Simulation results shows that proposed fuzzy logic based adaptive cruise controller guarantees string stability. But it does not guarantee string stability for infinite string. Therefore, more analytic method is demanded for evaluating string stability of fuzzy ACC controller as future works.

Higher performance of proposed fuzzy ACC controller is expected by tuning of width and center point of membership functions and scaling factor. The tuning by evolutionary computation, such as genetic algorithms, is expected as future works.

REFERENCES

[1] Caudill, R. J. and Garrard, W. L. “Vehicle Follower Longitudinal Control for Automated Transit Vehicles, J. of Dynamic Systems, Measurement, and Control, pp. 241-248, December, 1977

[2] R. Holve and P. Protzel, “Generating Fuzzy Rules for the Acceleration Control of an Adaptive Cruise Control System” NAFIPS, Biennial Conference of the North American, pp415-455, June 1996

[3] Hyun Mun Kim, Julie Dickerson and Bart Kosko, “ Fuzzy throttle and brake control for platoons of smart cars”, Fuzzy Sets and Systems, 1996 209-234

[4] Chi-Ying Liang and Huei Peng, “Optimal Adaptive Cruise Control with Guaranteed String Stability”, Vehicle System Dynamics, pp.313–330, 1999

[5] José E. Naranjo, Carlos González, Jesús Reviejo, Ricardo García, and Teresa de Pedro, “Adaptive Fuzzy Control for Inter-Vehicle Gap Keeping”, IEEE Transaction on Intelligent Transportation Systems, Vol. 4, No. 3, pp 132-142, September 2003

[6] Jing Zhou and Huei Peng, “Range Policy of Adaptive Cruise Control for Improved Flow Stability and String Stability”, IEEE Transaction on Intelligent Transportation Systems, Vol. 6, No. 2, June 2005

[7] José E. Naranjo, Carlos González, Ricardo García, and Teresa de Pedro, “ACC+Stop&Go Maneuvers With Throttle and Brake Fuzzy Control”, IEEE Transaction on Intelligent Transportation Systems, Vol. 7, No. 2, pp 213-225, June 2006

[8] Hidehisa Yoshida1 , Shinichi Awano, Masao Nagai and Takayoshi Kamada, “Target Following Brake Control for Collision Avoidance Assist of Active Interface Vehicle”, SICE-ICASE International Joint Conference 2006, Busan, Korea

[9] Jooho Park, Donghyun Sung and Woon-Sung Lee, “A Driving Simulator Study on Adaptive Cruise Control Failure”, SICE-ICASE International Joint Conference 2006, Busan, Korea