The 2009 IEEE/RSJ International Conference on
Intelligent Robots and Systems
October 11-15, 2009 St. Louis, USA

Improvement of Adaptive Cruise Control System based on Speed Characteristics and Time Headway

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***Abstract*—An adaptive cruise control (ACC) which was implemented on an AIT Intelligent Vehicle, a Mitsubishi Galant car, has been improved and added with more features to allow the vehicle to act with better performance compared with the previous system. An important feature of the new adaptive cruise control system is the ability to maintain a proper inter-vehicle gap based on the speed of leading vehicle and time headway (THW). To develop adaptive cruise control system, the conventional throttle valve system is modified to the drive-by-wire system which uses a DC motor to control the throttle valve position based on PD control with command compensation. In the automatic braking system, a DC motor is installed with steel cable transmission in order to pull the brake pedal to the desired level automatically by applying torque control. The brake control and velocity control have been merged together to control the speed to any desired speeds as fast as possible without jerk and steady-state error. A micro switch is installed at the brake pedal to allow the driver to take over the control of the vehicle anytime. There are three important inputs of the ACC system, speed of leading vehicle read from electronic control unit (ECU), THW set by driver, and actual gap measured from a laser scanner. The ACC processes these three inputs in order to calculate distance error and relative velocity which are used as the two inputs of a fuzzy controller. The fuzzy controller determines the desired speed command to maintain a proper gap based on current speed of the leading vehicle and the desired time headway. Experiments are conducted to evaluate the performance of the ACC system in various conditions. The results show good performance of the adaptive cruise control system.**

I. INTRODUCTION

Cruise control system has been developed to assist the driver for driving in long distance on highway. At congested traffic, the conventional cruise control system becomes less useful. Adaptive cruise control (ACC) system is developed to cope up with this situation. The conventional cruise control has one mode of control, velocity control. On the other hand, ACC has two modes of control, velocity and distance control. ACC assists driver in the congested traffic by acting as a longitudinal control pilot. ACC can work like the conventional cruise control for maintaining the vehicle preset speed. Unlike the cruise control, ACC can automatically adjust velocity in order to maintain a proper distance between leading vehicle and the host vehicle equipped with ACC. Laser or radar is used in ACC to measure the relative distance between the host vehicle and the leading vehicle. The throttle valve and braking pedal of the host vehicle are manipulated to control the vehicle speed so as to maintain a safe inter-vehicle gap based on time headway and speed of the leading vehicle. When the roadway ahead is clear or the leading vehicle changes to other lane, the vehicle with ACC automatically changes to the desired preset speed again.

In this research, an ACC system is developed on the AIT intelligent vehicle, Mitsubishi Galant. The authors design and implement fuzzy controller on the developed ACC system. The two inputs of the fuzzy controller are distance error and relative velocity calculated from three inputs; speed of leading vehicle read from electronic control unit (ECU), time headway assigned from driver, and gap distance to leading vehicle measured from the laser scanner, SICK, LMS 291. Output of the controller is either braking command or velocity command depending on the current distance error and relative velocity.

II. MECHANISM AND HARDWARE

New mechanisms, hardware, and sensors are designed, developed and installed on the AIT intelligent vehicle. They are described in this section.

A. AIT intelligent vehicle

The intelligent vehicle is developed on Mitsubishi Galant GLSi, 1993 as shown in Fig.1. This vehicle has a 2.0 liter, gasoline engine, with automatic transmission.

Fig.1. AIT intelligent vehicle, Mitsubishi Galant GLXi, 1993

B. Automatic braking system

To automatically control the braking system, a DC motor is used. The motor mounted on motor mounting plate is connected with braking pedal via a pulley by a steel cable as shown in Fig.2. When the motor rotates, the brake pedal is pulled down.

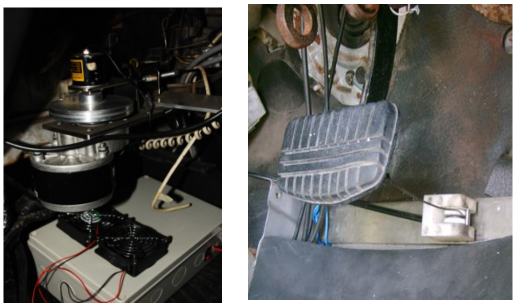

(a) (b)

Fig.2. Automatic braking system (a) DC motor installed in the vehicle. (b) brake pedal connected with steel cable

C. *Brake Switch*

A micro switch is installed at brake pedal as shown in Fig.3 in order to allow the driver to take control the vehicle anytime. When the brake pedal in ACC mode is pushed by the driver, the system switches to manual mode in order to allow the driver to control brake pedal and accelerator pedal. The system is switched to ACC mode again when the driver selects ACC mode.

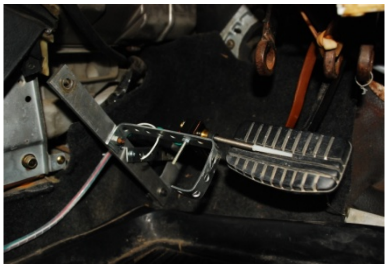


Fig.3. Micro switch at brake pedal

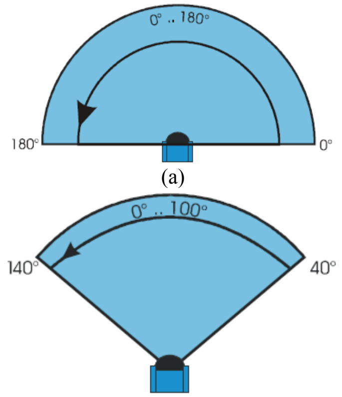
D. *Throttle valve control system*

The original throttle valve system is changed to a drive-by-wire system for the ACC system. A 12V DC motor is installed to control the throttle valve position. A potentiometer is installed at accelerator pedal to measure the pedal level in manual mode. The drive-by-wire controller implemented on ARM7 microcontroller reads the required throttle position from the voltage level of the potentiometer in manual mode or from the command of ACC system in automatic mode. Fig.4 shows the drive-by-wire throttle valve system.


Fig.4. Drive-by-wire throttle valve system

E. *Leading vehicle detecting sensor*

The leading vehicle detecting sensor used in the ACC system is a laser scanner, SICK LMS 291. The sensor is installed at the front bumper of the vehicle. This sensor measures the distance based on a time-of-flight principle. A single laser pulse is emitted and reflected by an object which is within the operation range of the sensor. The elapsed time between emission and reception of the laser pulse is used to calculate the distance to the object. The range of measurement can be set to 100° or 180° as shown in Fig.5.



(a)

(b)

Fig.5. Measurement range (a) range 0° - 180° (b) range 0° - 100°

III. CONTROL ALGORITHM

A. *Throttle valve position control*

Block diagram of the throttle valve position control is shown in Fig.6. The inner loop is the velocity control loop, while the outer loop is the position control loop. The sampling time of the control loop is 2 ms controlled by ARM7 microcontroller. Digital low-pass filter with 20 Hz cutoff frequency is used to remove noises from the velocity signal.

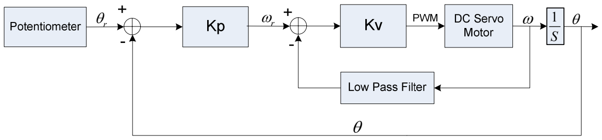


Fig.6. Throttle valve position control block diagram

With position control, the motor is driven by the control signal which is proportional to the amount of position error and velocity error, as expressed in Equations (1) and (2).

$$Output_P = K_P\left(\theta - \theta_r\right) \tag{1}$$

$$Output_V = K_V\left(\omega - \omega_r\right) \tag{2}$$

B. *Brake level control*

Torque control is proposed to control the brake level. Torque mode in Microspeed Plus Servo Amplifier which is used as a motor driver board is selected. Fig.7 shows the block diagram of the automatic braking system using torque control.

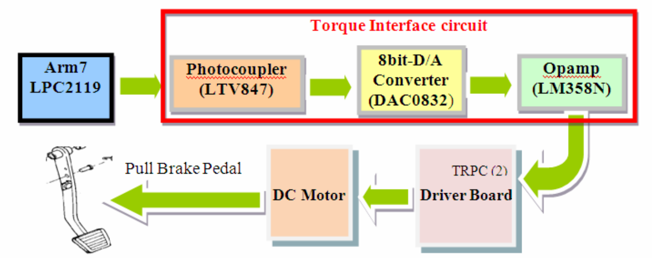


Fig.7. Automatic braking system block diagram using torque control

The required torque of the brake motor is sent from ARM7 microprocessor to the motor driver in voltage to control the level of braking.

C. Adaptive cruise control

ACC has two modes of operation according to the situation. The first mode is velocity control mode which is operated when there is no leading vehicle in front of the host vehicle or when the leading vehicle runs at the speed faster than the preset speed of the host vehicle. The other mode is distance control mode which is operated when the host vehicle finds a leading vehicle running slower than the preset speed.

In the velocity control mode, the vehicle velocity is controlled by proportional and derivative (PD) control algorithm with command compensation on ARM 7 microcontroller. The control signal of the PD control is described by Equation (3).

$$Output_{PD} = K_P e + K_D \frac{de}{dt} \qquad (3)$$

There are two levels of control in the distance control mode, low and high levels. In the low level, ARM7 microcontroller controls throttle valve and brake system according to the desired speed command obtained from the high level. In the high level, fuzzy controller is used to determine the desired speed command depending on distance error and relative velocity in order to maintain a safe inter-vehicle gap. The overview of adaptive cruise control system is shown in Fig. 8.

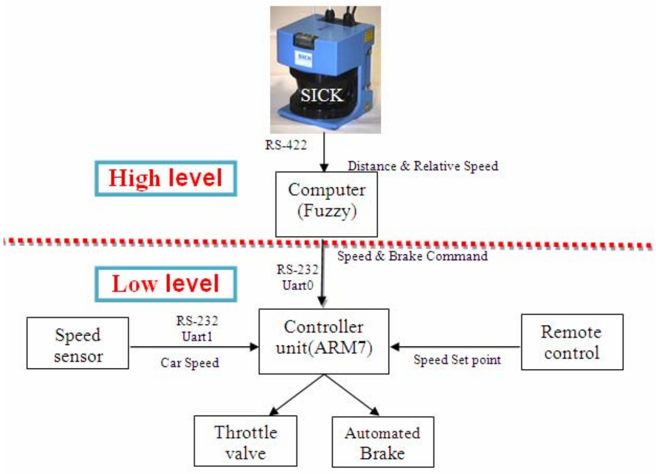


Fig.8. Overview of adaptive cruise control system

D. Low level control

In order to control the vehicle to run at the desired speed both throttle valve and brake systems are controlled. Block diagram of the low level control of ACC is shown in Fig.9.

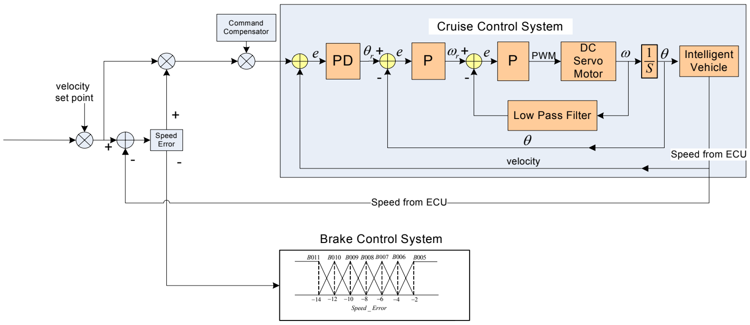


Fig.9. Block diagram of low level control of ACC

The ACC system determines whether the vehicle should be accelerated or decelerated depending on the speed error. If the system needs to accelerate, ACC sends the command to the throttle valve position controller. If the system needs to decelerate, ACC sends the command to the brake torque controller. The speed error is the difference between the desired speed and the current speed of vehicle. Flowchart of speed control in low level of ACC system is illustrated in Fig.10.

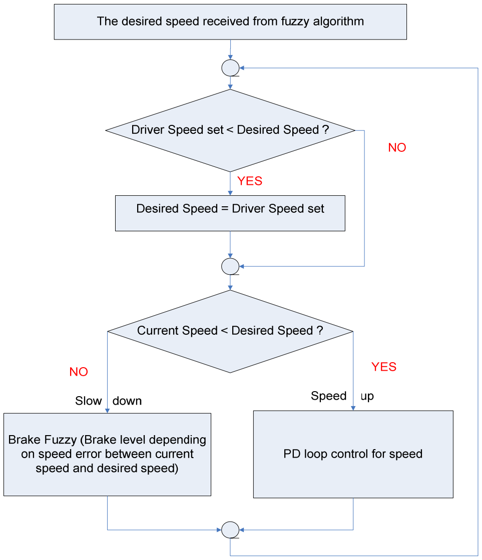


Fig.10. Flowchart of speed control in low level of ACC system

E. High level control

In this research, the inter-vehicle gap is determined based on the current speed of the leading vehicle and time headway (THW). There are three inputs for high level of ACC system; speed of the host vehicle read from electronic control unit (ECU), time headway (THW) assigned by the driver, and the current gap measured from the laser scanner. High level of ACC system processes these three inputs then determines distance error and relative velocity which are two inputs for the fuzzy controller. Fig.11 shows block diagram of the fuzzy controller used in high level of ACC system.

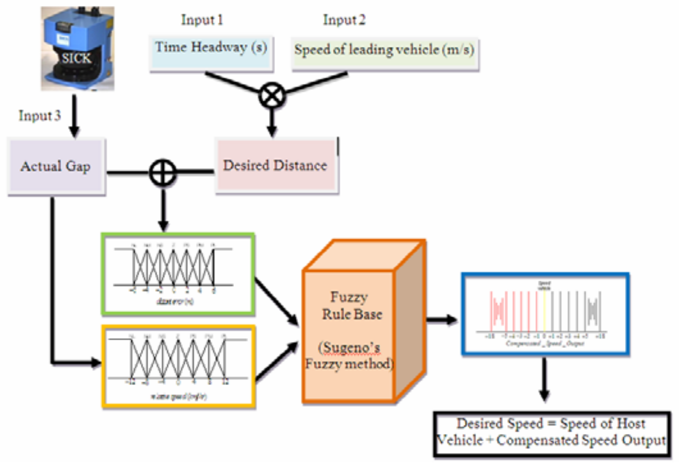


Fig.11. Fuzzy control of ACC block diagram

The desired inter-vehicle gap distance depends on the speed of leading vehicle and time headway. It is the multiplication of the speed of leading vehicle with the specified time headway according to Equation(4) and shown in Fig.12.

$$Gap = THW \text{ x } V_{leading\ car} \qquad (4)$$

where

THW : time headway
$V_{leading\ car}$: speed of leading vehicle.
Gap : inter-vehicle gap.

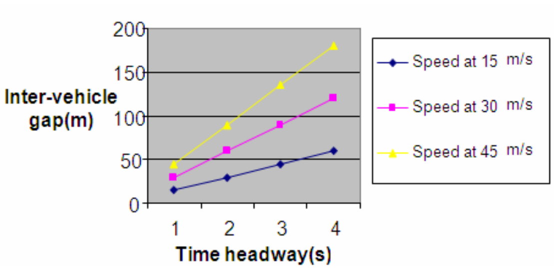


Fig.12. Relation between time headway and inter-vehicle gap at different speeds of leading vehicle.

The distance error is obtained by subtracting the desired inter-vehicle gap distance from the current gap distance between leading vehicle and host vehicle according to Equation(5). The relative velocity is the difference of the velocity of leading vehicle and the host vehicle according to Equation(6). The parameters are defined as shown in Fig. 13.

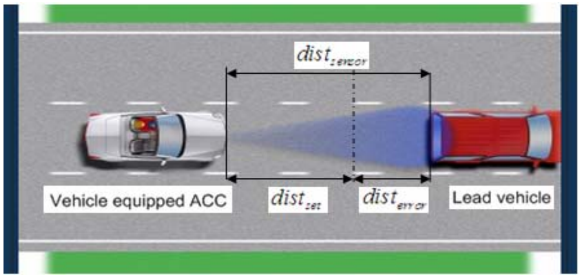


Fig.13. Definitions of parameters in ACC

$$dist_{error} = dist_{sensor} - dist_{set} \qquad (5)$$

$$relative\ speed = V_{obs} - V_{host} \qquad (6)$$

The distance error and the relative velocity are two inputs of the fuzzy controller which is the high level control of ACC system. Fuzzy controller is suitable for multi-parameters and nonlinear control problems. The triangular and trapezoidal membership functions are used in the inputs and output of the controller. Sugeno's fuzzy inference method with singleton output membership functions are used to determine the compensated speed of the host vehicle as shown in Fig.14.

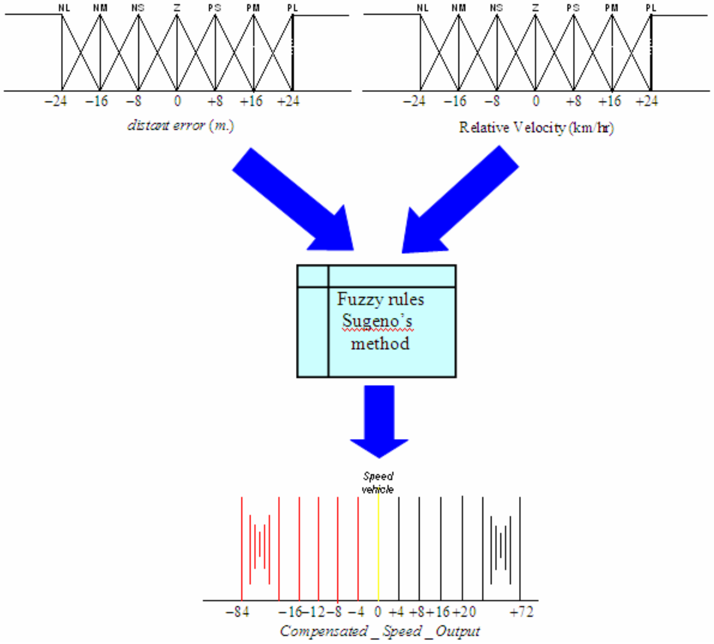


Fig.14. Fuzzy controller used in ACC system

The fuzzy inference rules of the ACC system are the collection of linguistic statements in the form of if-then statement. There are 2 inputs of the fuzzy controller and each input has 7 membership functions, there are totally 49 rules. The fuzzy inference rules as shown in Table 1 are designed based on speed characteristics that control the host vehicle to run smoothly.

Table 1 Fuzzy rules (column: distance error, row: relative velocity)

Dist err / Rel vel	NL	NM	NS	Z	PS	PM	PL
NL	-84	-64	-44	-24	-8	+8	+24
NM	-76	-56	-36	-16	0	+16	+32
NS	-68	-48	-28	-8	+8	+24	+40
Z	-60	-40	-20	0	+16	+32	+48
PS	-52	-32	-12	+8	+24	+40	+56
PM	-44	-24	-4	+16	+32	+48	+64
PL	-36	-16	+4	+24	+40	+56	+72

The values of the output in Table 1 are the compensated speed. The output of the fuzzy controller is computed from Equation (7).

$$Final\ output = \frac{\sum_{i=1}^{N} w_i z_i}{\sum_{i=1}^{N} w_i} \quad (7)$$

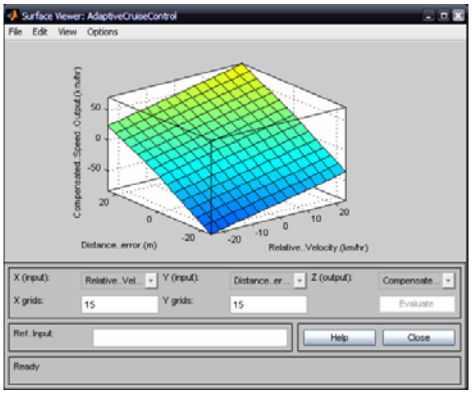
where

$Final\ output$: output of fuzzy controller

w_i : weight of membership function of output i

z_i : value of output i

The output surface obtained from the fuzzy inference rules in Table 1 is plotted and shown in fig.15.



X (input): Relative..Vel...
Y (input): Distance..er...
Z (output): Compensate...
X grids: 15
Y grids: 15
Ref. Input:
Ready

Fig.15. Output surface of fuzzy inference rules of ACC system

The desired speed is calculated from Equation (8).

$$Desired\ Speed = Current\ Speed\ of\ Host\ Vehicle + Compensated\ Speed\ Output \quad (8)$$

The desired speed command is then sent to the low level control of ACC system.

IV. EXPERIMENTAL RESULTS

A. Velocity control experiment

This experiment is conducted to evaluate the velocity control performance of the ACC system. The steady state error, transient and steady-state responses of the vehicle are determined.

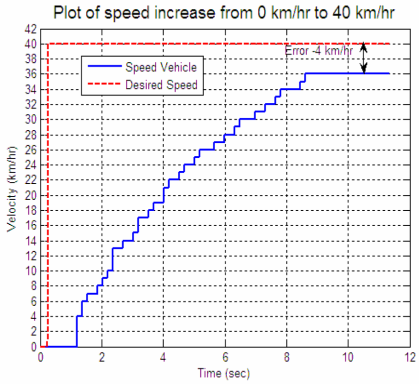


Fig.16. Velocity control performance of ACC system without command compensation

At the desired speed of 40 km/hr, the steady-state error is 4 km/hr as shown in Fig.16. Many experiments are conducted to determine the steady-state response at different desired speed commands in order to find the command compensation according to Equation (9). The results are shown in Table 2.

$$\text{Compensation} = \frac{\text{velocity}_{\text{setpoint}}}{\text{velocity}_{\text{actual}}} \quad (9)$$

Table 2 Compensation at different speed

Input range (km/hr)	Compensation
0-4	1.10
5-9	1.38
10-19	1.29
20-29	1.21
30-39	1.19
40-49	1.15
50-59	1.14

After adding command compensation of PD speed controller, the steady-state error reduces significantly as shown in Fig.17.

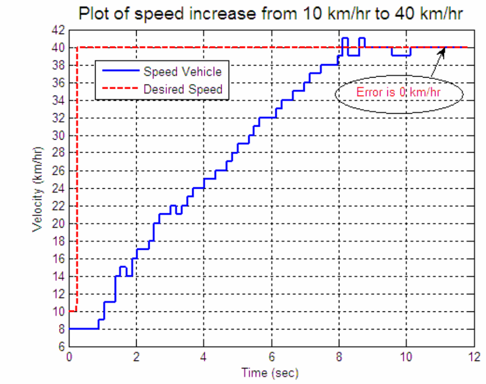


Fig.17. Velocity control performance of ACC system with command compensation

B. Distance control experiment

This experiment is conducted to evaluate distance control performance of the ACC system. The actual gap distance and the relative velocity are determined.

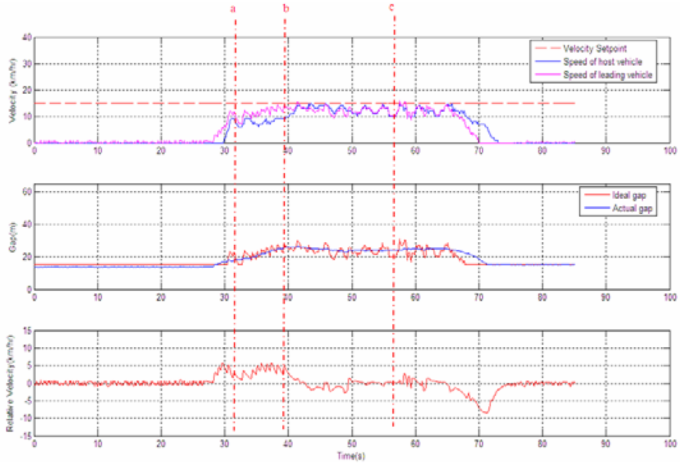


Fig.18. Experiment result: velocity setpoint = 15 km/hr and THW = 7 sec

From Fig.18 Time Headway is selected at 7 sec, the leading car accelerates during the 28th sec to 40th sec. Then the speed of the leading vehicle is maintained constantly at about 14 km/hr. The leading car decelerates until stops during the 65th to 70th sec. At time a, b and c, the desired gap distances based on the speed of the leading vehicle and THW are calculated.

At time (a) speed of the leading car = 10 km/hr;
The desired gap = (10/3.6 m/s) x (7 sec) = 19.44 m
At time (b) speed of the leading car = 14 km/hr;
The desired gap = (14/3.6 m/s) x (7 sec) = 27.22 m
At time (c) speed of the leading car = 13 km/hr;
The desired gap = (13/3.6 m/s) x (7 sec) = 25.28 m

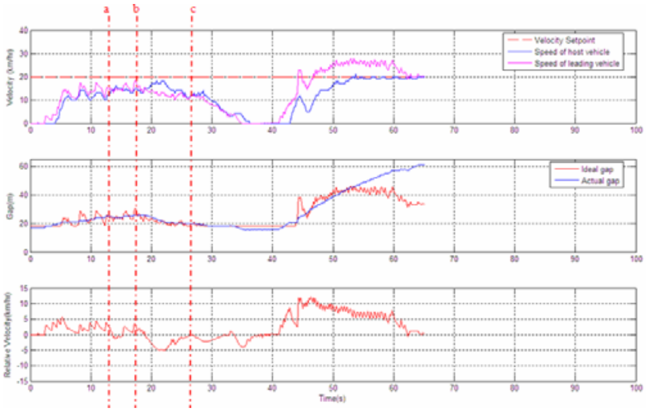


Fig.19. Experiment result: velocity setpoint = 20 km/hr and THW = 6 sec

From Fig.19 Time Headway is selected at 6 sec, the leading car accelerates at the 3rd sec. Then the speed of the leading vehicle is maintained constantly at about 15 km/hr. The leading car decelerates until stops during the 20th to 35th sec. The leading car accelerates at the 42nd sec. The velocity control mode is automatically switched when the leading car runs faster than the setpoint of 20 km/hr. At time a, b and c, the desired gap distances based on the speed of the leading vehicle and THW are calculated.

At time (a) speed of the leading car = 15 km/hr;
The desired gap = (15/3.6 m/s) x (6 sec) = 25 m
At time (b) speed of the leading car = 16 km/hr;
The desired gap = (16/3.6 m/s) x (6 sec) = 26.67 m
At time (c) speed of the leading car = 12 km/hr;
The desired gap = (12/3.6 m/s) x (6 sec) = 20 m

V. CONCLUSION

The experimental results demonstrated that the AIT intelligent vehicle was able to run at the desired velocity with small steady-state error of the velocity without causing jerk and it could also maintain the desired inter-vehicle gap distance accurately with small relative velocity. It was found that the relative velocity was larger when the leading vehicle changed the speed. It is because the inter-vehicle gap distance is higher priority when the authors designed the fuzzy inference rules. Consequently, the inter-vehicle gap distance followed the desired distance very well. Although the leading vehicle changed the speed, the ACC system could still maintain the desired gap distance precisely based on speed characteristics and Time Headway.

ACKNOWLEDGMENT

This research project is financially supported by National Electronics and Computer Technology Center.

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