Implementation and vehicle tests of a vehicle stop-and-go cruise control system

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Abstract: Implementation and vehicle tests of a vehicle longitudinal control algorithm for stop-and-go cruise control have been performed. The vehicle longitudinal control scheme consists of a set-speed control algorithm, a speed control algorithm, and a distance control algorithm. A desired acceleration for the vehicle for the control of vehicle-to-vehicle relative speed and clearance has been designed using linear quadratic optimal control theory. Performance of the control algorithm has been investigated via vehicle tests. Vehicle tests have been conducted using two test vehicles. A 2000 cm^3 passenger car equipped with a radar distance sensor, throttle/brake actuators and a controller has been used as a subject vehicle in the vehicle tests. A millimetre wave radar sensor has been used for distance measurement. A step motor and an electronic vacuum booster have been used for throttle/brake actuators. It has been shown that the implemented vehicle longitudinal control system can provide satisfactory performance in vehicle set-speed control and vehicle clearance control at lower speeds.

Keywords: vehicle longitudinal control, clearance, throttle, brake, distance control, optimal control

NOTATION

a	vehicle acceleration
a_{des}	desired acceleration
c_{act}	actual clearance
c_{d}	desired clearance
d_{offset}	offset distance
$f(\cdot)$	friction scaling function
k_1, k_2	control gain
K	gain
t_{g}	time gap
v_{c}	velocity of the subject vehicle
v_{f}	velocity of the front vehicle
v_{offset}	offset speed
v_{set}	set speed
μ	tyre–road friction coefficient

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1 INTRODUCTION

Vehicle longitudinal control for application to automated highway systems has been in progress for several decades [**1**–**3**]. Driver assistant systems have been active topics of research and development since the 1990s owing to the potential for improved driving comfort and increased vehicle safety. Driver assistant systems currently under development by most automotive manufacturers around the world and recently commercialized by several companies are adaptive cruise control (ACC) and stop-and-go (SG) cruise control systems. The goal of SG is a partial automation of the longitudinal vehicle control and the reduction of the workload of the driver with the aim of supporting and relieving the driver in a convenient manner in busy urban traffic. ACC and SG systems control both speed and distance to front vehicles and can both improve the driving comfort and reduce the danger of rear-end collisions. A vehicle with SG can follow other cars in dense traffic while keeping a safe distance in SG driving situations.

The basic requirements for realizing an SG cruise control system have been discussed by Venhovens *et al*. [**4**]. Since the bandwidth of an ACC vehicle is very low and the clearance (the vehicle-to-vehicle distance) is large, the powertrain dynamics of a vehicle have insignificant impact on the performance of the vehicle acceleration control. In the case of SG driving situations, the bandwidth of the longitudinal vehicle control system should be increased significantly to reduce the clearance and to be meaningful on the busy urban traffic highway. Since the speed ratio of the torque converter pump and turbine speeds changes significantly in the case of SG driving, the throttle/brake control laws have been designed taking into account the torque converter dynamics [**5**].

Although SG is no longer limited to the simple task of following a vehicle immediately in front of the SG vehicle, vehicle-to-vehicle clearance control is one of the key features of the SG systems. The brake and throttle controls should be gently applied so that the driver feels comfortable and is not surprised by the control actions, while the speed control error and the errors between the desired clearance and the actual vehicle-to-vehicle clearance are kept within acceptable limits. A vehicle speed and vehicle-to-vehicle distance control algorithm for a vehicle SG system has been proposed in this paper. The control algorithm consists of speed and distance control algorithms and a combined throttle/brake control law. Linear quadratic optimal control theory has been used to design a desired acceleration for the vehicle for vehicle-to-vehicle distance control. The engine throttle control law has been designed taking into account the torque converter dynamics.

2 VEHICLE LONGITUDINAL CONTROL SYSTEM AND THE TEST VEHICLE

Vehicle tests have been conducted using two test vehicles. A 2000 cm^3 passenger car equipped with a radar distance sensor, throttle/brake actuators and a controller has been used as a subject vehicle in the vehicle tests. Figure 1 shows a vehicle longitudinal control system. The system consists of a radar sensor, a controller (ECU), a brake actuator and a throttle actuator.

The test vehicle used in this study, a controller, a radar sensor, and throttle and brake actuators are shown in Fig. 2. The vehicle is equipped with a millimetre wave (MMW) radar distance sensor, a controller, a solenoid valve controlled electronic vacuum booster (EVB) and a step motor controlled throttle actuator.

3 VEHICLE LONGITUDINAL CONTROL ALGORITHM

Vehicle longitudinal control algorithms have been studied widely for applications to vehicle intelligent cruise control and automated highways in the last decade [**2**–**17**]. The vehicle control algorithm described in reference [**5**] has been extended and used in this study.

Figure 3 shows a block diagram of the vehicle longitudinal control algorithm for application to SG cruise control. The control algorithm consists of a set-speed control algorithm, a speed control algorithm, a distance control algorithm and a combined throttle/brake control law. Desired time gap and set speed are the input to the controller from the driver. If there is no vehicle in front of the subject vehicle, the controller activates throttle/brake actuators on the basis of the set-speed control algorithm. The desired acceleration has been designed using a simple proportional control so that the controlled vehicle speed tends to the set speed, v_{set}, as follows:

$$a_{des} = K(v_{set} - v_c) \tag{1}$$

where K is a gain and v_{set} is the set speed determined by the driver.

When a front vehicle is detected, the controller uses either the speed control algorithm or the distance control algorithm depending on the detected vehicle-to-vehicle distance, i.e. the clearance. If the current actual clearance, c_{act}, is greater than the transition distance which is defined as the desired clearance plus offset distance, $c_{des} + d_{offset}$, then the speed control algorithm is used.

In this case, the desired acceleration has been computed as follows:

$$a_{des} = K(v_{des} - v_{cc}) \tag{2}$$

where K is a gain, and the desired speed, v_{des}, has been defined as

$$v_{des} = v_f + v_{offset} \tag{3}$$

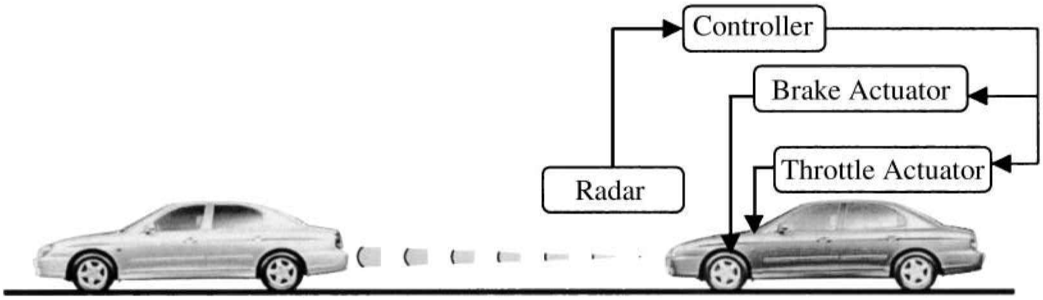

Fig. 1 Vehicle longitudinal control system

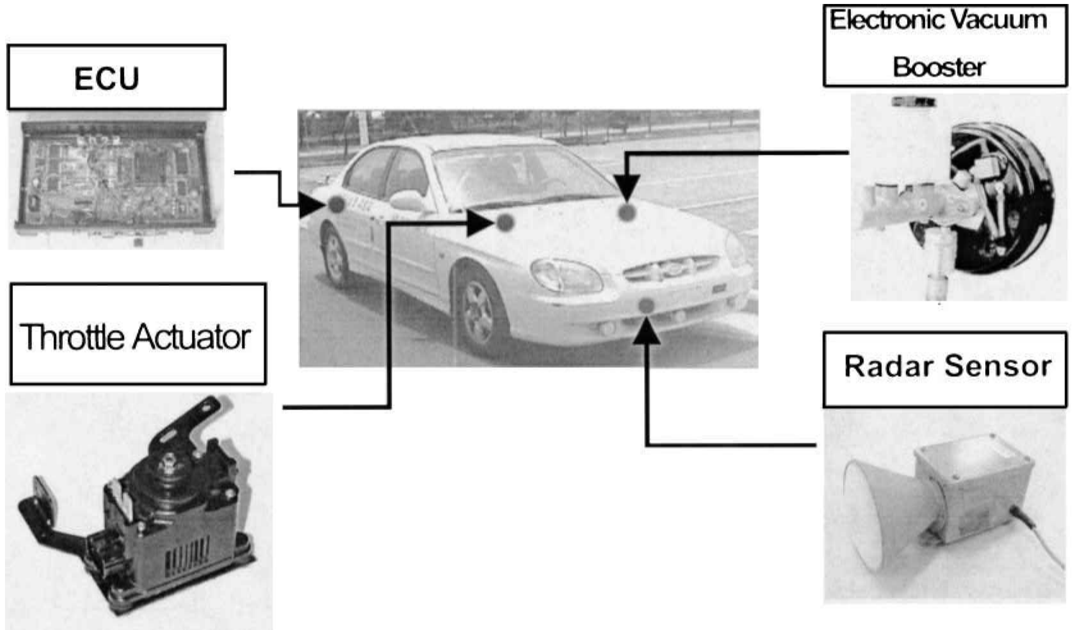

Fig. 2 Test vehicle equipped with a controller, a millimetre wave (MMW) radar sensor, a brake actuator and a throttle actuator

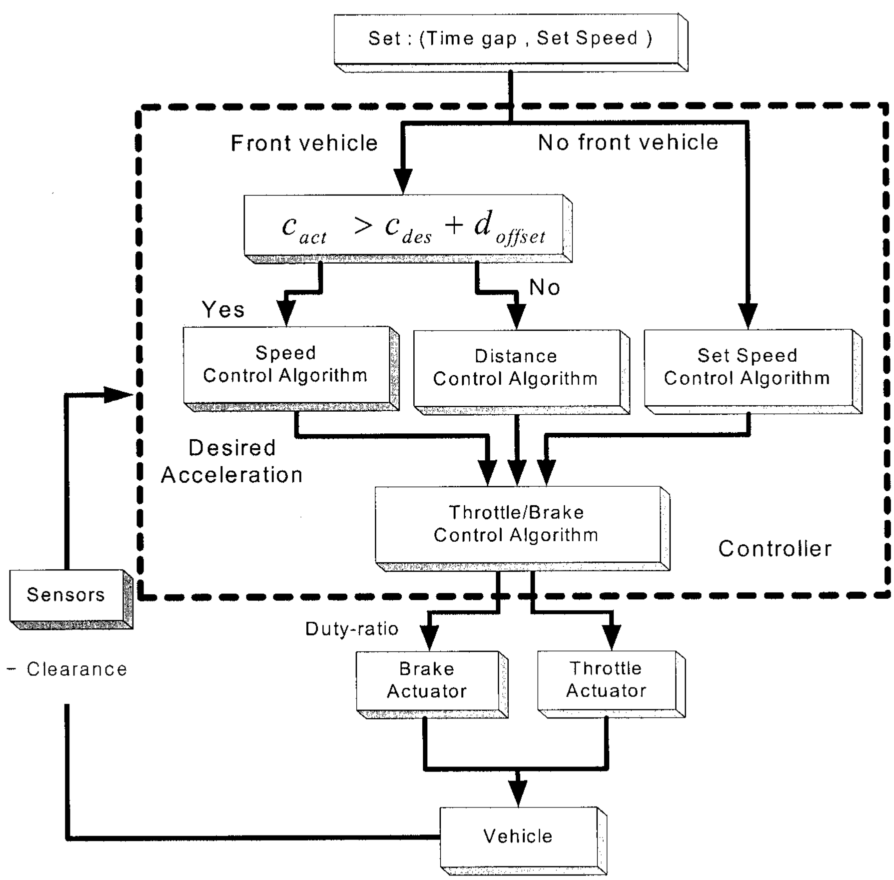

Fig. 3 Vehicle longitudinal control algorithm

In order to guarantee that the speed control mode changes to the distance control mode in a finite time, the desired speed represented in equation (3) has been used. It should be noted that, although a simple PI control without the offset speed, v_{offset}, guarantees that the controlled vehicle speed converges to the preceding vehicle speed, it does not guarantee that the relative distance becomes less than the transition distance, $c_{\text{des}} + d_{\text{offset}}$, in a finite time. v_{offset} of 5 km/h has been used in this study. The offset value has been tuned on the basis of vehicle test results. The gain K has been tuned to limit the jerk of the controlled vehicle and 0.8 has been used in this study.

The speed control algorithm is used until the clearance becomes smaller than the transition distance, and then, if the clearance is less than the transition distance, the distance control algorithm is used for the computation of the desired vehicle acceleration. In the case of the distance control algorithm, the desired acceleration has been designed on the basis of the clearance and relative speed measurements as follows:

$$a_{\text{des}} = -k_1(c_{\text{des}} - c_{\text{act}}) - k_2(v_{\text{f}} - v_{\text{c}}) \tag{4}$$

where k_1 and k_2 are the gains, c_{des} and c_{act} are the desired and relative distances between the front and controlled vehicles respectively and v indicates velocity. Subscripts, f and c, indicate the front and the controlled vehicles respectively. The gains have been chosen using optimal control theory [**5**, **14**]. In order to incorporate the effect of the tyre–road friction on the vehicle braking distance and the driving pattern of a driver into the desired clearance, c_{des}, it has been defined as follows:

$$c_{\text{des}} = f(\mu)c_0 \tag{5}$$

$$c_0 = v_{\text{f}} t_{\text{g}} + d_0 \tag{6}$$

where $f(\cdot)$ is the friction scaling function [**18**], μ the tyre–road friction coefficient, t_{g} the time gap and d_0 a clearance offset. Control inputs to the throttle/brake actuators have been determined by the throttle/brake control algorithm so that the vehicle acceleration tracks the desired acceleration as closely as possible [**5**].

4 THROTTLE AND BRAKE ACTUATORS

A stepper motor and an EVB have been used as the throttle/brake actuators [**19**]. The stepping time of this motor is 4 ms and the step angle is 0.075°. Figure 4 shows the step motor test result. The command and actual throttle angles are compared. The throttle angle has been measured using a throttle position sensor (TPS). Figure 5 shows the experimental step responses of the EVB. Measured differential pressures of the EVB for alternative constant duty inputs to the solenoid are compared in the figure. It has been indicated that the EVB has non-linear characteristics.

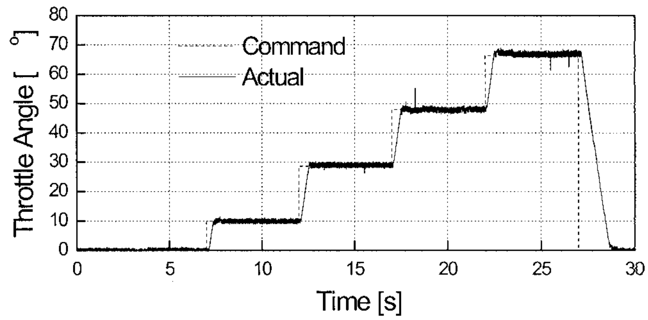

Fig. 4 Throttle actuator response

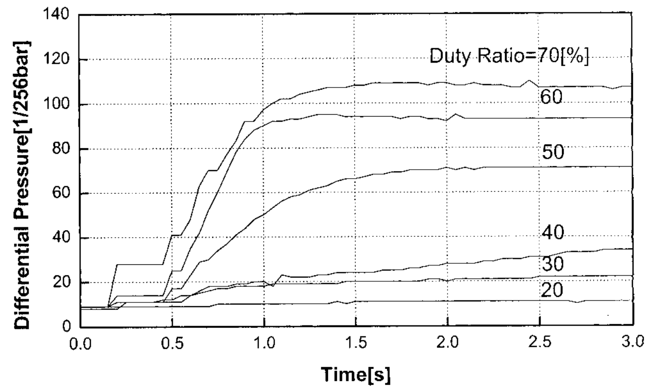

Fig. 5 Step input responses of the EVB

5 BRAKE LINE DYNAMICS

A linear first-order system model and an incompressible flow model for the brake hydraulic dynamics were presented in reference [**20**]. It has been shown that it is more accurate to represent the dynamics in the standard fashion as incompressible flow through an orifice. The differential pressure of the EVB and brake caliper pressure (wheel pressure) were measured for a constant duty input to the solenoid control valve to investigate the brake line dynamics of the test vehicle. Figure 6 shows the dynamics of the pressure at the wheel (wheel press-

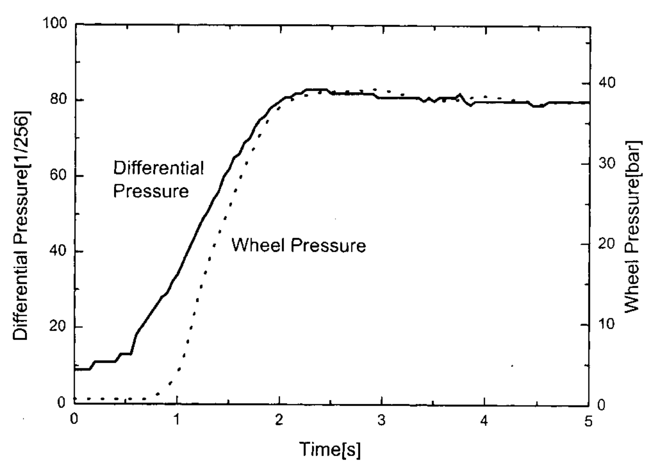

Fig. 6 Brake line dynamics

ure) relative to those of the pressure at the EVB (differential pressure).

6 VEHICLE TEST RESULTS

Vehicle tests have been conducted using a test vehicle, a 2000 cm^3 passenger car equipped with an MMW radar distance sensor, a solenoid valve controlled EVB and a step motor controlled throttle actuator and a controller. The controller was implemented using a Siemens C167 CR controller. The tests have been performed on a test track using two vehicles.

6.1 Constant speed control

In order to test the performance of the set-speed control algorithm, it has been assumed that the front vehicle drives with a constant speed of 15 km/h, the initial speed of the controlled subject vehicle is zero and the initial clearance between the vehicles is 10 m. The test results are shown in Fig. 7. A comparison of vehicle speeds is shown in Fig. 7a. Desired and actual clearances are compared in Fig. 7b. It has been indicated that the subject vehicle speed is controlled on the basis of the speed control algorithm until the clearance drops below the transition distance, and then, if the clearance is less than the transition distance, the distance control algorithm is used. A TPS has been used for the measurement of the throttle angle of the engine. The time histories of the throttle angle and differential pressure of the EVB are shown in Figs 7c and d respectively. The differential pressure sensor outputs 8-bit digital values and it shows an offset of 7 (1/256 bar). It has been noted that the offset value of the EVB differential pressure sensor ranges between 6 and 9 (1/256 bar) depending on the test conditions. It has been illustrated that the speed is controlled using only the brake and the actual vehicle speed and the actual clearance are very close to the desired ones.

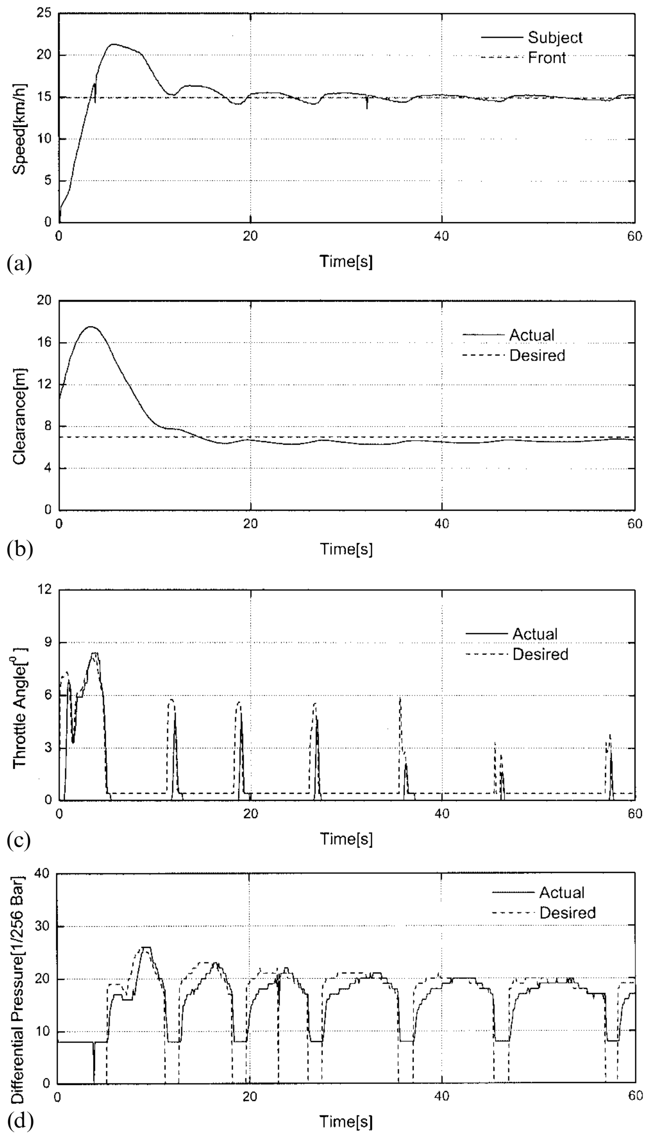

Fig. 7 Test results for constant speed control. (a) Front and subject vehicles' speeds. (b) Desired and actual clearances. (c) Desired and actual throttle angles. (d) Desired and actual differential pressures

6.2 Front vehicle following

Front vehicle following tests have been done using two vehicles: a controlled vehicle and a front vehicle. Test results are shown in Fig. 8. A comparison of vehicle speeds is shown in Fig. 8a. Desired and actual clearances are compared in Fig. 8b. Both vehicles were at rest for 3 s and the initial clearance was approximately 12.5 m. In this test, the clearance offset was set to be 5 m. The desired and actual accelerations of the controlled (subject) vehicle are compared in Fig. 8c. The desired acceleration has been computed so that the difference between the desired and actual clearances and relative speed are kept as small as possible without violating the acceleration constraint. The controller activates the throttle and brake actuators in order that the vehicle acceleration tracks the desired acceleration. It is illustrated that the vehicle acceleration tracks the desired one very closely. The time histories of the throttle angle and differential pressure of the EVB are shown in Figs 8d and e respectively. The differential pressure sensor outputs 8-bit digital values and it shows an offset of 9 (1/256 bar). As shown in Fig. 8a, the front vehicle speed varies between 0 and 20 km/h and the controlled vehicle (subject vehicle) speed is close to the front vehicle speed. It has been shown in Fig. 8b that the difference between the desired and actual clearances quickly decreases and the actual clearance is very close to the desired one after 10 s.

6.3 A cut-in test

Figure 9 shows test results for a low speed driving situation with a cut-in vehicle. In this test, the clearance

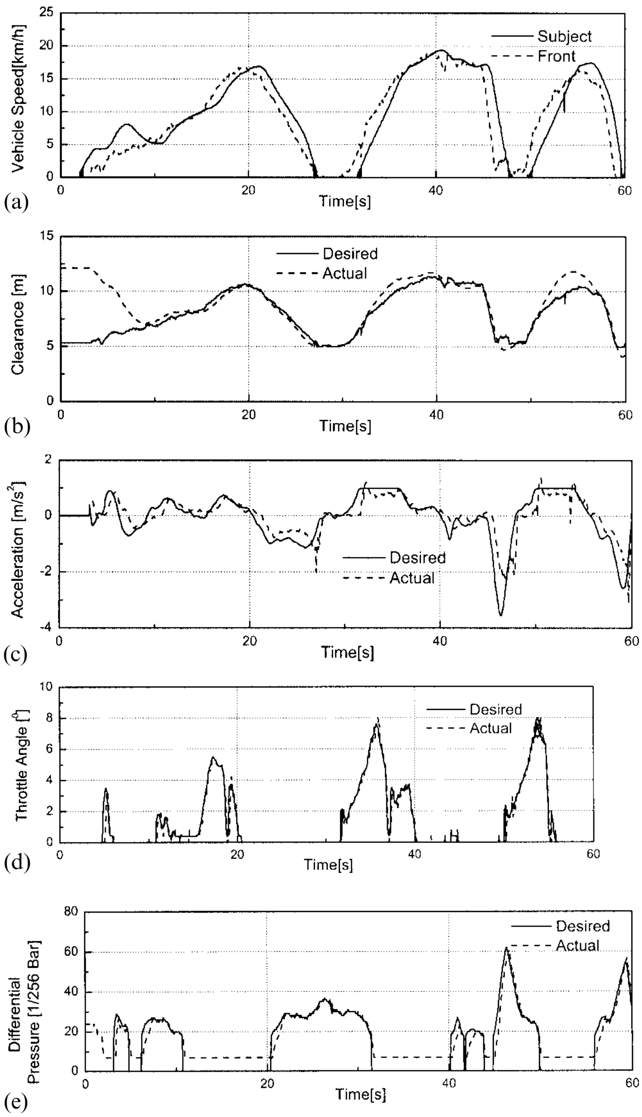

Fig. 8 Test results for a front vehicle following case. (a) Front and subject vehicles' speeds. (b) Desired and actual clearances. (c) Desired and actual vehicle accelerations. (d) Desired and actual throttle angles. (e) Desired and actual differential pressures

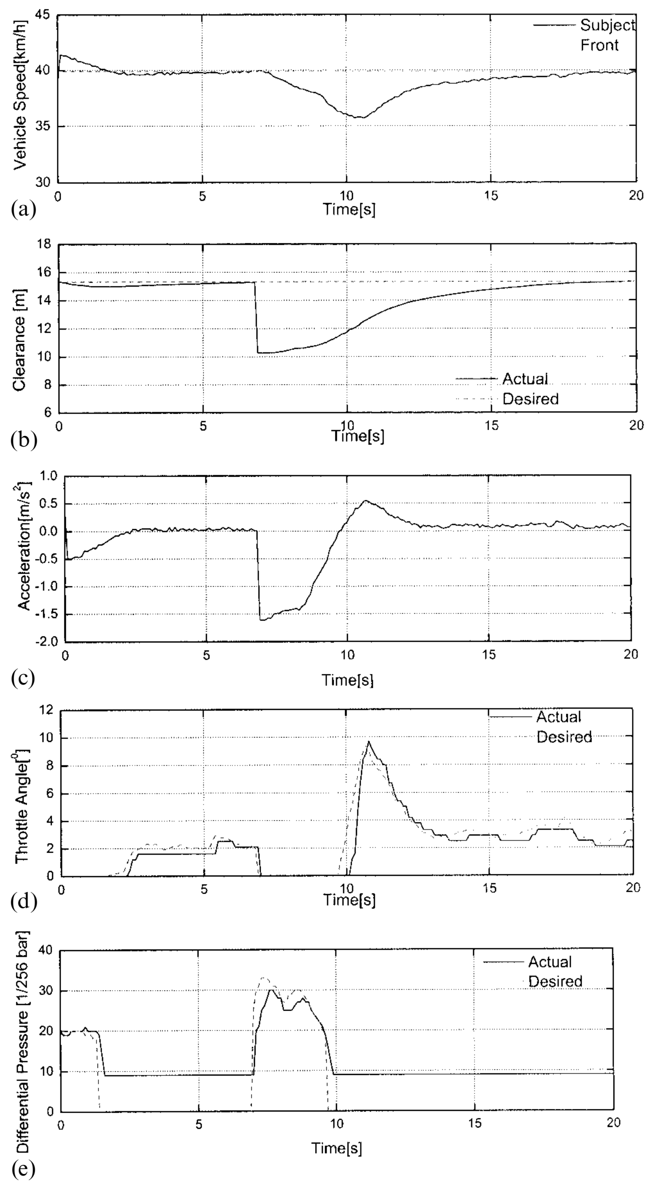

Fig. 9 Test results for a cut-in vehicle case. (a) Front and subject vehicles' speeds. (b) Desired and actual clearances. (c) Vehicle accelerations. (d) Desired and actual throttle angles. (e) Desired and actual differential pressures

offset was set to be 2 m. A time gap of 1.2 s has been used in this cut-in test. The initial vehicle speed was 40 km/h and a cut-in vehicle with a speed of 40 km/h has appeared in front of the subject vehicle at 6.5 s. The initial clearance, d_{ci}, between the subject and the cut-in vehicles was about 10 m. The vehicle speeds and clearances are compared in Figs 9a and b respectively. Vehicle accelerations are shown in Fig. 9c. The desired and actual throttle angles are shown in Fig. 9d. Comparisons of the desired and actual differential pressures of the EVB are shown in Fig. 9e. As indicated in the figures, throttle angle was set to be zero and brakes were applied at first when the cut-in vehicle appeared to reduce the vehicle speed and to increase the clearance. Then, the controller activates the throttle actuator to increase the subject vehicle speed again so that the relative velocity converges to zero. As illustrated in Figs 9a and b, the subject vehicle speed and the clearance converge smoothly to the front vehicle speed and the desired clearance respectively. The actual differential pressure of the EVB shows a sensor offset when the brake command is not applied.

6.4 Stop and go with large accelerations

An SG driving situation with large accelerations has been tested using two vehicles. The test results are shown in Fig. 10. The front vehicle accelerates until the vehicle speed increases to 30 km/h and then decelerates until it reaches full stop. The acceleration and deceleration were approximately 3.5 and -3.5 m/s^2 respectively. A comparison of vehicle speeds is shown in Fig. 10a. Desired and actual clearances are compared in Fig. 10b. Both vehicles were at rest for 3 s and the initial clearance was approximately 5 m. In this test, the clearance offset was set to be 5 m. The front vehicle's speed was computed using the Kalman filter based on the vehicle-to-vehicle distance measurement by the MMW radar sensor. The subject vehicle speed was computed from the wheel speed measurements. The negative speed of the front vehicle at 11 s in Fig. 10a is due to the measurement noise of the distance sensor. It has been illustrated that the subject vehicle stops smoothly while maintaining the actual clearance very close to the desired one.

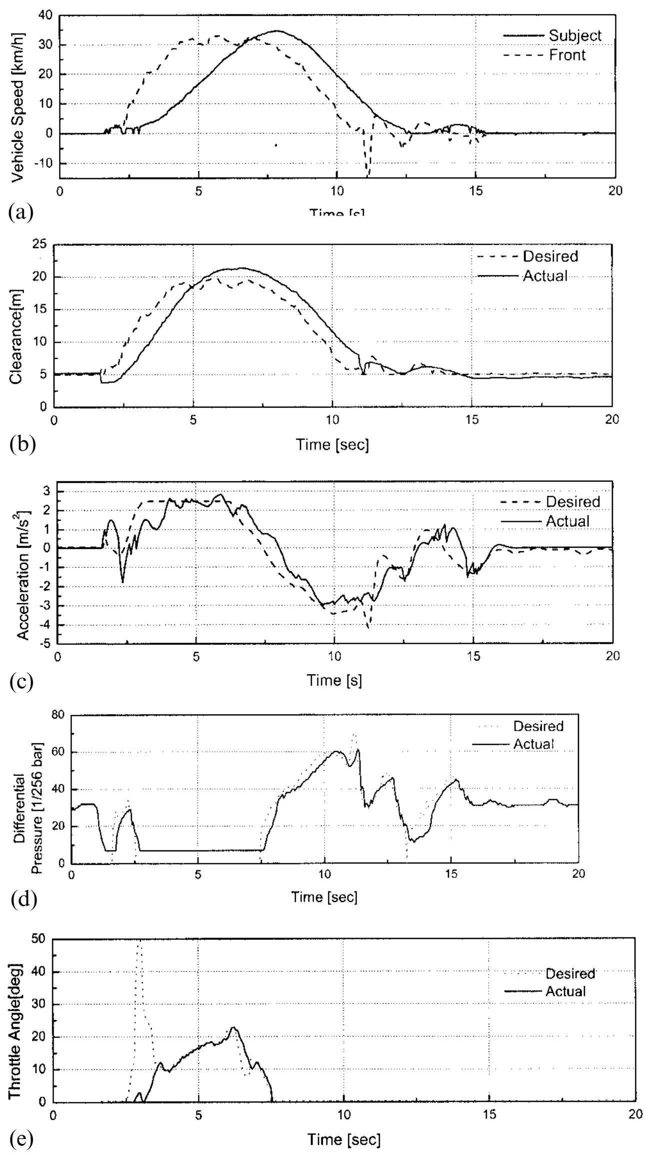

Fig. 10 Test results for SG with large accelerations. (a) Front and subject vehicles' speeds. (b) Desired and actual clearance. (c) Desired and actual acceleration. (d) Desired and actual differential pressure. (e) Desired and actual throttle angles

The desired and actual accelerations of the controlled (subject) vehicle are compared in Fig. 10c. The desired acceleration has been computed so that the difference between the desired and actual clearances and relative speed are kept as small as possible without violating the acceleration constraint. It should be noted from Fig. 10c that the desired accelerations were limited to 2.5 m/s^2 for ride quality of the controlled vehicle. The actual acceleration was computed from the wheel speed measurements using the Kalman filter. The controller activates the throttle and brake actuators in order that the vehicle acceleration tracks the desired acceleration. The time histories of the throttle angle and differential pressure of the EVB are shown in Figs 10d and e respectively. In this test, the differential pressure sensor shows an offset of 9 (1/256 bar). There is a large discrepancy between desired and actual throttle angles from 3 to 4 s in Fig. 10e.

Although it takes 1.066 s for the stepper motor to change the throttle angle by 20°, if the difference between the desired and actual throttle angles is greater than 25° then the throttle controller deactivates the throttle actuator. In addition, the throttle angle has been limited to 50° in the tests. Since the desired acceleration is greater than the actual one and the acceleration has not been increased rapidly as a result of reasons such as engine torque production delay and uncertain driving loads etc. at 3 s, the desired throttle angle has been increased to produce more engine torque output. As the difference between the desired and actual throttle angles is greater than 25° approximately at 3.15 s, the throttle controller has deactivated the throttle actuator. Therefore, a large discrepancy between desired and actual throttle angles from 3 to 4 s in Fig. 10e has been observed. It can be seen that the throttle actuator has been at 3.5 s and the actual throttle angle converges to the desired one.

7 CONCLUSIONS

Vehicle test results of a vehicle longitudinal control scheme for SG cruise control have been presented. The vehicle longitudinal control scheme consists of a set-speed control algorithm, a speed control algorithm and a distance control algorithm. The vehicle longitudinal control system has been implemented using an MMW radar sensor, a stepper motor, an EVB and a Siemens C167 CR controller. The performance of the implemented system has been tested using two test vehicles. Vehicle tests results have shown that the system can provide good speed and clearance control performance. It can be concluded from the vehicle test results that the implemented vehicle longitudinal control system can be used for an SG cruise control system to reduce the workload of the driver in a congested traffic flow. Development of a robust control algorithm for severe driving load variations and vehicle string stability of SG cruise control vehicles are the topics of the present authors' current research.

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