Semi-Autonomous Adaptive Cruise Control Systems

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***Abstract*—The concept of a semi-autonomous adaptive cruise control (SAACC) system is developed, which enjoys significant advantages over present day adaptive cruise control (ACC) systems in terms of highway safety and traffic flow capacity. The semi-autonomous systems combine the deployment advantages of autonomous vehicles with the performance advantages of fully automated highway systems (AHSs) in which vehicles operate cooperatively as a platoon. Unlike platoon systems, the semi-autonomous systems will be immediately deployable on present day highways, where both manually driven and adaptive cruise controlled vehicles can coexist. The theoretical results in this paper show that the proposed system would be able to safely maintain smaller time gaps, would be string stable, and would be guaranteed to have smaller actuator inputs than a standard autonomous ACC system. The simulation results in the paper indicate that more accurate and smoother tracking, smaller time gaps, smaller control efforts, and increased robustness to vehicle dynamics are achieved by semi-autonomous control.**

***Index Terms*—Adaptive cruise control, inter-vehicle communication, vehicle control.**

I. Motivation

ADAPTIVE cruise control (ACC) systems are currently being developed by several automotive manufacturers and will enhance cruise control by adding the ability to maintain a desired spacing with respect to a preceding car that has been detected in the lane [1], [2], [7]. These ACC systems will be "autonomous"—they will use only on-board sensors such as radar range and range rate sensors to accomplish the task of maintaining the desired spacing.

A more long term approach to vehicle automation is through the development of automated highway systems (AHSs) [3]–[6]. The concept of fully AHSs has been explored by various research and development organizations under the National Automated Highway Systems Consortium (NAHSC) [3]. Fully AHSs assume the existence of dedicated highway lanes where all the cars are fully automated with the steering, brakes, and throttle being controlled by a computer. A very successful architecture for such AHSs has been shown to be the operation of vehicles in "platoons" with very small constant spacing between the cars in the platoon and with the existence of wireless radio communication between the cars in the platoon [3], [5].

The new semi-autonomous systems suggested in this paper would combine the advantages of state-of-the-art ACC systems and fully automated AHS platoon systems. Unlike AHS platoons that are expected to be deployable in 15–20 years, the new semi-autonomous ACC (SAACC) systems would be immediately deployable on today's highways, where both manually driven and automated cars can coexist. At the same time, the SAACC systems would recover many of the performance and traffic flow advantages of the AHS platoon systems.

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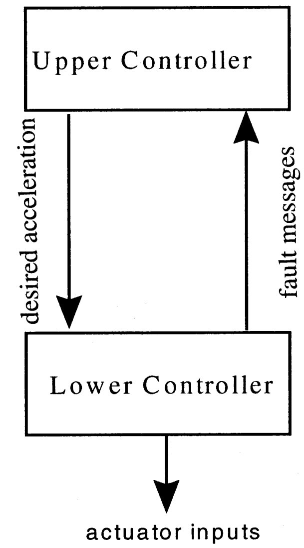


Fig. 1. Structure of longitudinal control system.

II. Performance Limitations of Autonomous ACC Systems

The longitudinal vehicle control system is typically designed to be hierarchical and consists of an upper level controller and a lower level controller, as shown in Fig. 1. 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 [3]–[5]. In this paper, we shall deal exclusively with the design of the upper level controller and assume that a reasonable lower level controller exists. Designing the upper level controller to be robust to the performance of the lower level controller will be considered.

The upper level controller typically determines the desired acceleration for each vehicle based on its own speed and its spacing and relative velocity from preceding vehicles in the same lane on the highway. An important consideration in the design of the upper level controller is the need to ensure "string stability". The string stability of a string of vehicles refers to a property in which spacing errors are guaranteed not to amplify as they propagate toward the tail of the string [4]–[6]. For example, string stability ensures that any errors in spacing between the second and third cars do not amplify into an extremely large spacing error between cars 10 and 11 further up in the string. A precise mathematical definition of string stability can be found in [5]. Let the spacing errors ε_i and ε_{i-1} of consecutive cars be related by the transfer function

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

Then the condition

$$\|\hat{H}(s)\|_\infty \leq 1 \tag{2}$$

guarantees that $\|\varepsilon_i\|_2$ never amplifies upstream.

In the case of a fully automated highway system with vehicles operating in platoons, the objective is to maintain constant small spacing between the vehicles in the platoon. In this case, the spacing error ε_i for the ith vehicle is defined as

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

where L is the desired constant spacing between vehicles in a platoon (typically 2–10 m). Results in [5] show that the following upper control algorithm ensures string stability in the platoon:

$$\begin{aligned}\ddot{x}_{i\_\text{des}} = {} & (1-C_1)\ddot{x}_{i-1} + C_1\ddot{x}_\ell - (2\xi - C_1(\xi + \sqrt{\xi^2-1})) \\ & \times \omega_n \dot{\varepsilon}_i - (\xi + \sqrt{\xi^2-1}))\omega_n C_1(v_i - v_\ell) - \omega_n^2 \varepsilon_i. \end{aligned} \tag{4}$$

Here, v_ℓ and $\ddot{x}_\ell$ are the speed and acceleration of the lead vehicle, $\ddot{x}_{i-1}$ is the acceleration of the preceding vehicle, ε_i is the spacing error defined by (3), and v_i is the velocity of the present vehicle. $C_1, \xi$and ω_n are control gains. The gain C_1 takes on values $0 \leq C_1 < 1$ 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 one for critical damping. The gain ω_n is the bandwidth of the controller. Note that each vehicle needs access to the lead vehicle speed (v_ℓ) and acceleration $(\ddot{x}_\ell)$ and preceding vehicle acceleration $(\ddot{x}_{i-1})$. The platoon algorithm, therefore, needs wireless radio communication between the cars in a platoon.

Vehicles with ACC, on the other hand, are designed to operate on today's highways and do not have intervehicle communication. Their operation is said to be autonomous. It is impossible to maintain string stability in a string of autonomous vehicles if the constant spacing policy of (3) is used.

An autonomous control system can, however, be designed to be string stable if the desired spacing is variable with speed [5], [6]

$$x_{i\_\text{des}} = x_{i-1} - L - hv_i. \tag{5}$$

The constant of proportionality h is called the "time gap."

The spacing error in this case is defined as

$$\delta_i = x_i - x_{i-1} + L + h\dot{x}_i \tag{6}$$

and string stability is maintained if

$$\|\hat{H}(s)\|_\infty = \left\| \frac{\delta_i}{\delta_{i-1}} \right\|_\infty \leq 1. \tag{7}$$

The following control law:

$$\ddot{x}_{i\_\text{des}} = -\frac{1}{h}(\dot{x}_i - \dot{x}_{i-1} + \lambda \delta_i) \tag{8}$$

ensures that

1) $\delta_i \to 0$ in the absence of lead vehicle acceleration;
2) string stability is maintained in the presence of lead vehicle acceleration/deceleration as long as

$$h > 2\tau_\text{lag} \tag{9}$$

where τ_lag is the lag in tracking the desired acceleration specified by (7). In other words, if the actual acceleration were related to the desired acceleration by

$$\tau \dddot{x}_i + \ddot{x}_i = \ddot{x}_\text{des} \tag{10}$$

then string stability is ensured by satisfying (8). The tracking of the desired acceleration so as to satisfy (10) is ensured by the lower level controller. The control gain λ determines the rate of convergence of the spacing error δ_i.

High traffic throughput can be achieved with the above autonomous controller if the time gap h can be made small. However, the string stability condition of (9) means that the time gap must remain above the critical value $2\tau_\text{lag}$. The lag τ_lag arises due to lag in actuators, the bandwidth of the lower level controller that tracks the desired acceleration and filtering of the radar, etc. Analytical and experimental studies show that τ_lag typically has a value of the order of 0.5 s [4].

Typical commercial ACC systems designed with a time gap spacing policy achieve a time gap between 1 and 2 s. This translates into 30–60 m spacing between cars at highway speeds. Besides the overall detrimental effect on traffic flow, such a large spacing between cars also results in "cut ins" by other manually driven vehicles so that the driver of the ACC car might question the value of the ACC system.

Another limitation of the above controller, as seen from (8), is that the control effort is inversely proportional to the time gap so that the time gap cannot be made too small.

The typical ACC system also suffers from a significant tradeoff between ride quality and spacing accuracy due to noisy range-rate signals [4]. Frequency modulated continuous wave (FMCW) radar sensors used in ACC systems typically yield good range measurements but have very noisy range rate signals. In the case of the platoon system, the existence of wireless communication between vehicles in a platoon means that range rate can be calculated using the speed of the preceding vehicle obtained from communication. This is a major advantage for the platoon system in the sense that spacing accuracy and ride quality can both be achieved with relative ease [4].

III. SAACC System Operation

The semi-autonomous system developed in this paper combines the advantages of the autonomous ACC systems with the performance and traffic flow advantages of the platoon system. In Section IV, we show how communication with only the preceding vehicle on the highway can be used to recover much of the performance, robustness, and traffic flow advantages of the platoon system. In this section, we propose a very simple communication system that could be used for communication between succeeding vehicles without the need for any vehicle to have an "address."

Each vehicle with a SAACC system would be equipped with a radio receiver on its front bumper and a radio transmitter on its rear bumper. It would be able to receive communicated information from its immediately preceding similarly equipped target vehicle in the same lane. The radio communication system would, thus, function like line-of-sight radar or infrared sensors. No centralized spectrum assignment or receiving stations would, therefore, be required. All SAACC cars could be equipped with similar equipment and could receive and transmit completely autonomously at one single radio frequency.

The SAACC system developed in this paper does not require formation of vehicles into platoons, dynamic assignment of frequencies for intraplatoon communication as platoon size and geographic locations change, platoon-to-roadside communication, etc.

A SAACC vehicle would cruise at user defined speed until it identifies a target vehicle in its lane. If the target vehicle is also a SAACC radio equipped vehicle, it would close the gap to a few meters and take advantage of the higher accuracy and smoother ride of the SAACC system. If the target vehicle is not radio equipped, the SAACC vehicle would perform like a well designed autonomous ACC vehicle and operate at larger intercar spacing. As more and more vehicles on the highway become SAACC radio equipped, the traffic flow of the highway could increase significantly.

IV. Theoretical Results

A. Derivation of Control Algorithm

The objective of our control design is to recover the performance of the platoon system while using communication from only the preceding vehicle on the highway. We, therefore, assume the structure of the controller to be

$$u_{\text{syn}} = -k_1\ddot{x}_{i-1} - k_2\ddot{x}_i - k_3\dot{\varepsilon}_i - k_4\varepsilon_i - k_5\dot{x}_i. \tag{11}$$

The controller has the same type of linear feedback structure as the "platoon" controller of (4) and the autonomous controller of (8). All the variables available for feedback in the presence of communication with the preceding vehicle are used in the control law.

The design approach is to use the constant time gap spacing policy, but to design the control law to use the additional communicated information from the preceding car to overcome the shortcomings of the autonomous controller described in Section II.

The derivatives of δ_i defined in (6), are obtained as follows:

$$\dot{\delta}_i = \dot{\varepsilon}_i + h\ddot{x}_i \tag{12}$$
$$\ddot{\delta}_i = \ddot{\varepsilon}_i + h\dddot{x}_i. \tag{13}$$

In the presence of unknown actuator dynamics represented by a first-order lag, we have

$$\tau\dddot{x}_i + \ddot{x}_i = u_{\text{syn}}. \tag{14}$$

Substituting from (11)

$$\tau\dddot{x}_i + \ddot{x}_i = -k_1\ddot{x}_{i-1} - k_2\ddot{x}_i - k_3\dot{\varepsilon}_i - k_4\varepsilon_i - k_5\dot{x}_i. \tag{15}$$

From (13), $\ddot{x}_{i-1}$ can be obtained as follows:

$$\ddot{x}_{i-1} = \ddot{x}_i - \ddot{\delta}_i + h\dddot{x}_i. \tag{16}$$

Substituting from (12), (13), and (16) into (15) and rearranging, we obtain

$$\begin{aligned}\tau\dddot{x}_i + \ddot{x}_i = &-k_1h\dddot{x}_i + \ddot{x}_i(-k_1 - k_2 + k_3h)\\ &+ \dot{x}_i(k_4h - k_5) + k_1\ddot{\delta}_i - k_3\dot{\delta}_i - k_4\delta_i.\end{aligned} \tag{17}$$

If we impose the following relations between the gains k_1, k_2, k_3, k_4 and k_5

$$-k_1h = \tau \tag{18}$$
$$k_4h = k_5 \tag{19}$$

and

$$-k_1 - k_2 + k_3h = 1 \tag{20}$$

then the closed-loop dynamics of δ_i can be described by

$$k_1\ddot{\delta}_i - k_3\dot{\delta}_i - k_4\delta_i = 0. \tag{21}$$

Since the actuator dynamics are unknown, it will not be possible to choose k_1 according to (18). Closed-loop dynamics and string stability when τ is unknown are discussed in Section IV-B.

If k_1 is negative and k_3 and k_4 are both positive, then the poles of the closed-loop dynamics $-k_1\ddot{\delta}_i + k_3\dot{\delta}_i + k_4\delta_i = 0$ are in the negative left half plane if

$$k_3^2 + 4k_1k_4 > 0. \tag{22}$$

Accordingly, by choosing

$$k_3 = \frac{1}{h}(1 - k_1k_4h^2) \tag{23}$$

we obtain

$$\begin{aligned}k_3^2 + 4k_1k_4 &= \frac{1}{h^2}\left(1 + k_1^2k_4^2h^4 - 2k_1k_4h^2\right) + 4k_1k_4\\ &= \frac{1}{h^2}\left(1 + k_1^2k_4^2h^4 + 2k_1k_4h^2\right)\\ &= \left(\frac{1}{h} + hk_1k_4\right)^2 > 0\end{aligned} \tag{24}$$

ensuring that (22) is satisfied.

The gains and k_4 can be expressed in terms of k_1 and k_5 so that there are only two gains to be chosen in all. From (19) and (23), k_3 is obtained as

$$k_3 = \frac{1}{h}(1 - k_1k_5h). \tag{25}$$

From (20) and (25), k_2 is obtained as

$$k_2 = -k_1 - hk_1k_5. \tag{26}$$

The coordinated control algorithm is, therefore, given by

$$u_{\text{syn}} = -k_1\ddot{x}_{i-1} + (k_1 + hk_1k_5)\ddot{x}_i - \frac{1}{h}(1 - k_1k_5h)\dot{\varepsilon}_i - \frac{k_5}{h}\varepsilon_i - k_5\dot{x}_i. \quad (27)$$

B. Proof of String Stability and Robustness to Internal Vehicle Dynamics

We investigate string stability of an infinite number of vehicles operating under the semi-autonomous control algorithm of (27).

From the definition $\delta_i = \varepsilon_i + h\dot{x}_i$, we obtain

$$\dot{x}_i = \frac{\delta_i - \varepsilon_i}{h}. \quad (28)$$

Substituting from (27) and (28) into (14) and after considerable algebraic simplification, we obtain

$$\varepsilon_i = \delta_i\left\{\frac{\tau s^2 + s - k_1k_5hs + k_5}{(\tau + k_1h)s^2}\right\}. \quad (29)$$

To analyze the string stability of the system, we obtain a relation between the spacing errors of consecutive vehicles

$$\delta_i - \delta_{i-1} = \varepsilon_i - \varepsilon_{i-1} + h\dot{\varepsilon}_i. \quad (30)$$

Substituting from (29) and then simplifying, we obtain the following transfer function:

$$\frac{\delta_i}{\delta_{i-1}} = \frac{1}{1 + hs\left\{\frac{\tau s^2 + s - k_1k_5hs + k_5}{-k_1hs^2 + s - k_1k_5hs + k_5}\right\}}. \quad (31)$$

The H_∞-norm of the transfer function $H(s) = (\delta_i/\delta_{i-1})(s)$ is equivalent to the supremum of the ratio of 2-norms $(\|\delta_i\|_2)/(\|\delta_{i-1}\|_2)$.

Substituting $s = j\omega$ in (31) and then calculating absolute values, we find (see (32) at the bottom of the page.) Hence, we need

$$\begin{aligned}(k_5 + k_1h\omega^2)^2 + (1 - k_1k_5h)^2\omega^2 &\le (k_5 + k_1h\omega^2 - h\omega^2 + k_1k_5h^2\omega^2)^2 \\ &\quad + \omega^2(1 - k_1k_5h - \tau h\omega^2 + k_5h)^2.\end{aligned}$$

After algebraic simplification, we find

$$\begin{aligned}&\|H(j\omega)\| \le 1 \\ &\Leftrightarrow 0 \le -2h\omega^2(1 - k_1k_5h)(k_5 + k_1h\omega^2) \\ &\quad + h^2\omega^4(1 - k_1k_5h)^2 + \omega^2h^2(k_5 - \tau\omega^2)^2 \\ &\quad + 2h\omega^2(1 - k_1k_5h)(k_5 - \tau\omega^2)\end{aligned}$$

which further simplifies to

$$\begin{aligned}0 \le{}& 2h\omega^2(1 - k_1k_5h)(-k_1h\omega^2 - \tau\omega^2) \\ &+ h^2\omega^4(1 - k_1k_5h)^2 + h^2\omega^2(k_5 - \tau\omega^2)^2. \quad (33)\end{aligned}$$

If the gain k_1 is chosen as follows:

$$-k_1h > \tau \quad (34)$$

then $\|H(j\omega)\| \le 1$. Note that if k_1 is chosen in accordance with (34), it will be a negative constant. Since k_5 will be a positive constant, we have $(1 - k_1k_5h) > 0$. Hence, (34) is the only condition that requires to be satisfied. The requirement that k_1 be negative and k_5 be positive was already clear from the closed-loop stability condition for (21) in Section IV.

Note also, that satisfying (34) does not require accurate knowledge of the constant τ, but only an estimate of the maximum value of τ. This is important since τ represents lower level vehicle dynamics and is likely to vary with operating conditions as well as from vehicle to vehicle.

With the above control law, string stability can be maintained in the string of vehicles even for very small h and even in the presence of the lag τ_{lag} in the lower level controller performance.

C. Comparison of Actuator Effort

From (8), the control effort for the ith car in the case of the autonomous control system is given by

$$u_i = -\frac{1}{h}(\varepsilon_i + \lambda\delta_i). \quad (35)$$

Using the transfer function

$$\begin{aligned}G_{\text{auto}}(s) &= \frac{\delta_i(s)}{\delta_{i-1}(s)} \\ &= \frac{\varepsilon_i(s)}{\varepsilon_{i-1}(s)} \\ &= \frac{s + \lambda}{h\tau s^3 + hs^2 + (h\lambda + 1)s + \lambda}\end{aligned}$$

we obtain

$$\begin{aligned}U_{i\_\text{autonomous}}(s) &= -\frac{1}{h}[s\varepsilon_i(s) + \lambda\delta_i(s)] \\ &= -\frac{1}{h}G_{\text{auto}}(s)[s\varepsilon_{i-1}(s) + \lambda\delta_{i-1}(s)]. \quad (36)\end{aligned}$$

Similarly, we find that the equation for semi-autonomous control effort is given by

$$U_{i\_\text{semi-autonomous}}(s) = -\frac{1}{h}G_{\text{semi}}(s)[s\varepsilon_{i-1}(s) + \lambda\delta_{i-1}(s)] \quad (37)$$

with

$$G_{\text{semi}} = \frac{ks^2 + (1 + k\lambda)s + \lambda}{h\tau s^3 + (h + k + k\lambda h)s^2 + (1 + k\lambda + k\lambda h)s + \lambda}. \quad (38)$$

The Bode magnitude plots of $G_{\text{auto}}(s)$ and $G_{\text{semi}}(s)$ are shown in Fig. 2. Equations (36) and (37) imply that for the same

$$\|H(j\omega)\|^2 = \frac{(k_5 + k_1h\omega^2)^2 + (1 - k_1k_5h)^2\omega^2}{(k_5 + k_1h\omega^2 - h\omega^2 + k_1k_5h^2\omega^2)^2 + \omega^2(1 - k_1k_5h - \tau h\omega^2 + k_5h)^2}. \quad (32)$$

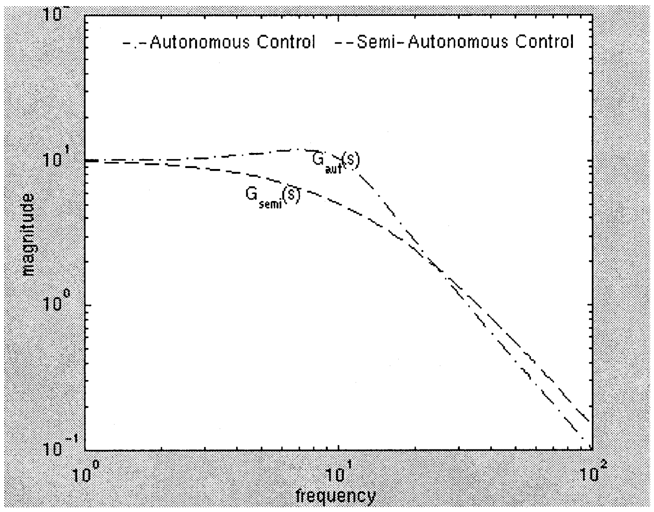


Fig. 2. Bode comparison of control effort.

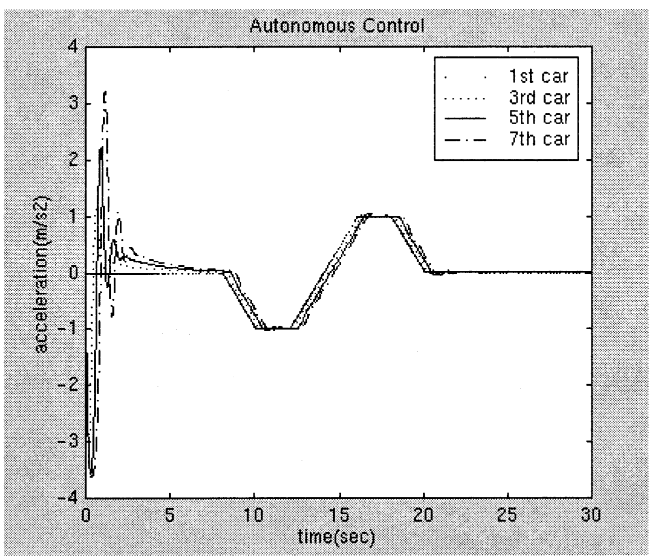


Fig. 3. Autonomous ACC response to initial spacing errors.

spacing errors in vehicle $i-1$, the control effort of vehicle i would always be smaller in the case of semi-autonomous control compared to autonomous control.

V. Simulation Studies

The simulation studies in the paper show that the semi-autonomous controller provides superior ride and spacing accuracy for various operational maneuvers. Moreover, it does so by always using smaller actuator efforts.

A. Transient Response to Initial Spacing Error

Consider five cars traveling together and an initial spacing error of 1.0 m in each of the four following cars. Figs. 3 and 4 show the response of autonomous and SAACC systems to the initial spacing error. In addition, after the initial transient, the lead car executes an acceleration maneuver as shown in the plot.

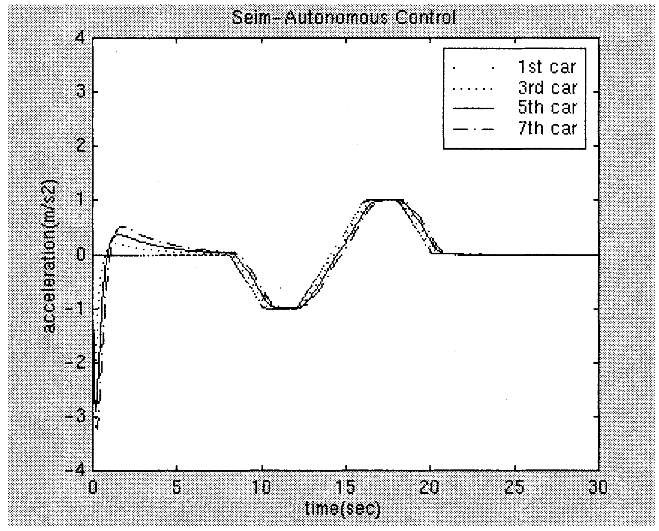


Fig. 4. Semi-autonomous response to initial spacing errors.

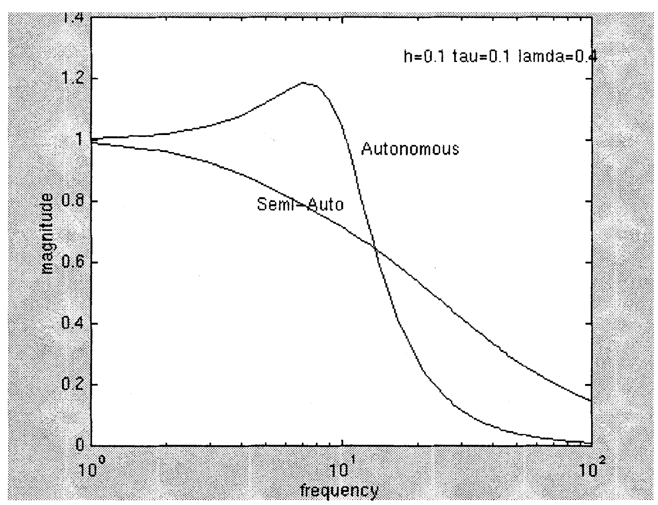


Fig. 5. Bode magnitude plots for string stability.

A headway time of 0.1 s and $\tau_{\text{lag}} = 0.1$ have been assumed for both systems. The step change in spacing error causes the autonomous ACC system to have large oscillatory transients that keep increasing toward the tail of the string of vehicles. The semi-autonomous system, on the other hand, has a well-damped response in which the cars quickly reach their correct steady-state spacing values.

B. Maneuvers at String Unstable Frequency

A comparison of the Bode magnitude plots of the string stability transfer functions $G(s) = \frac{\delta_i}{\delta_{i-1}}(s)$ for the autonomous and SAACC systems is shown in Fig. 5. For $h = 0.1$, $\tau_{\text{lag}} = 0.1$ and $\lambda = 0.4$, we see that the autonomous system is not string stable and $|G(j\omega)|$ exceeds one with a resonant peak in the magnitude plot occurring at $\omega = 7$ rad/s. The semi-autonomous system, on the other hand, is string stable.

The lead vehicle is assumed to have a sinusoidal component of acceleration with a frequency of 7 rad/s. Fig. 6 shows the accelerations of the lead, third, and fifth cars in the string of

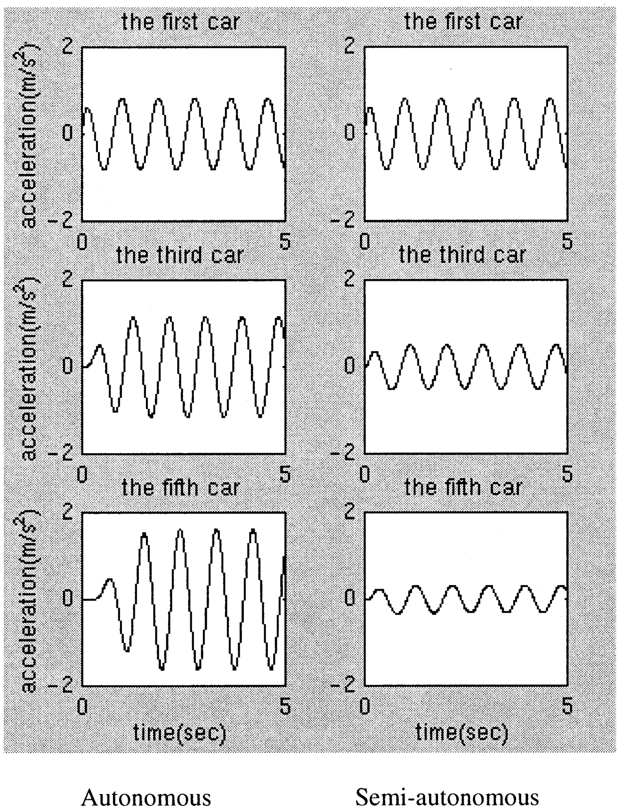


Fig. 6. Response to sinusoidal maneuvers of lead car.

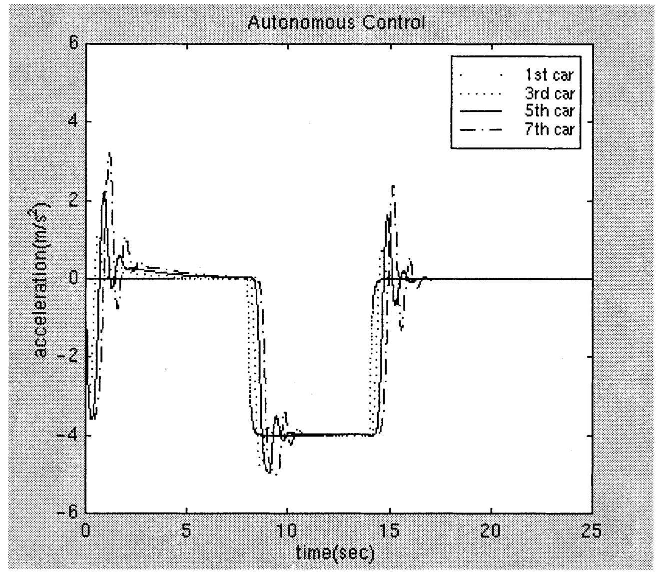


Fig. 7. Autonomous response to hard braking by the lead car.

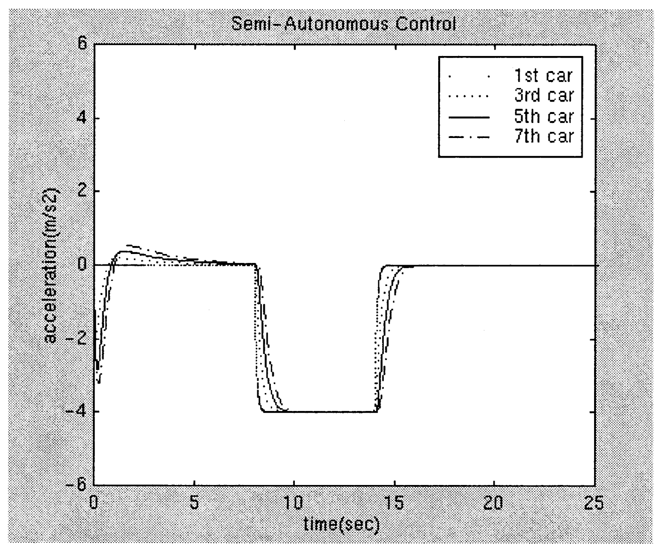


Fig. 8. Semi-autonomous response to hard braking by the lead car.

vehicles. In the case of the autonomous ACC system, the accelerations keep increasing toward the tail of the string of vehicles. The fifth car has a peak acceleration twice as much as the first car. On the other hand, the accelerations of the vehicles keep decreasing toward the tail of the platoon in the case of the semi-autonomous system. The sinusoidal oscillatory maneuvers of thelead car lead to decreasing oscillations as the oscillations propagate toward the tail.

C. Emergency Hard Braking

Hard braking of a vehicle is an expected emergency scenario on a highway. In Figs. 7 and 8, the lead car in a string of vehicles brakes continuously at -4 m/s^2 for a period of 5 s (between 10 and 15 s on the plot). The four vehicles following the lead car are allowed to brake at a maximum deceleration rate of -4.5 m/s^2 (after which the brake actuators saturate). Fig. 7 shows the response of the autonomous ACC system. In response to the step input in desired acceleration, we see that the following vehicles have an oscillatory response in the case of autonomous ACC, as predicted by the resonant peak in Fig. 5. Furthermore, the string instability causes this oscillation at the resonant frequency to amplify as it propagates toward the tail of the string of vehicles. In the case of the semi-autonomous vehicles, on the other hand, (Fig. 8), the response to the step input is over damped and no oscillations are seen.

The simulation results in the three scenarios described above show that the semi-autonomous system maintains string stability for very small headway even in the presence of unmodeled lower controller or internal vehicle dynamics. The use of the semi-autonomous system leads to smoother, safer, and a better damped transient response with lower magnitudes of actuation effort compared to autonomous control.

VI. Conclusion

The concept of a SAACC system was developed in this paper that utilizes an intervehicle communication system that can be implemented in an "autonomous" manner. The semi-autonomous systems would be immediately deployable on today's highways, where both manually driven and adaptive cruise control vehicles can coexist.

The limitations of present day autonomous ACC systems were explained. The semi-autonomous system overcomes these limitations and provides significant advantages over present-day ACC systems in terms of highway safety and traffic flow.

The paper showed analytically that the proposed system would be able to safely maintain smaller time gaps, would be string stable, and would be guaranteed to have smaller actuator inputs than a standard autonomous ACC system. The simulation results in the paper confirmed the theoretical results and indicated that, in general, safer and smoother transient performance with use of smaller control efforts are achieved by semi-autonomous control.

References

[1] P. Ioannou, C. C. Chien, and J. Hauser, "Autonomous intelligent cruise control," in Intelligent Vehicle Highway Systems America, Washington D.C., May 1992.

[2] "Intelligent cruise control field operational test (Interim Rep.)," Univ. Michigan Transportation Res. Inst., Ann Arbor, MI, Rep. UMTRI-97-11, Aug. 1997.

[3] R. Rajamani, H. S. Tan, B. Law, and W. B. Zhang, "Demonstration of integrated lateral and longitudinal control for the operation of automated vehicles in platoons," *IEEE Trans. Contr. Syst. Technol.*, vol. 8, pp. 695–708, July 2000.

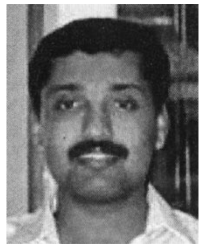
[4] R. Rajamani and S. E. Shladover, "An experimental comparative study of autonomous and cooperative control systems for automated vehicles," *J. Transport. Res., Pt. C—Emerging Technol.*, vol. 9, no. 1, pp. 15–31, Feb. 2001.

[5] "String stability of interconnected systems: an application to platooning in automated highway systems," Ph.D. Dissertation, Dept. Mech. Eng., Univ. Calif., Berkeley, 1995.

[6] D. Swaroop, J. K. Hedrick, C. C. Chien, and P. Ioannou, "A comparison of spacing and headway control laws for automatically controlled vehicles," *Vehicle Syst. Dynamics J.*, vol. 23, no. 8, pp. 597–625, Nov. 1994.

[7] T. Watanabe, N. Kishimoto, K. Hayafune, K. Yamada, and N. Maede, Development of an intelligent cruise control system, Mitsubishi Motors Corp. Rep., Japan.

[8] D. Yanakiev and I. Kanellakopoulos, "Variable time headway for string stability of automated heavy-duty vehicles," in *Proc. 34th IEEE Conf. Decision and Control*, New Orleans, LA, Dec. 1995, pp. 4077–4081.



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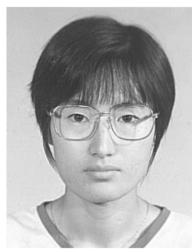

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