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Design and Experimental Implementation of Longitudinal Control for a Platoon of Automated Vehicles

This paper presents the design and experimental implementation of a longitudinal control system for the operation of automated vehicles in platoons. The control system on each vehicle is designed to have a hierarchical structure and consists of an upper level controller and a lower level controller. The upper controller determines the desired acceleration for each vehicle in the platoon so as to maintain safe string-stable operation even at very small intervehicle spacing. The lower controller utilizes vehicle-specific parameters and determines the throttle and/or brake commands required to track the desired acceleration. A special challenge handled in the design of the lower level controller is low-speed operation that involves gear changes and torque converter dynamics. The paper also presents the design of longitudinal intra-platoon maneuvers that are required in order to allow any car in the platoon to make an exit. The paper presents extensive experimental results from the public NAHSC demonstration of automated highways conducted in August 1997 at San Diego, California. The demonstration included an eight-car platoon operating continuously over several weeks with passenger rides given to over a thousand visitors. The maneuvers demonstrated included starting the automated vehicles from complete rest, accelerating to cruising speed, allowing any vehicle to exit from the platoon, allowing new vehicles to join the platoon and bringing the platoon to a complete stop at the end of the highway. [S0022-0434(00)01903-1]

1 Introduction

The Automated Highway Systems (AHS) Program at California PATH aims to reduce congestion on highways by achieving significantly higher traffic flow through closer packing of automatically controlled vehicles into platoons. Studies have shown that over 90 percent of highway accidents occur due to driver-related errors (United States DOT Report [1]). The AHS system would thus also improve safety by drastically reducing the burden of the driver. Preliminary studies of automatic control of the longitudinal and lateral motion of cars were previously undertaken to establish feasibility of the AHS concept (Choi and Hedrick [2], Choi and Devlin [3], Tan et al. [4], and Tomizuka and Hedrick [5]).

This paper documents the longitudinal control system used in the NAHSC[1] public demonstration of eight fully automated cars traveling together at small inter-vehicle spacing as a platoon. The demonstration was held in August, 1997 in San Diego using a 7.6 mile two-lane highway that had been equipped with magnets installed in the centers of both lanes. The magnets served as reference markers that were used by the automated steering control system to keep each car centered in its lane. Each vehicle was equipped with a radar that measured inter-vehicle spacing and many other on-board sensors that measured vehicle-specific variables. In addition, a wireless radio communication system enabled each vehicle to share real-time speed and acceleration data with other vehicles in the platoon.

Over a thousand visitors were given passenger rides in the platoon vehicles which operated continuously for several hours a day for three weeks. The maneuvers demonstrated in San Diego included starting the automated vehicles from complete rest, accelerating to cruising speed, allowing any vehicle to exit from the platoon, allowing new vehicles to join the platoon and bringing the platoon to a complete stop at the end of the highway. These maneuvers are essential to an AHS. The controllers for all these maneuvers and the finite state machines used to transition between them will be presented in the paper. The special modifications to the control system needed to ensure smooth and accurate operation at low speeds where the torque converter is unlocked and the drive torque drops to zero during each gear shift transition will also be presented. Experimental data documenting the performance for all these different maneuvers will also be detailed. This paper serves as the technical documentation of a platoon of fully automated vehicles that was in continuous operation for an extended period of time and used for public demonstration rides.

2 Longitudinal Control System Design

The longitudinal control system developed at PATH for platooning is hierarchical and consists of an upper level controller and a lower level controller. The upper level controller determines the desired or ''synthetic'' acceleration for each car in the platoon. The lower level controller determines the throttle and/or brake commands required to track the desired acceleration. This section describes the basic longitudinal control system used for operation at typical highway speeds. The modifications needed to this control system to ensure accurate and smooth tracking at low speeds are described in Section 3. Further modifications to the controller for performing entry and exit maneuvers such as allowing a car to leave the platoon and allowing a car to join the platoon are described in Section 4.

2.1 Upper Level Controller. The upper level controller determines the desired acceleration for each car so as to

1 maintain constant small spacing between the cars
2 and ensure string stability of the platoon (Fig. 1) (see explanation below).

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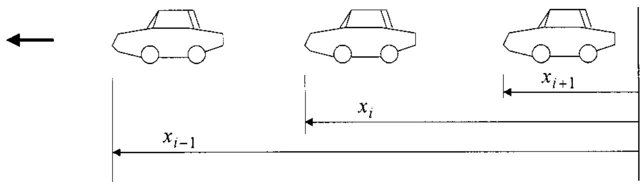

Fig. 1 Platoon of cars—upper controller notation

As far as the upper level controller is concerned, the plant model used for control design is

$$\ddot{x}_i = u \tag{1}$$

where the subscript i denotes the ith car in the platoon. The acceleration of the car is thus assumed to be the control input. However, due to the finite bandwidth associated with the lower level controller, each car is actually expected to track its desired acceleration imperfectly. The performance specification on the upper level controller is therefore stated as that of meeting objectives 1 and 2 robustly in the presence of a first-order lag in the lower level controller performance

$$\ddot{x}_i = \frac{1}{\tau s + 1}\ddot{x}_{i\_des} = \frac{1}{\tau s + 1} u_i \tag{2}$$

Equation (1) is thus assumed to be the nominal plant model while the performance specifications have to be met even if the actual plant model were given by Eq. (2).

The spacing error for the ith vehicle is defined as

$$\varepsilon_i = x_i - x_{i-1} + L \tag{3a}$$

where L is the desired inter-vehicle spacing. In terms of spacing error, the above objectives of the upper controller can be mathematically stated as follows

$$\begin{aligned} &1)\ \ \varepsilon_{i-1} \to 0 \Rightarrow \varepsilon_i \to 0 \\ &2)\ \ \|\hat{H}(s)\|_\infty \leqslant 1 \end{aligned} \tag{3b}$$

where $\hat{H}(s)$ is the transfer function relating the spacing errors of consecutive cars in the platoon

$$\hat{H}(s) = \frac{\varepsilon_i}{\varepsilon_{i-1}}. \tag{3c}$$

The string stability of the platoon (objective 2, Eq. (3b)) refers to a property in which spacing errors are guaranteed not to amplify as they propagate toward the tail of the platoon (Swaroop and Hedrick [6]. Swaroop et al. [7], and Yanakiev and Kanellakopoulos [8]). For example, string stability ensures that any errors in spacing between the 2nd and 3rd cars does not amplify into an extremely large spacing error between cars 7 and 8 further down in the platoon. In addition to (3b), a condition that the impulse response function $h(t)$ corresponding to $\hat{H}(s)$ does not change sign is desirable (Swaroop and Hedrick [6]). The reader is referred to Swaroop and Hedrick [7] for details.

Longitudinal control algorithms that guarantee string stability in the platoon of vehicles include autonomous, semiautonomous and radio-communication based algorithms. A comparison of the performance and deployment advantages of the three types of algorithms is provided in Rajamani and Zhu [9]. The NAHSC demonstration implemented a radio communication based algorithm described below.

The sliding surface method of controller design (Slotine and Li [10]) is used. Define the following sliding surface

$$S_i = \dot{\varepsilon}_i + \frac{\omega_n}{\xi + \sqrt{\xi^2 - 1}} \frac{1}{1 - C_1} \varepsilon_i + \frac{C_1}{1 - C_1}(\nu_i - v_\ell) \tag{4}$$

Setting

$$\dot{S}_i = -\lambda S_i \ \ \text{with}\ \ \lambda = \omega_n(\xi + \sqrt{\xi^2 - 1}) \tag{5}$$

we find that the desired acceleration of the car is given by

$$\begin{aligned} \ddot{x}_{i\_des} = {} & (1 - C_1)\ddot{x}_{i-1} + C_1 \ddot{x}_\ell - (2\xi - C_1(\xi + \sqrt{\xi^2 - 1}))\omega_n \dot{\varepsilon}_i \\ & - (\xi + \sqrt{\xi^2 - 1})\omega_n C_1(\nu_i - \nu_\ell) - \omega_n^2 \varepsilon_i \end{aligned} \tag{6}$$

The control gains to be tuned are C_1, ξ, and ω_n. The gain C_1 takes on values $0 \leqslant C_1 < 1$ and can be viewed as a weighting of the lead vehicle's speed and acceleration. The gain ξ can be viewed as the damping ratio and can be set to 1 for critical damping. The gain ω_n is the bandwidth of the controller.

Equation (5) ensures that the vehicle states converge to the sliding surface S_i. If all the cars in the platoon use this control law, results in Swaroop and Hedrick [6] and Swaroop et al. [7] show that the cars in the platoon are able to track the preceding car with a constant spacing and further that the system is string stable, i.e., the spacing errors never amplify down the platoon. Results on the robustness of the above controller, especially to lags induced by the performance of the lower level controller, can also be found in Swaroop and Hedrick [6]. A wireless radio communication system is used between the cars to obtain access to all of the required signals. Each car thus obtains communicated speed and acceleration information from two other cars in the platoon—the lead car and the preceding car.

Setting $C_1 = 0$ for a two car platoon, we obtain the following classical second-order system

$$\ddot{x}_{i\_des} = \ddot{x}_{i-1} - 2\xi\omega_n \dot{\varepsilon}_i - \omega_n^2 \varepsilon_i$$

2.2 Lower Level Controller. In the lower controller, the throttle and brake actuator inputs are determined so as to track the desired acceleration described in (6). The following simplified model of vehicle dynamics is used in the development of the lower level controller. This simplified model is based on the assumptions that the torque converter in the vehicle is locked and that there is zero-slip between the tires and the road (Hedrick et al. [11]). These assumptions relate the vehicle speed directly to the engine speed (see Nomenclature for explanation of symbols)

$$\dot{x}_i = \nu_i = (Rh\omega_e)_i \tag{7}$$

The dynamics relating engine speed ω_e to the pseudo-inputs "net combustion torque" T_{net} and brake torque T_{br} can be then modeled by (Hedrick, et al. [11])

$$\dot{\omega}_e = \frac{T_{\text{net}} - c_a R^3 h^3 \omega_e^2 - R(hF_f + T_{\text{br}})}{J_e} \tag{8}$$

where $J_e = I_e + (mh^2 + I_\omega)R^2$ is the effective inertia reflected on the engine side, R is the gear ratio and h the tire radius.

$T_{\text{net}}(\omega_e, m_a)$ is a nonlinear function of engine speed and mass of air in the intake manifold (obtained from steady state engine maps available from the vehicle manufacturer). The dynamics relating m_a to the throttle angle α can be modeled as

$$\dot{m}_a = \dot{m}_{ai} - \dot{m}_{ao} \tag{9}$$

where $\dot{m}_{ai}$ and $\dot{m}_{ao}$ are the flow rate into the intake manifold and out from the manifold, respectively, and

$$\dot{m}_{ai} = \text{MAX}\ \ TC(\alpha)\text{PRI}(m_a) \tag{10}$$

where MAX is a constant dependent on the size of the throttle body. $TC(\alpha)$ is a nonlinear invertible function of the throttle angle and PRI is the pressure influence function that describes the choked flow relationship which occurs through the throttle valve. $\dot{m}_{ao}$ is the mass flow rate into the combustion chamber (again available as a nonlinear function of P_m and ω_e from the engine manufacturer). The ideal gas law is assumed to hold in the intake manifold

$$P_m V_m = m_a R_g T \tag{11}$$

The control design for the lower level controller is based on a modification of the standard sliding surface control technique (Slotine and Li [10]). If the net combustion torque is chosen as

$$(T_{\text{net}})_i = \frac{J_e}{Rh}\ddot{x}_{ides} + [c_a R^3 h^3 \omega_e^2 + R(hF_f + T_{br})]_j \tag{12}$$

then, from Eq. (8), the acceleration of the car is equal to the desired acceleration defined by the upper level controller: $\ddot{x}_i = \ddot{x}_{ides}$.

Once the required combustion torque is obtained from (12), the throttle angle required to provide this torque is calculated by the following procedure. The pressure of air in the manifold P_m and temperature T are measured and m_a is then calculated using the ideal gas law (11). The map $T_{net}(\omega_e, m_a)$ is inverted to obtain m_{ades}.

A sliding surface controller is then used to calculate the throttle angle α necessary to make m_{ades} track m_a. Define the surface

$$s_2 = m_a - m_{ades} \tag{13}$$

Setting

$$\dot{s}_2 = -\eta_2 s_2 \tag{14}$$

we obtain

$$\text{MAX} \quad TC(\alpha)\text{PRI}(m_a) = \dot{m}_{ao} + \dot{m}_{ades} - \eta_2 s_2 \tag{15}$$

Since $TC(\alpha)$ is invertible, the desired throttle angle can be calculated from Eq. (15).

If the desired net torque defined by (12) is negative, the brake actuator is used to provide the desired torque. An algorithm for smooth switching between the throttle and brake actuators is designed in Choi and Devlin [3] and will be used by the longitudinal control system.

3 Intra Platoon Maneuvers

In a realistic automated highway system, any car in the platoon should be allowed to take an exit at the request of its driver. This requires the exiting car as well as the car behind the exiting car to split to a larger spacing. Both these cars then switch to speed control during which the use of the radar for spacing control is suspended. The split to a larger spacing is necessary because close-spaced operation under purely speed control is unsafe. After the exiting car makes an automated lane change, the car behind it reverts back to spacing control and also speeds up to close the gap left by the exited car.

The communication hardware used for the NAHSC demonstration allowed the operation of only one platoon system at a time. To allow a car in the middle of the platoon to make a lane change, the car behind it could not split and become the leader of a new platoon.

Intra-platoon maneuvers were therefore designed to allow cars to execute split and join maneuvers in the platoon while still being a part of the platoon. Assume that the desired inter-car spacing is a slowly varying trajectory $L_i(t)$. Then for the splitting/joining car, the terms $\varepsilon_i, \dot{\varepsilon}_i$ should be calculated as functions of $L_i(t)$ and $\dot{L}_i(t)$. When the desired spacing is a function of time, the sliding surface methodology of Section 2 leads to following control law for desired acceleration.

$$\begin{aligned}\ddot{x}_{i\_\text{des}} &= (1-C_1)(\ddot{x}_{i-1} - \ddot{L}_i) + C_1(\ddot{x}_\ell - \ddot{L}_i) \\ &\quad - (2\xi - C_1(\xi + \sqrt{\xi^2-1}))\omega_n \dot{\varepsilon}_i(\dot{L}_i, L_i) \\ &\quad - (\xi + \sqrt{\xi^2-1}))\omega_n C_1(\nu_i - \nu_\ell + \dot{L}_i) - \omega_n^2 \varepsilon_i(L_i)\end{aligned} \tag{16}$$

For the cars behind the splitting car, the terms associated with the preceding car speed and acceleration are independent of L_i, since it does fall back with respect to the lead car but does not fall back with respect to the preceding car. The control law for the cars behind the splitting/joining car is therefore

$$\begin{aligned}\ddot{x}_{i\_\text{des}} &= (1-C_1)\ddot{x}_{i-1} + C_1(\ddot{x}_\ell - \ddot{L}_i) - (2\xi - C_1(\xi + \sqrt{\xi^2-1}))\omega_n \dot{\varepsilon}_i \\ &\quad - (\xi + \sqrt{\xi^2-1})\omega_n C_1(\nu_i - \nu_\ell + \dot{L}_i) - \omega_n^2 \varepsilon_i\end{aligned} \tag{17}$$

The desired spacing for a split maneuver can be obtained from the following (relative) acceleration trajectories

$$\begin{aligned}\ddot{L}_i(t) &= \frac{a_0}{2}\{1-\cos(\omega t)\} \quad t < \frac{2\pi}{\omega} \\ \ddot{L}_i(t) &= -\frac{\alpha_0}{2}\{1-\cos(\omega t)\} \quad t \geqslant \frac{2\pi}{\omega}\end{aligned} \tag{18}$$

which ensures that both relative jerk and acceleration are zero at $t=0$ and $t=2\pi/\omega$. The variables a_0 and ω can be analytically calculated given the distance to split/join and either the maximum allowable relative velocity (a safety consideration) or the maximum allowable relative acceleration (an actuator consideration). For instance, given the maximum allowable relative acceleration a_0 and the distance to split H, $\omega = \pi\sqrt{2a_0/H}$ and the maximum relative velocity is $\nu_0 = -\pi a_0/\omega$.

The intra-platoon maneuvers described above are valuable even when the communication hardware does not have the constraint described above and two platoons can operate in the same vicinity. This is because their accuracy and ride quality would provide superior and safer performance at small inter-car spacing compared to autonomous control on the splitting or joining car.

Note that the maneuvers described above require communication from both the lead car and preceding car during the split/join and are performed as intra-platoon maneuvers. Communication is also required to coordinate the maneuvers between the cars in the platoon.

Figures 2 and 3 describe the process of a lane change and the coordination required in the platoon for the same. Figure 2 shows the state machine for a car that requests an exit from the platoon while being a follower. The request is transmitted to the lead car which grants permission only if all the other cars in the platoon are in the FOLLOWER state and have not requested an exit. While granting permission to the car to exit, the lead car also instructs the car behind it to SPLIT (Fig. 3). This is necessary because the car behind the lane changing car has to suspend use of radar and operate open-loop while the lane change takes place. When both the exiting car and the car behind have completed splitting, the lead car grants permission to do the lane change. If the requesting car is unable to do a lane change (for example, due to cars in the other lane on a real highway), it informs the lead car and then moves to the JOIN state. After the join is completed, the car comes back to the FOLLOWER state. In this case the lead car instructs the following car also to move to the JOIN and then FOLLOWER states.

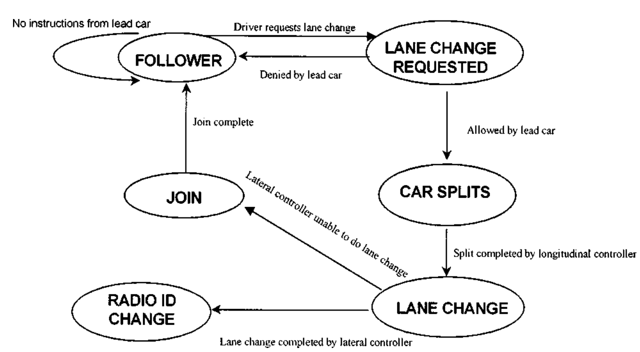

Fig. 2 Finite state machine for car requesting an exit

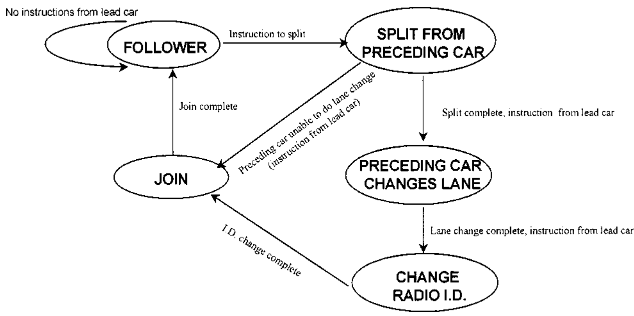

Fig. 3 Finite state machine for vehicle behind exiting car in platoon

If the requesting car successfully performs a lane change, Radio I.D. changes are done so that the cars in the platoon establish communication with their appropriate preceding cars in the new platoon order.

While in the SPLIT and JOIN states, the desired acceleration is determined by Eqs. (16) and (18) as derived in this section. The cars in the platoon behind the splitting/joining cars use the desired acceleration maneuver of Eq. (17).

4 Low Speed And Transient Operation

The standard lower level controller, as seen in Eq. (7), relates the engine rotational acceleration to the desired acceleration of the car by assuming that the torque converter is locked and that there is no slip between the tires and the road. However, at low speeds (in the first and second gears), the torque converter is not locked and so the speed of the vehicle cannot be directly related to the engine speed.

Using a mathematical model of the torque converter, a controller based on inverting the torque converter dynamics can be designed for accurate control at low speeds (Hedrick et al. [12]). This controller would need turbine speed as an additional sensor signal and would be based on torque converter charts that relate speed ratio (engine speed and turbine speed), capacity ratio and torque ratio. A simpler control algorithm that did not explicitly invert the torque converter charts was implemented for low speed operation in the NAHSC demonstration. The idling speed of the Buick Le Sabres used in the NAHSC demonstration was measured to be 5.5 mph. Even with supposedly zero throttle angle, the Le Sabre moves at 5.5 mph. Equation (9) for the calculation of the desired net combustion torque was modified for speeds below 5.5 mph as follows

$$T_{\text{net}-\text{des}}=\frac{J_e}{Rh}a_{\text{synthetic}}+c_aR^3h^3\omega_e^2+RhF_f+T'(\nu) \qquad (19)$$

The function $T'(\nu)$ accounts for the extra torque available due to the torque converter and nonzero throttle angle. $T'(\nu)$ was modeled as a linear function based on experimentally measured values of T_{net} at 2 different speeds.

Acceleration of the vehicle from rest to cruising speed involves a series of gear change transitions, during each of which the drive torque briefly drops to a value close to zero for a period of about one second. For a typical automatic transmission, the gear shift points depend on both the engine speed and the throttle angle. Using the throttle angle measurement, the gear shift algorithm takes into account the desired torque. For instance, if the driver accelerates very gradually, the upshifts occur at lower speeds. If the driver accelerates rapidly, then the gears upshift at higher vehicle speeds. Since the drive torque drops briefly to zero during each gear change, the occurrence of consecutive gear shifts at very small time intervals causes large error build up and actuator saturation under automatic longitudinal control.

Table 1 Gear shift points

Gear	Upshift speed (mph)	Downshift speed (mph)
1	19	-
2	40	17
3	71	38
4	-	69

To overcome this problem, two modifications to the control system were carried out. The embedded controller in the powertrain control module was modified so that the gear shift points became purely a function of engine speed. By eliminating the dependence on throttle angle, one could ensure that the gear shifts occurred at predetermined speeds which could be spaced sufficiently wide apart. For instance, the following gear shift points (Table 1) were chosen for the Buick Le Sabres.

The longitudinal control system computer could not directly command gear changes—these were done by the embedded powertrain control module based on the shift schedule described above.

In addition, the control gain ω_n was gain scheduled during the gear change transition. ω_n was dropped to 50 percent of its value at the beginning of the gear change (the time at which the gear change has been commanded) and then slowly increased back to 100 percent at 5 seconds later.

5 Experimental Results From the NAHSC Demonstration

Eight GM Buick Le Sabres were used in the August, 1997 NAHSC demonstration. The demonstration was held in San Diego using a 7.6 mile two-lane highway that had been equipped with magnets installed in the centers of both lanes. The magnets served as reference markers that were used by the automated steering control system to keep each car centered in its lane. Visitors were given passenger rides in the platoon vehicles which operated continuously for several hours a day for three weeks. The objective of this demonstration was to show that cars could travel in a platoon safely and comfortably and also that each car in the platoon could take an exit anytime at the request of its driver.

The finite state machine describing the discrete event response of the lead car during the run is shown in Fig. 4. The scenario in each demonstration run is described below. All of the eight cars start together from rest at arbitrary initial inter-car spacing (INITIAL SWITCH ON). The driver of each car turns on the automation switches and moves the gear from park to drive. The automatic controller applies brakes to keep the car stationary. It checks to see if all of the driver actions have been correctly completed. Then the car transitions to the READY state where it sends out a handshake communication message to the lead car of the platoon. Once the lead car receives handshake messages from all of the cars in the platoon it sends out the ACCELERATE command to all the cars in the platoon. The cars accelerate together until they reach a cruising speed of 60 mph with a steady-state inter-car spacing of 6.5 meters between them (CRUISE). Once the CRUISE state has been reached, any car in the platoon can request a lane change. The co-ordination between the cars in this case has been described in Section 3.

Finally, when the lead car passes a coded magnetic marker in the lane which indicates that the end of the 7.6 mile highway is approaching, it moves to the SLOW DOWN state. All of the cars decelerate together and maintain their 6.5 meter spacing even as they come to a complete stop (STOP).

The lead car of the platoon does not allow more than one exit request to be permitted in the platoon (it allows one exit only when all cars in the platoon are in the CRUISE/FOLLOWER state). Once a car in the platoon has been given permission to exit, no other car in the platoon is allowed permission to exit until all

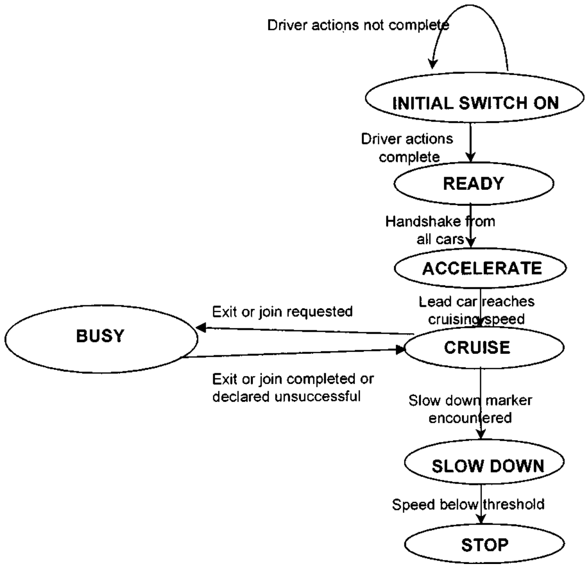

Fig. 4 Finite state machine for the lead car in the 1997 NAHSC Demonstration

cars are in the CRUISE/FOLLOWER state. The above scenario described a fault-free operation where the only failure allowable is failure to execute the lane change.

The following figures document the performance achieved during the August 1997 NAHSC Demonstration. Figure 5 shows the desired speed trajectory for the lead car of the 8-car platoon. The desired speed trajectory starts from zero speed, ramps up and then smooths out exponentially before cruising at approximately 60 mph. The desired trajectory stays constant at 60 mph until the user-specified magnetic marker is reached to start decelerating to a stop. The deceleration to a stop is achieved using a speed profile consisting of a ramp combined with a sinusoid. In the acceleration and deceleration trajectories, two gear changes (1 to 2 and 2 to 3) take place in the automatic transmission system.

Figures 6(*a*), 6(*b*), and 6(*c*) show the spacing performances of cars 6, 7, and 8 which form the tail of the 8-car platoon. The cars start with arbitrary initial spacing. The steady state desired spacing between the cars is 6.5 meters. During the entire 7.6 mile run on the San Diego highway, the spacing error between these tail vehicles of the platoon remains within ± 0.2 meters. This includes the spacing performance while the lead car accelerates, cruises, decelerates to a complete stop and other cars accelerate and decelerate while splitting and joining. The scenario also includes steep uphill and downhill grades during which the maximum spacing error occurs. Figure 6(*a*) shows the initial arbitrary spacing between cars during start-up and the convergence to the steady state 6.5 meter spacing. Figures 6(*b*) and 6(*c*) show close-ups of the inter-car spacing to indicate the accuracy and smoothness of the longitudinal controller.

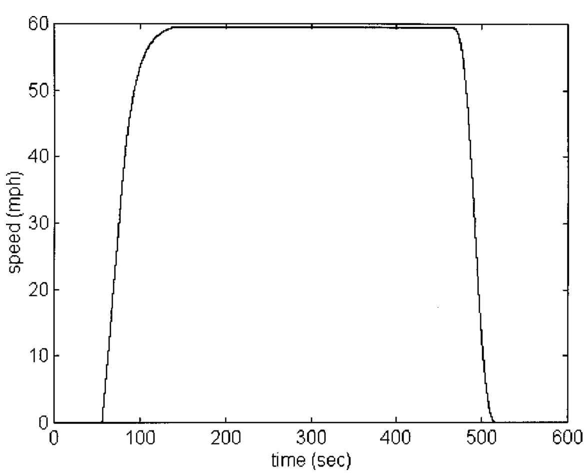

Fig. 5 Desired speed profile for lead car

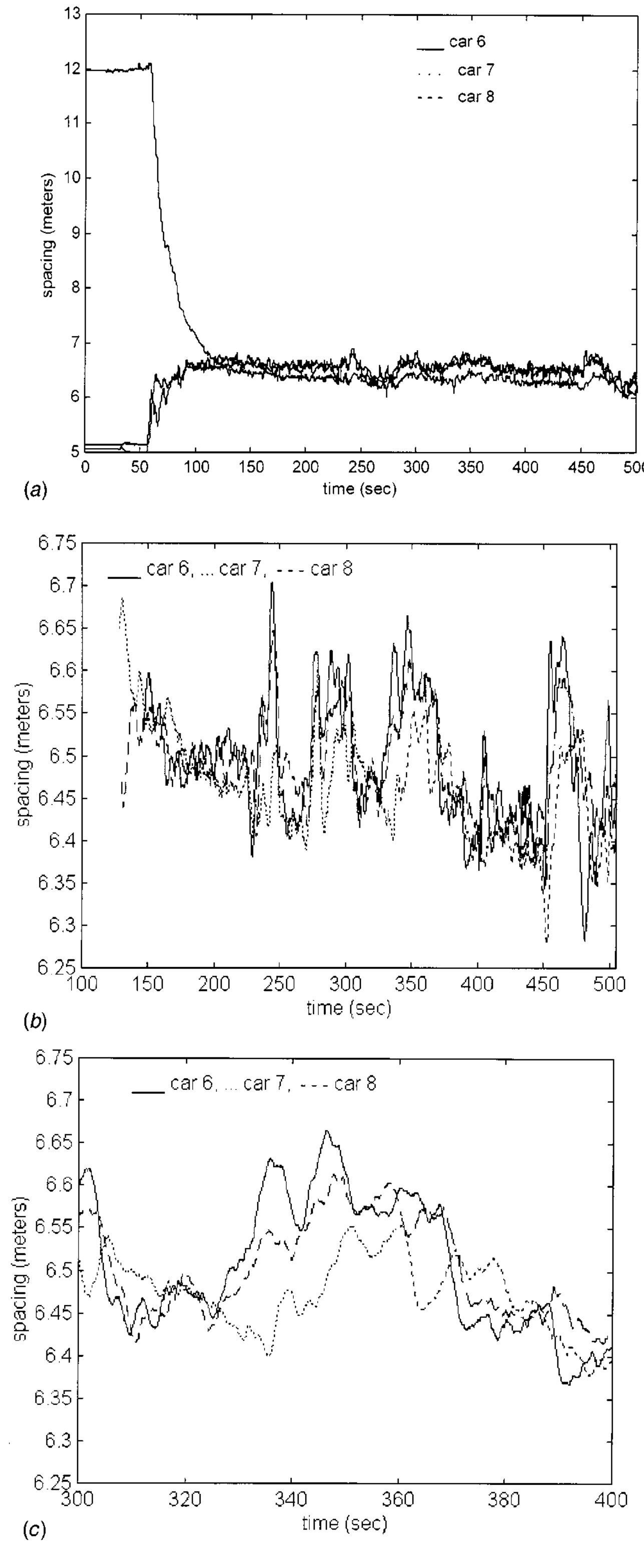

Fig. 6 6(*a*) Spacing performance of cars 6, 7 and 8 of the 8-car platoon (raw radar); (*b*) and (*c*) estimated inter-car spacing

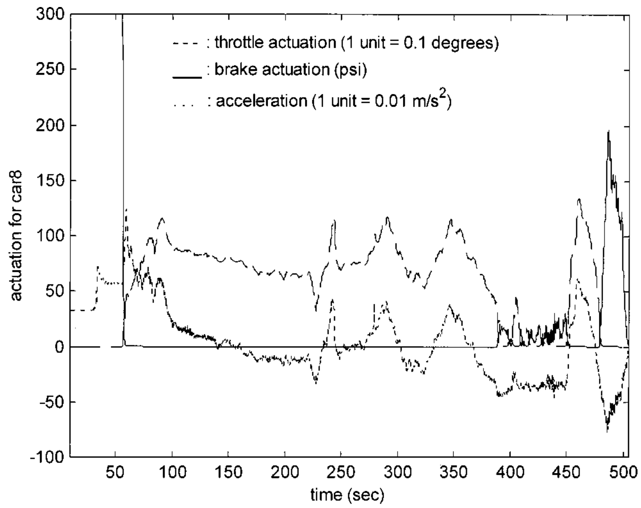

Fig. 7 Desired acceleration, throttle and brake for car 8

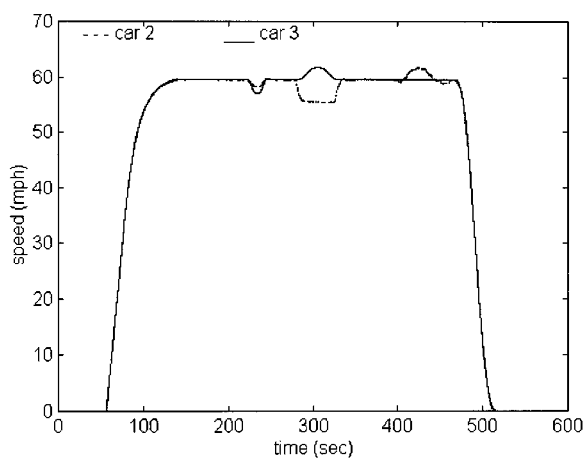

Fig. 8 Speed profiles of cars 2 and 3 in the platoon

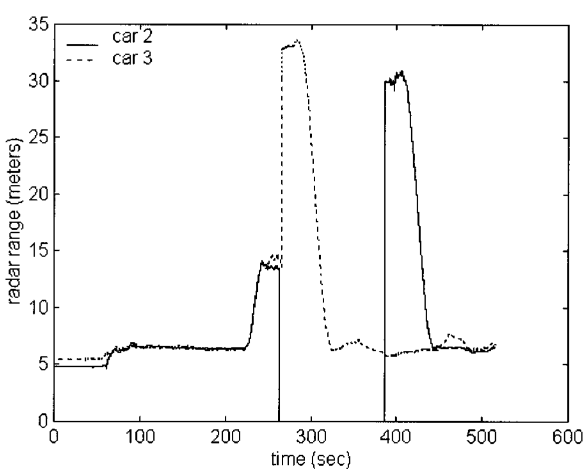

Fig. 9 Spacing performance of cars 2 and 3 of the 8-car platoon (raw radar)

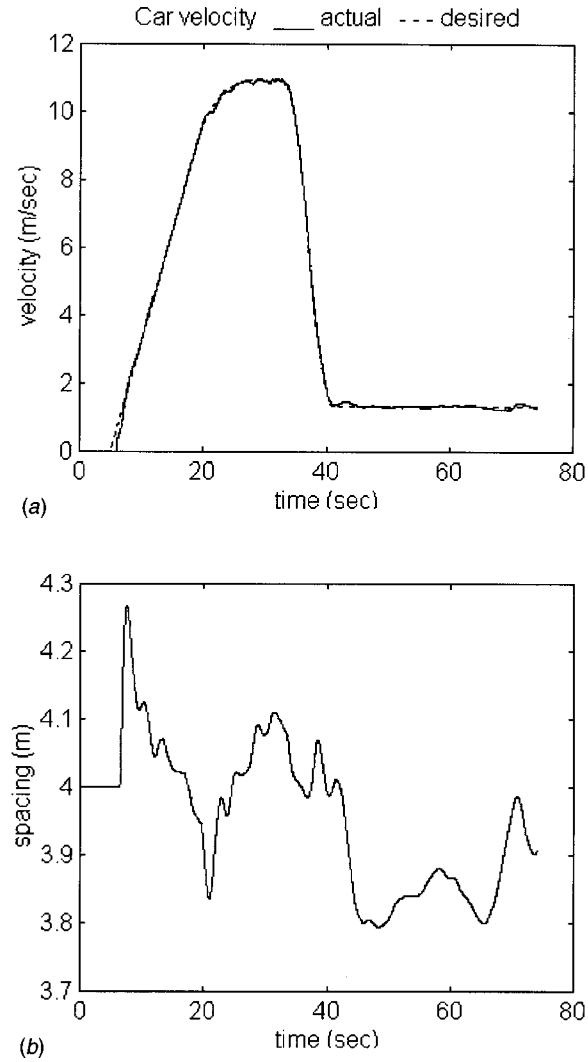

Fig. 10 (*a*) Low speed performance of a single car; (*b*) low speed spacing performance

Figure 7 shows the desired acceleration, throttle and brake actuation for car 8. Initially all the cars are at rest and the brake actuator maintains 300 psi pressure in the master cylinder to keep the car stationary. The throttle angle of the actuator stays at zero. During the initial acceleration maneuver of the platoon, the throttle angle increases to as much as 12 degrees. The maximum value in throttle angle is required during the gear change from gear 1 to gear 2 which takes place during an uphill grade on the highway. The steady-state throttle angle during cruise on flat ground is less than 10 degrees. The variations in throttle angle due to steep uphill and downhill grade variations are also seen in the figure. At approximately 475 seconds, the cars begin to decelerate to stop and the throttle angle then gradually drops to zero. The brake actuator is mostly not used once the car starts moving, except at the very end of the 7.6 mile highway during the downhill and during the deceleration maneuver. During the final deceleration to a stop maneuver, the car decelerates at 0.05 g which translates into a maximum braking pressure requirement of about 200 psi. This figure illustrates the use of both actuators and the smooth switching between them for conducting all the maneuvers described in the demonstration scenario.

In the demonstration, the driver of any of the cars could request an exit from the platoon. In this particular set of data, car 2 requests and performs a lane change to exit from the platoon. Figure 8 shows the speed profiles and Fig. 9 shows the spacing variation for cars 2 and 3 of the platoon. At approximately 225 seconds, the driver of car 2 requests an exit from the platoon. In response, car 2 splits smoothly to a larger spacing of 13.5 meters. Simultaneously, car 3 is also commanded by the lead car to split to a spacing of 13.5 meters with respect to car 2. After the two split maneuvers are complete, at approximately 265 seconds, car 2 makes an automated lane change. Since car 2 no longer has a preceding car that it tracks or any other target, its spacing as measured by the radar drops to zero. The spacing as measured by the radar on car 3 increases to 34 meters. Once car 2 indicates via radio communication that it has completed its lane change, car 3 then initiates a join maneuver and decrease the spacing between itself and car 2. The steady-state spacing between car 3 and car 1 comes back smoothly to 6.5 meters. Car 2 decelerates to the tail of the platoon in the other lane and then makes a lane change to come back to the original lane. Its radar measurement reads 31 meters when it comes back to the original lane. It then initiates a join maneuver and joins with car 7 to decrease its final spacing to 6.5 meters. The speed profile of car 2 shows the maneuvers accelerate, cruise, split, lane change, fall back, join and decelerate. The speed profile of car 3 shows accelerate, cruise, double split, join and decelerate.

Figures 10(*a*) and 10(*b*) show the low speed performance of a single car in more detail. In this run, the car tracks a speed profile of 3 mph after decelerating from a cruising speed of 25 mph. The speed of 3 mph is below the idling speed of the engine. The car therefore uses the brake actuator to track this speed profile. As the figure shows, the car is able to do excellent cruise control even at this low speed. Figure 10(*b*) shows the spacing performance of this car in terms of its distance from an imaginary car whose longitudinal distance is obtained by integrating the desired speed profile of the car. The car is able to maintain a desired distance of 4 meters and delivers excellent spacing performance. The initial spacing error of 20 cm arises due to the speed sensor being unable to measure very low speeds below 0.5 mph.

6 Conclusions

As a part of the National Automated Highway System Consortium (NAHSC) demonstration held in August, 1997, an eight car platoon was demonstrated in San Diego with many visitors being given demonstration rides over a 7.6-mile highway. The eight car platoon was demonstrated with continuous operation for 6–8 hours each day and for three weeks in a row. The control system had the reliability and robustness necessary for such continuous operation. This paper documented the longitudinal control system used in the demonstration. The maneuvers demonstrated included starting the automated vehicles from complete rest, accelerating to cruising speed, allowing any vehicle to exit from the platoon, allowing new vehicles to join the platoon and bringing the platoon to a complete stop at the end of the highway. These maneuvers are essential to an automated highway system. Test results presented in this paper show that the system was able to perform accurate speed and spacing control as well as provide excellent ride quality comparable to that of extremely good human drivers. Under normal operation of a platoon of cars, the spacing was maintained to within an accuracy of 20 cm even in the case of an eight-car platoon. The switching from brakes to throttle and vice-versa was almost imperceptible to the passengers. The algorithms and protocols for split and join maneuvers provided accurate and reliable performance.

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Nomenclature

x_i = longitudinal position of the ith vehicle
$\dot{x}_i$ or ν_i or ν = longitudinal velocity of the ith vehicle
$\epsilon_i = x_i - x_{i-1} + L$ = longitudinal spacing error of the ith vehicle, with L being the desired spacing
ν_l = longitudinal velocity of the lead vehicle of the platoon
$\ddot{x}_l$ = longitudinal acceleration of the lead vehicle of the platoon
C_1 = control gain used in upper longitudinal controller (relative weight for lead car signal feedback compared to preceding car signal feedback).
ω_n = control gain used in upper longitudinal controller (bandwidth)
$\eta_1,\ \eta_2$ = sliding surface control gains
T_{net} = net combustion torque of the engine
T_{br} = brake torque
ω_e = engine angular speed
c_a = aerodynamic drag coefficient
R = gear ratio
h = tire radius
F_f = rolling resistance of the tires
J_e = effective inertia reflected on the engine side
$\dot{m}_{ai}$ = rate of mass flow into engine manifold
$\dot{m}_{a0}$ = rate of mass outflow from engine manifold
$\dot{m}_a$ = rate of air mass flow in engine manifold
P_m = pressure of air in engine manifold

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