Vehicle-Follower Control With Variable-Gains for Short Headway Automated Guideway Transit Systems[1]

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The use of the vehicle-follower approach for the longitudinal control of vehicles in an automated transit system is discussed for the short headway (0.4 to 3.0 s) range of operation. It is shown, if one adopts a constant gain approach, that the required bandwidth of such controllers increases rapidly with a decrease in nominal headway if safe operation is to be assured. Initial conditions typically encountered during merge and overtake maneuvers can cause unacceptably large jerk and acceleration levels if applied to such constant gain controllers. A candidate for overcoming these problems is a control technique which first employs gains appropriate to the initial conditions and then varys the gains to achieve the desired values as controller errors are reduced. Under nominal operating conditions, this time-varying gain approach is also demonstrated to satisfy performance requirements based upon the kinematics of ride quality constraints.

Introduction

Automated Guideway Transit (AGT) Systems have received considerable attention as a means of providing a level of service that will attract people from the automobile while reducing or maintaining operating costs at an acceptable level in comparison with other forms of public transit. Much of the emphasis in the development of these systems has been placed upon the design of the longitudinal control system, i.e., the regulation of vehicle speeds and spacings. One approach to longitudinal control referred to as vehicle-following essentially proposes that vehicles maintain speeds and spacings in a manner determined by the state of the immediately preceding vehicle. Several investigators [1–5][2] have successfully applied optimal control theory in the design of a vehicle-follower controller. The feasibility of using a linear, time-invariant controller employing a realistic propulsion system has been demonstrated for headways as low as 4 seconds [6–9].

Some forms of AGT, such as Personal Rapid Transit (PRT), which use small 4 to 6 passenger vehicles, may require operation at headways of one second or less in order to achieve their required capacities. This paper examines the requirements and constraints that will be imposed on a control system employing vehicle-following at headways from 0.4 to 3.0 seconds and at speeds from 8.0 to 24.0 m/s. The current analysis is limited to control systems operating under nominal conditions, as opposed to emergency operation.

In the following sections, the dynamic characteristics of vehicle-follower control are described and problems peculiar to very short headways are identified. It is shown that a constant gain controller which has acceptable regulation performance may be unsuited for transient conditions. A kinematic analysis is then presented in order to illustrate the requirements imposed on the dynamic controller by transient maneuvers characteristic of nominal operation under given acceleration and jerk constraints. Finally, a time-variable-gain control approach is developed which may provide the required control at very short headways by the application of smoothly increasing gains during a transition.

Vehicle-Follower Control Characteristics

The vehicle-follower approach to longitudinal vehicle control employs two nominal modes of operation which may be referred to as the regulation mode and the velocity-command mode. In the regulation mode, a vehicle is assumed to be initially close to its desired speed and spacing (or headway) and the controller responds to perturbations or errors from these nominal values by varying vehicle propulsion commands. A vehicle operates in the velocity-command mode when its spacing is sufficiently large to render precise spacing control unnecessary. In this latter mode, the controller provides vehicle propulsion commands to maintain a designated speed. In addition to functioning in the two modes, the controller must be capable of handling the transition from

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one mode to the other while satisfying constraints imposed by passenger comfort criteria. Previous vehicle-following studies have primarily centered on the design of a controller for the regulation mode of operation as opposed to the mode transition problem, which is significant at short headways. To understand the nature of the mode transition problem, the characteristics of nominal regulation control are now discussed, along with the kinematics of mode transitions.

Linear Second-Order Model

Classical techniques may be applied to the design of a vehicle-follower controller that can operate in either the regulation or velocity-command mode. For purposes of this discussion a second-order model is adopted which provides a good approximation to higher order models that take into account many more vehicle and plant parameters [8, 10]. The second-order representation permits an analytical interpretation of the effects of headway on controller design.

A block diagram of the second-order controller is shown in Fig. 1. The variables, a, v, and x in Fig. 1 refer to acceleration, velocity, and position, respectively; while the subscripts, p and t, denote preceding and trailing vehicles, respectively. In the regulation mode, the controller is designed to operate under a constant headway policy, i.e., steady state vehicle spacing is given by the desired headway, h, times vehicle speed. The transfer function for the system shown in Fig. 1, is given by

$$\frac{V_t(s)}{V_p(s)} = \frac{G_v s + G_x}{s^2 + (G_v + hG_x)s + G_x}, \tag{1}$$

where s is the Laplace operator, G_x is the gain constant associated with position error, and G_v is the gain constant associated with relative velocity between the vehicles. Although designed for regulation mode operation, the controller model is readily adapted to operate in the velocity-command mode by forcing G_x to zero and substituting a desired speed command in place of v_p.

The physical significance of the controller gains in the regulation mode and their relationship to the design headway may be obtained by comparing (1) to the standard form second-order transfer function

$$\frac{C(s)}{R(s)} = \frac{\omega_n^2(\alpha s + 1)}{s^2 + 2\zeta\omega_n s + \omega_n^2}. \tag{2}$$

From this the damping coefficient of the response is given by

$$\zeta = \frac{hG_x + G_v}{2\sqrt{G_x}}. \tag{3}$$

A smooth, stable, but rapid transient response characteristic is obtained [7] by choosing $\zeta = 1.0$. The relative velocity gain can be found from

$$G_v = \beta\sqrt{G_x}, \tag{4}$$

where $0 \leq \beta \leq \sqrt{2}$ is a constant of proportionality representing the relative dependence of the control on each of the gains G_x and G_v. On the basis of previous results [6], β is chosen to be 0.6.

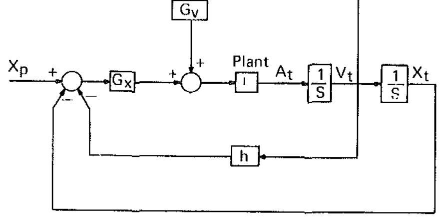

Fig. 1 Block diagram of second-order controller

The actual relationship between the required bandwidth of the system, as approximated by natural frequency ω_n, and the design headway may then be obtained by comparison of (1), (2), and (4) to obtain

$$\omega_n = \sqrt{G_x} = \frac{2 - \beta}{h}. \tag{5}$$

The controller gains, and in turn the bandwidth of the system, thus increase rapidly with decreasing headway for constant gain designs such as shown in Fig. 1.

In addition, since the response of a vehicle must be limited to acceptable levels of jerk and acceleration, the allowable magnitude of the spacing and velocity error variables introduced to a constant gain controller decreases rapidly with headway. This is easily seen by examining the equation of motion for the system shown in Fig. 1, which is

$$A_c = G_x S_e + G_v v_e \tag{6}$$

where A_c is the acceleration command to the vehicle,

$$S_e = x_p - x_t - hv_t \tag{7}$$

is the spacing error, and

$$v_e = v_p - v_t \tag{8}$$

is the relative velocity between the vehicles. If one assumes an accepted limit on service acceleration, for example 2.6 m/s², and computes G_x from (5) it will be revealed that spacing errors on the order of meters may be tolerated at three second headways, but only on the order of tenths of meters for fractional second headways. Similar results apply to the allowable relative velocity, v_e, if limits not only on acceleration but also on jerk are considered [11]. These constraints on the error variables require that the range of initial conditions that may be encountered in the operation of short headway systems be examined.

Kinematics of Overtaking Maneuvers

In addition to operation in the nominal modes discussed above, vehicles in AGT systems must be capable of accomplishing transient maneuvers such as merging with other traffic and the overtaking of slower moving vehicles. These events characteristically require vehicles at relatively large initial spacings to close to the minimum spacing of nominal operation and to do so by performing a maneuver which is both safe and is carried out within acceleration and jerk limits. Discussion herein is limited to overtaking maneuvers, as this suffices to illustrate the large range of initial conditions that a vehicle-follower controller must accommodate in short headway operation. Two specific cases, which may realistically occur in nominal operation, will be examined. The first case presents an example of the size of the initial condition errors that may be encountered, while the second case shows the implications of potential lead vehicle actions.

Extreme Overtake Situation. An extreme overtake situation is one in which a trailing vehicle is accelerating at service rate A_s to the maximum guideway speed, $v_{\max}$, and detects a preceding vehicle moving at the minimum guideway speed, $v_{\min}$. The large initial difference in vehicle velocities allows the possibility of a collision if corrective action is not taken. Because of the service jerk limit, J_s, the trailing vehicle will continue to accelerate for a brief period before it can commence a braking action resulting in a further increase in the velocity difference.

It is desired to find the minimum initial spacing S_m at which the trailing vehicle must begin decelerating such that it can reach nominal spacing $S_0 = hv_{\min}$ at the end of the maneuver without resorting to emergency braking. Assuming a deceleration maneuver on the service jerk and acceleration limits, S_m for the trailing vehicle can be determined kinematically [11] as

$$S_m = \frac{(v_{ti} - v_{\min})^2}{2A_s} + \frac{2A_s}{J_s}(v_{ti} - v_{\min}) + \frac{17}{24}\frac{A_s^3}{J_s^2} + hv_{\min} \quad (9)$$

where v_{ti} is the initial velocity of the trailing vehicle. For $h = 0.4$ s, $v_{ti} = 22.7$ m/s, $v_{\min} = 8.0$ m/s, $A_s = 2.6$ m/s^2, and $J_s = 2.6$ m/s^3, $S_m = 76.0$ meters, considerably greater than the nominal spacing of $S_0 = 3.2$ meters at the end of the maneuver. Fig. 2 presents a scale drawing of the initial and final spacings for the extreme overtake case. The initial spacing error S_{me} seen by the trailing vehicle is then given by

$$S_{me} = S_m - hv_{ti} \quad (10)$$

or in this example, $S_{me} = 66.9$ meters. This value is far from compatible with a constant gain controller designed to operate at fractional second headways.

Nominal Overtake Situation. As a second example, consider the effect of unexpected preceding vehicle maneuvers on the minimum initial spacing required for an overtake maneuver by the trailing vehicle. Assume that a trailing vehicle is moving at a constant speed $v_{\max}$ and suddenly encounters a preceding vehicle traveling at $v_{pi} = v_{\max}/2$. The trailing vehicle initiates a braking maneuver to achieve v_{pi} and nominal spacing S_0 behind the preceding vehicle. However, should the preceding vehicle unexpectedly decide to brake to $v_{\min} < v_{\max}/2$, the possibility of a collision exists if the trailing vehicle had not begun its deceleration maneuver soon enough. The minimum spacing needed for the trailing vehicle to attain a nominal spacing should the preceding vehicle remain traveling at $v_{\max}/2$ can be found from [11]

$$S_m = \frac{(v_{\max} - v_{pi})^2}{2A_s} + v_{\max}\frac{A_s}{2J_s} + v_{pi}\left(h - \frac{A_s}{2J_s}\right). \quad (11)$$

Using $v_{\max} = 24$ m/s with other parameter values equivalent to those in the previous example yields $S_m = 38.5$ meters, which corresponds to a $S_{me} = 28.9$ meters. Fig. 3(a) depicts this nominal overtake situation. However, Fig. 3(b) indicates that for the same initial S_m but both vehicles now maximally braking at rate, $-A_s$ to $v_{\min} = 8.0$ m/s, the trailing vehicle will find itself ahead (conceptually) of the preceding vehicle if no emergency braking is applied. The appropriate S_m for this situation is given by [11]

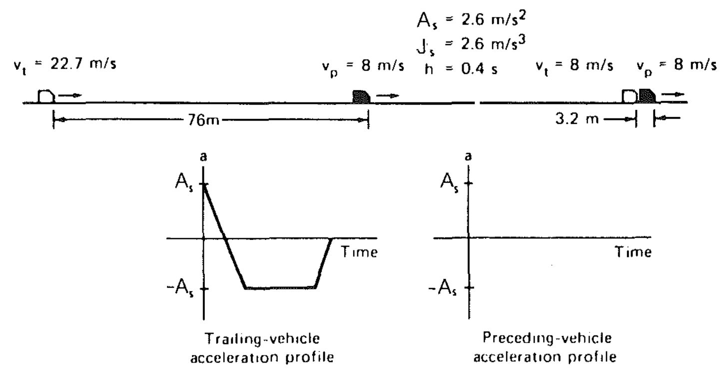

Fig. 2 Case 1 — Extreme overtake

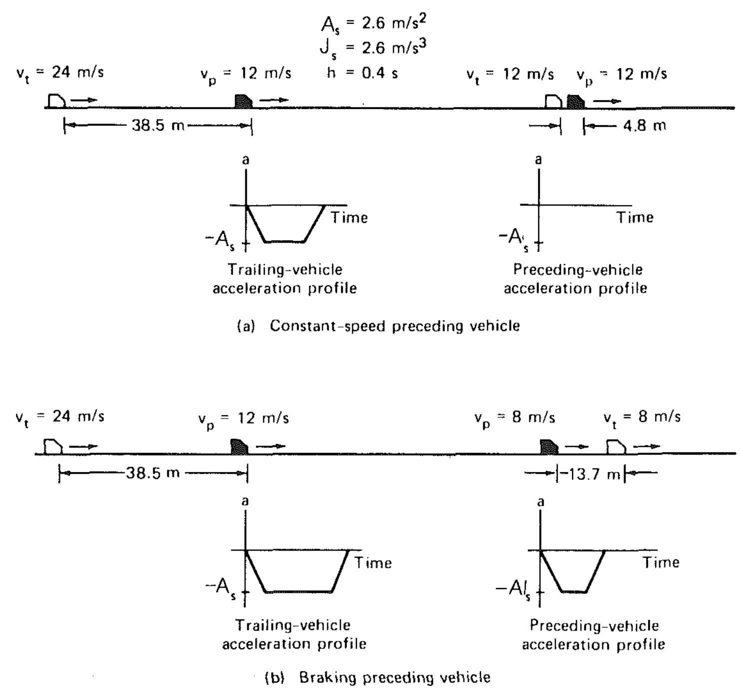

Fig. 3 Case 2 — Nominal overtake

$$S_m = \frac{3}{8}\frac{v_{\max}^2}{A_s} + v_{\max}\frac{A_s}{4J_s} - v_{\min}\left(\frac{v_{\max}}{2A_s} - h\right) \quad (12)$$

or in this case, $S_m = 55.4$ meters which corresponds to $S_{me} = 45.8$ meters. Thus, since the trailing vehicle has no knowledge of the preceding vehicle's future actions, overtake situations require a trailing vehicle to react at spacing errors appropriate to the worst case maneuver capable of being performed by itself or the preceding vehicle.

Both the nominal and extreme overtake situations have shown that the initial controller errors during a mode transition may not be compatible with the admissable errors of a fixed-gain, short headway controller. A feasible short headway AGT system must incorporate a mechanism that can accept large initial errors and provide a controlled transition to short headway regulation.

Time-Varying Gain Method

The previous discussion has shown the need of a control mechanism for short headway operations that can also accommodate the large errors associated with mode transitions while satisfying jerk and acceleration constraints. An examination of simple state limiting techniques has shown them to be unsatisfactory due to instabilities in the controller response when acceleration and jerk limits are severely applied [11]. A more viable approach to designing the mode transition mechanism is to vary the error sensitivity of the controller by manipulating the controller gains, thus enhancing the capability to accept large initial spacing and velocity errors.

In overtake situations such as those discussed above, the controller sensitivity can be reduced by initially implementing the gains associated with long headway operations, thus allowing large initial errors. The transition to short headway operation can then be accomplished by increasing these initial gains as errors are reduced, finally attaining the desired values of the gains. It is possible to employ a gain variation scheme in which the gains at any instant are identical to those for a fixed-gain controller designed for some particular headway. Interruption of the mode transition process by ending the gain variation is then acceptable since a stable, fixed-gain controller would be in operation although not at the desired headway. For the second-order controller model (Fig. 1), changing the headway term, h, in (5) from a constant to a time-varying function is sufficient to implement such a gain variation strategy.

The formulation of the time-varying gain approach, a discussion of the criterion for switching from the velocity-command mode to variable-gain control during overtake maneuvers, and simulation results which illustrate the viability of the technique are presented below. It is shown that the approach can successfully adjust to unpredictable behavior of a lead vehicle once an overtake maneuver is initiated.

Functional Description

The time-varying gain approach for the control of mode transitions in short headway operation is based in part on the known characteristics of the second-order model shown in Fig. 1, and in part on the selection of a time variable function $h(t)$ to replace h in Fig. 1. As a result, G_x and G_v also become functions of time such that, from (4) and (5),

$$G_x(t) = \left(\frac{2-\beta}{h(t)}\right)^2, \quad (13)$$

and

$$G_v(t) = \frac{2\beta - \beta^2}{h(t)}. \quad (14)$$

Note that satisfaction of (13) and (14) assures that whenever $h(t)$ becomes constant, a stable, well behaved system results because (3) will be satisfied automatically.

The general form for the headway function is

$$h(t) = h_D + (h_I - h_D)f(t) \quad (15)$$

where h_D is the desired headway, h_I is an initial headway to be defined and $f(t)$ is a monotonically decreasing function from one to zero. We now discuss the determination of h_I, the choice of the function $f(t)$, and the time constant of $f(t)$.

Choice of Initial Headway. The value of the initial headway used in (15) is related to the initial spacing, S_m, required between vehicles such that the overtake maneuver may be accomplished without exceeding acceleration and jerk limits. Specific examples of the calculation of S_m were presented in the previous section. In general, S_m may be calculated as a function of all possible combinations of initial velocities and accelerations of each vehicle [11]. Now it is clear that the variable gain controller must be activated (or the overtaking maneuver be initiated) at an initial spacing

$$x_p - x_t = S_I = K_I S_m \quad (16)$$

where $K_I \geq 1.0$ is a constant. Also, at the instant the maneuver is initiated, the acceleration command to the trailing vehicle may be expressed, by use of (6), (7), and (16) as

$$A_c = G_x(0)(S_I - v_t h_I) + G_v(0)v_e. \quad (17)$$

If we now impose the intuitive constraint that the initial acceleration command should be zero, (13), (14), and (17) may be combined to obtain the initial headway

$$h_I = \frac{S_I(2-\beta)}{v_t(2-\beta) - \beta v_e}. \quad (18)$$

It may be seen that if the relative velocity between vehicles is zero, the initial headway for an overtaking maneuver is exactly equal to the true headway between vehicles for the conditions of constant speed v_t and spacings S_I.

Choice of Time Function. The time function $f(t)$ and its time constant, i.e., the characteristic time of the variation in headway between h_I and h_D, control the response of the vehicle during an overtaking maneuver. The time function must be chosen such that a given maneuver is carried out safely when initiated at spacing S_I, and such that service rates on acceleration and jerk are not exceeded regardless of subsequent unexpected preceding vehicle maneuvers characteristic of nominal operation. The motivation for the latter concern results from the fact that the behavior of the preceding vehicle cannot be predicted with certainty. For example, the preceding vehicle may slow as part of its involvement in a merging maneuver while a trailing vehicle is simultaneously overtaking it.

In general, there is a minimum instantaneous spacing, $S_m(t)$, for any time during an overtaking maneuver from which the maneuver can be completed without exceeding service limits on acceleration and jerk, regardless of the behavior of the lead vehicle. General expressions for $S_m(t)$ have been developed [11] and are similar in form to those presented herein for S_m. Availability of these expressions then allows continuous comparison of the actual spacing error, $S_e(t)$, given by (7) during an overtaking maneuver, with

$$S_{me}(t) = S_m(t) - v_t h_D \quad (19)$$

to determine if a candidate function $f(t)$ maintains nominal kinematic constraints on such maneuvers.

Several candidate time functions for $f(t)$ were examined, including a linear variation in $f(t)$ from one to zero, segments of trigonometric functions, and exponential functions of the form

$$f(t) = e^{-t/\tau} \quad (20)$$

where τ is the time constant of the response. As will be shown, the latter form (with proper choice of τ) provided satisfactory vehicle response characteristics while satisfying the kinematic requirement that

$$S_e(t) \geq S_{me}(t) \tag{21}$$

for all t.

Choice of the time constant τ is based on the intuitive argument that it should be related to the magnitudes of the initial spacing and velocity errors to be overcome during the maneuver. The form

$$\tau = K_\tau \left| \frac{S_e(0)}{v_e(0)} \right| \tag{22}$$

was therefore chosen, where $K_\tau \geq 1.0$ is a design parameter and

$$S_e(0) = S_I - v_l h_D. \tag{23}$$

The rationale for the time varying gain approach, the choice of the time function and its time constant, and the determination of the initial spacings and headways for activating the control for an overtaking maneuver have now been established. The viability of the approach will next be discussed by means of some specific examples.

System Performance

The performance of the variable-gain vehicle-follower control approach was evaluated by computer simulation for various scenarios of nominal operation. This section describes the detailed plant and controller model used in the simulations, and presents simulation results for operation of the regulation mode (all vehicles operating at the design minimum headway), and for typical overtaking situations where variable-gain operation is used.

System Model

The system model used for simulation is shown in Fig. 4, and consists of a fourth-order plant model, a forward path filter containing acceleration and jerk limiters, and control consisting of the variable headway term $h(t)$ and the variable gains $G_x(t)$ and $G_v(t)$. These latter control parameters are chosen in a manner identical to that described above for the second-order model, which represents an approximation to the more detailed system shown in Fig. 4. The detailed model was chosen for the simulation because it permits verification of the selection of gains from a second-order approximation to a realistic system and because it allows the explicit inclusion of acceleration and jerk limiting to account for small excursions of the service limits.

The plant model shown in Fig. 4 is a phase variable representation of separately excited D.C. motor and the vehicle dynamics including a linearized approximation to aerodynamic drag [8, 10, 11]. For purposes of the present examples the parameters $K_m = 7.53$ m/V-s^3, $C_0 = 73.5$/s^2 and $C_1 = 39.1$/s were chosen so as to represent a 2250 Kg vehicle propelled by a 60 hp motor.

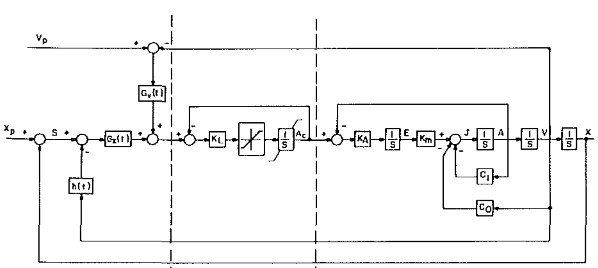

Fig. 4 Vehicle follower with time varying gains and acceleration — controlled plant

Values for the forward path gains, i.e., $K_L = 50.0$/s and $K_A = 40.0$ V-s/m, were determined by parametric design to provide adequate bandwidth and damping characteristics with the presence of hard limiters in the forward path. Finally, the limits of the input filter were chosen such that $A_c = A_s/A_{ss}$ and $\dot{A}_c = J_s/A_{ss}$ where A_{ss} is the dimensionless steady-state gain of the plant.

Operation in the Regulation Mode

Before proceeding to the operation of the system employing variable gains, we will verify the ability of the controller model shown in Fig. 4 to operate in the regulation mode by examining the response of a string of vehicles to a transient in the state of a lead vehicle when all trailing vehicles are initially operating at the design headway of the system. Such a situation implies zero initial conditions are applied to the controller, and that constant gain control, with gains given by (4) and (5), is employed.

Fig. 5 shows the response of a string of 6 vehicles (modeled according to Fig. 4) initially operating in the regulation mode to a jerk and acceleration limited lead vehicle speed reduction from 24 m/s to 12 m/s. The design headway is the minimum value considered in this study, i.e., $h = 0.4$ s. The response of each vehicle in the string is seen to be smooth but rapid, and that limits on acceleration and jerk are not exceeded. In addition, it may be seen that the response is string stable, or that the response of a given vehicle does not exceed in amplitude that of its predecessor. These results demonstrate that a constant gain controller can satisfactorily regulate the flow of vehicles at very short headways provided the vehicles are initially operating at the minimum or nominal design headway. This is in fact the situation that will prevail at the completion of overtake or merging maneuvers.

Operation During Overtake Maneuvers

The operation of the variable-gain technique will now be illustrated for two overtake scenarios typical of nominal operation. The first example, shown in Fig. 6, corresponds to the nominal overtake situation described previously (i.e., a transition from a large initial spacing down to a 0.4 s headway). The figure shows a string of three vehicles initially equally spaced and operating at a line speed of 24 m/s overtaking a lead vehicle operating at 12 m/s.

Control in this example is initiated when the actual spacing error is twice that required for kinematic feasibility, i.e., when, for each vehicle in the string,

$$S_e(0) = 2S_{me}(0). \tag{24}$$

This allows calculation of τ from (22) (assuming $K_\tau = 1.0$) and h_I from (18) and (23). It is important to note that the values of these parameters are different for each vehicle since the value of S_{me} for a given vehicle is, in its general form [11], dependent on the velocities and accelerations of that vehicle and its predecessor. For example, $S_{me} = 45.8$ m for vehicle 2 in Fig. 6 (as shown previously) and from (23) $S_I = 101.2$ m. Vehicle 2 thus begins to decelerate at zero time. Note, however, that vehicle 3 does not begin decelerating until the relative velocity between it and vehicle 2 reaches a value sufficient to trigger the kinematic requirement (24), or at a spacing corresponding to $S_I = 80$ m.

Fig. 6 shows that the variable-gain approach satisfactorily handles the nominal overtake situation by a smooth transition from large initial conditions down to the minimum spacing of 3.2 meters. The transition is accomplished within acceleration and jerk limits and with no overshoot in velocity or spacing.

Fig. 7 shows a second example case of an overtake situation in which all vehicles are initially operating in the open-loop mode at speed 24 m/s and equal 60 m spacings (minimum spacing at this speed for $h_D = 0.4$ s is 9.6 m). As in the previous case, it may be seen that the vehicles are close to minimum spacing within

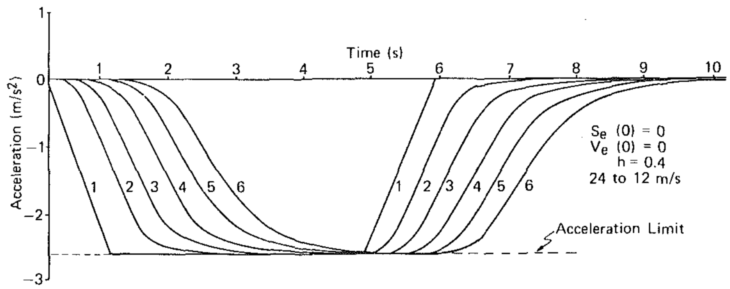

Fig. 5 String response of vehicles in regulation mode to a lead vehicle performing a speed change from 24 to 12 m/s

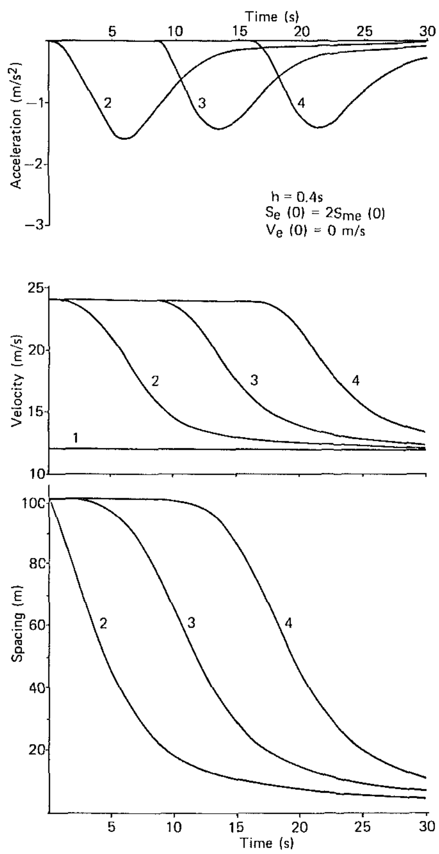

Fig. 6 Overtake response for a string of vehicles traveling at 24 m/s encountering a lead vehicle moving at 12 m/s

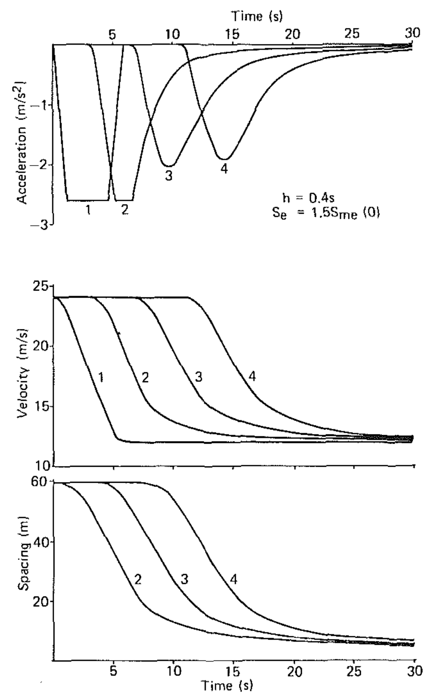

Fig. 7 Overtake string response to a lead vehicle performing speed change from 24 to 12 m/s

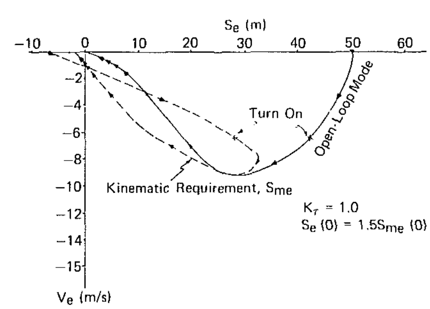

Fig. 8 A comparison of the error trajectory for a speed transition to its corresponding kinematic requirement, S_{me}

acceleration and jerk limits and with no overshoot in velocity. Also, for this example, the variable gain control was chosen to be initiated when $S_e(0) = 1.5\ S_{me}(0)$ for each vehicle. Because the velocity differences between vehicles are less severe, the control is applied at closer spacings than those of the previous example.

As a final simulation result, Fig. 8 illustrates the satisfaction of the kinematic requirement imposed on the maneuver by (21). Shown is a plot of velocity error versus spacing error for the maneuver negotiated by vehicle 2 in Fig. 7. The solid curve in Fig. 8 corresponds to the actual vehicle trajectory, while the dashed line is the plot of $S_{me}(t)$. The arrows on each plot represent two second intervals of the trajectory, with time increasing in the direction of the arrows. The significance of the result is that $S_e(t)$ is to the right of $S_{me}(t)$ at all times, showing that (21) holds. Thus, regardless of the behavior of the lead vehicle (within nominal operating points), the trailing vehicle can close to minimum spacing, $v_t h_D$ without exceeding ride quality limits.

Finally, the behavior of the $S_{me}(t)$ curve may at first seem peculiar in that the value of S_{me} first increases and then decreases in time. An heuristic explanation for this characteristic is that the larger the relative velocity between vehicles, the more space is required to accomplish the speed reduction.

The examples thus illustrate the potential viability of the variable-gain approach developed herein to safely negotiate overtaking maneuvers and to gradually increase the controller gains to those required for small perturbation operation at very short headways.

Conclusions

The significant results and conclusions of this study are presented below:

1. Vehicle-follower controller designs for very short headway operation require high bandwidths which result in high sensitivity to initial conditions and input errors.
2. Nominal vehicle operations in AGT systems, such as the overtaking of slow moving vehicles or merging maneuvers, require large distances to accomplish and introduce initial conditions which are incompatible with fixed-gain controllers designed for short headway operation. These initial conditions can cause the fixed-gain controllers to issue commands that greatly exceed jerk and acceleration constraints.
3. A time-variable gain control approach was examined which can accept large initial conditions using relatively low gains and subsequently increase the gains to those required for short headway operation as the spacing error between vehicles decreases. The technique is demonstrated for typical overtaking maneuvers.
4. All transient maneuvers involving the reduction of large initial conditions on velocity and spacing errors must satisfy a performance requirement based on the kinematics of ride quality constraints. The developed variable-gain control approach is shown capable of satisfying these constraints for overtaking maneuvers.

Finally, it may be concluded that the vehicle-follower approach appears viable for short headway applications. However, further study of the variable-gain approach discussed herein should include more rigorous analytical development of the heuristic techniques presented, and extension of these techniques to the problems of merging from a station and flow regulation.

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