ADVANCE-F 's Car-Following Policy On Vehicle Cruise and Automatic Speed Control

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Abstract

This paper proposes a linear car-following model for the automated vehicles. Basically, when an equipped vehicle, with the equipment of automation, travels on a highway, before becoming cruise speed, a transition period exists. Also, if the equipped vehicle travels along a mixed traffic lane, its front car may not be an equipped one such that the equipped vehicle is possibly still stayed in a transition state if the real-time situation is evaluated inadequate to create the cruise mode for speed control. Thus, two separated spacing functions are used for this car-following control model. One is for cruise speed, and the other is for transition stage. The control model contains a feedback loop whose gain matrix is derived here. From several simulations, the model is evaluated satisfactory to application. This development will contribute to the ADVANCE-F's project, which is being proposed for Taiwan highway automation.

1. Introduction

Since the number of passenger car rapidly increases, traffic congestion becomes a popular event in Taiwan. Unfortunately, adding highways is not a viable solution in many sites for less resource we have, especially lack of appropriate land in urban areas. In addition, the construction cost gradually rises up, as well as it is getting difficult to acquire whole right of land for road construction owing to that the humanistic pressure from environmental preservation is higher day by day. Thus, one possible way to improve highway capacity, in engineering point of view, is to use the current highways more efficiently through automatic driving control.

The project ADVANCE-F aims to ameliorate the traffic of Taiwan, which intends to develop an automated highway system including automatic driving and advanced communication. At first stage, the major work on research/development (R&D) is merely emphasized on automatic steering and automatic speed control for individual cars. Automatic steering control is being implemented on a test car, and automatic speed control is also being conducted in the research lab. After finishing the work of the first stage, one can drive the equipped car with six ways. Steering control (lateral control) has two options, and speed control (longitudinal control) has three alternatives. Figure 1 shows the driving ways of the ADVANCE-F 's vehicle ([1],[2]). In fact, about speed control, only the third alternative is developed in ADVANCE-F. Figure 2 reveals this new development. Obviously, access (3) in Figure 2 is our interesting of discussion here.

This paper is to describe the car-following policy on vehicle cruise and automatic speed control model of the ADVANCE-F's vehicle, which is subjected to that in a single lane with no passing behavior. This policy and model lead to smoother traffic flows and larger capacity than present existence due to the shorter safety headway the vehicle is driven.

2. Car-Following Policy On Vehicle Cruise And In Transition Stage

Choosing an adequate car-following policy is one of the most important issues to the vehicles equipped

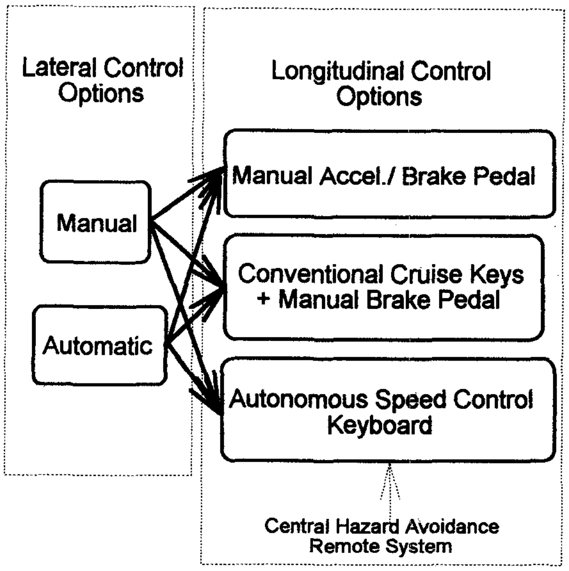

Figure 1. Driving Alternatives by ADVANCE-F

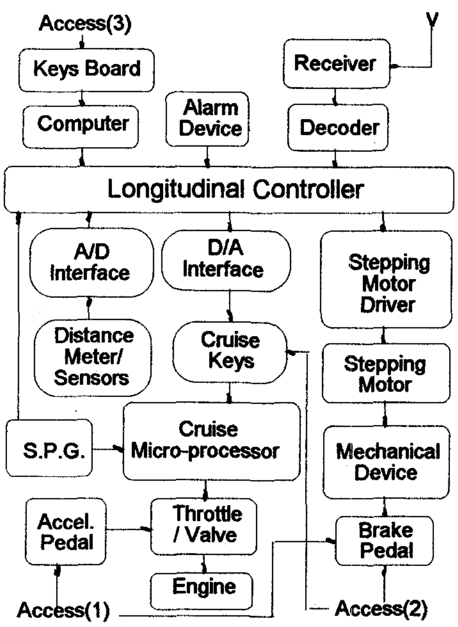

Figure 2. Longitudinal Control Structure of ADVANCE-F

with automatic speed control system. In order to improving highway traffic, many institutes have been paying a lot of resources to dealing with automated vehicle platoon control, and most traffic engineers convince that it is possible to increase highway capacity if wholly implementing automated vehicle platoon control. Of course, entire platoon control is the most efficient strategy for traffic. Indeed, in the transition period, there still exists many difficulties to execute entire platoon control especially under different compositions of equipped and non-equipped vehicles in a lane, and conservative driver behaviors to their equipped vehicles, as well as existing social environment and highway infrastructure. Thus, the policy of car-following of ADVANCE-F is proposed. During in transition state, such as (a) a short period after switching from manual control; (b) the front car is non-equipped; (c) the absolute difference of velocity between itself and the front car is greater than 5 kph, the mode of control is defined in transition, which requires more length of spacing to protect from causing rear-end collisions. When out of the situations of transition described above, or all vehicles in the platoon with automatic speed equipment traveling almost with identical speed., the platoon chain control is formed, then the cruise mode is worked.

Anyway, for safe operation, the equipped vehicle has to maintain a sufficient safety distance to avoid possible collisions caused from that if the front or leading vehicle suddenly brake in full. Basically, in cruising, the minimum separated distance d_s is defined as ([3])

$$d_s = V(t_s + t_d + t_b + \frac{D}{J_m}) - \frac{1}{6}\frac{D^3}{J_m^2} + \frac{(V - \frac{D^2}{2J_m})^2}{2D} - \frac{V_l^2}{2D_l}$$

where V is the velocity of the equipped vehicle (m/sec) which we are mentioning, t_s is the sensing delay of the equipment (sec), t_d is the decision delay of the controller (sec), t_b is braking delay (sec), D is deceleration (m/sec^2), J_m is jerk rate (m/sec^3), D_l is the deceleration of the leading vehicle, and V_l is the velocity of the leading vehicle. For the test car, d_s can be specified as

$$d_s = 0.0637[V^2 - V_l^2] + 0.35V \qquad (2.1)$$

which assumes the leading car and the equipped follower have the same brake capability. The total reaction time is about 350ms. But, when in transition state, for safety and psychological effectiveness, the minimum separated distance

$$d_s = 0.0637[V^2 - V_l^2] + 1.0125V \quad (2.2)$$

is provided in ADVANCE-F. This is most equivalent to human driver's model.[4]

3. Automatic Speeding Model

Base on dynamics, the following state space equation is constructed ([5])

$$\frac{\mathrm{d}}{\mathrm{d}t}\begin{bmatrix}\dot{x}_1\\ x_1\\ \dot{x}_0\\ x_0\end{bmatrix} = \begin{bmatrix}0&0&0&0\\1&0&0&0\\0&0&0&0\\0&0&1&0\end{bmatrix}\begin{bmatrix}\dot{x}_1\\ x_1\\ \dot{x}_0\\ x_0\end{bmatrix} + \begin{bmatrix}0\\0\\1\\0\end{bmatrix}[\ddot{x}_0] \quad (3.1)$$

or briefly

$$\dot{\mathbf{X}} = \mathbf{AX} + \mathbf{Bu}$$

where x_0, x_1 are expressed as the travel distance of the equipped following vehicle (follower), which we are analyzing, and its front car (or the leading car), respectively. Let's denote that d is the real spacing between the front car and the follower which is being controlled by the automatic speed system. Thus, for the consideration of safety and capacity, it is anticipated that

$$d + x_1 - x_0 = d_s$$

or

$$d - d_s = x_0 - x_1$$

So, we set

$$\mathbf{E} = \begin{bmatrix}\dot{x}_0 - \dot{x}_1\\ d - d_s\end{bmatrix} = \begin{bmatrix}-1&0&1&0\\0&-1&0&1\end{bmatrix}\mathbf{X} \quad (3.2)$$

If a feedback control of the dynamic system is defined as

$$\mathbf{u} = -\mathbf{k}\cdot\mathbf{E}$$

from (3.2) and (3.1), the following equation is satisfied:

$$\dot{\mathbf{E}} = \begin{bmatrix}0&0\\1&0\end{bmatrix}\mathbf{E} + \begin{bmatrix}1\\0\end{bmatrix}\mathbf{u}$$

or in brief

$$\dot{\mathbf{E}} = \tilde{\mathbf{A}}\mathbf{E} + \tilde{\mathbf{B}}\mathbf{u}$$

The feedback gain can be obtained by solving the Reccati equation

$$\Pi\tilde{\mathbf{A}} + \tilde{\mathbf{A}}^{\mathrm{T}}\Pi - \Pi\tilde{\mathbf{B}}\mathbf{R}^{-1}\tilde{\mathbf{B}}^{\mathrm{T}}\Pi + \mathbf{Q} = \mathbf{0}$$

which from minimizing the performance function

$$J = \frac{1}{2}\int_0^\infty (\mathbf{E}^{\mathrm{T}}\mathbf{Q}\,\mathbf{E} + \mathbf{u}^{\mathrm{T}}\mathbf{R}\,\mathbf{u})\mathrm{d}t$$

where the weighting matrices

$$\mathbf{Q} = \begin{bmatrix}q_1&0\\0&q_2\end{bmatrix}, \qquad \mathbf{R} = [r]$$

By means of calculation, it yields

$$\mathbf{k} = \mathbf{R}^{-1}\tilde{\mathbf{B}}^{\mathrm{T}}\Pi_\infty = \begin{bmatrix}\sqrt{\frac{1}{r}[q_1 + 2(rq_2)^{\frac{1}{2}}]} & \sqrt{\frac{1}{r}q_2}\end{bmatrix}$$

Since

$$(\dot{x}_0 - \dot{x}_1)^2 = 2\mu\cdot g\cdot\Delta$$

is taken, where g is the gravity acceleration, $\mu = 0.4 \sim 0.8$, $\Delta = |x_0 - x_1|$, we choose

$$q_1 = 1/(2\mu\cdot g\cdot\Delta)$$

$$q_2 = 1/\Delta^2$$

$$r = 1/(\mu\cdot g)^2$$

Then, we obtain

$$\mathbf{k} = \begin{bmatrix}\sqrt{\frac{5\mu\cdot g}{2\Delta}} & \frac{\mu\cdot g}{\Delta}\end{bmatrix}$$

For a little bit of conservation, let's take $\mathbf{G}$ instead of $\mathbf{k}$, where

$$\mathbf{G} = [\ \mathrm{Gv}\ \ \mathrm{Gx}\ ] = \begin{bmatrix}\sqrt{\frac{5\mu\cdot g}{2\cdot|d - d_s|}} & \frac{\mu\cdot g}{|d - d_s|}\end{bmatrix}$$

The whole system is expressed as

$$\dot{\mathbf{E}} = (\tilde{\mathbf{A}} - \tilde{\mathbf{B}}\mathbf{G})\mathbf{E}$$

or

$$\mathbf{E}(s) = [s\mathbf{I} - (\tilde{\mathbf{A}} - \tilde{\mathbf{B}}\mathbf{G})]$$

From above, it is easy to verify that

$$\mathbf{E}(t) = \mathrm{e}^{\Omega t}\cdot\mathbf{E}(0+)$$

where

$$\Omega = \tilde{\mathbf{A}} - \tilde{\mathbf{B}}\mathbf{G}$$

$\mathbf{E}(0+)$ = initial status of each executing cycle. The cycle length is about 350ms.

4. Simulations and Evaluations

A number of time response verification for varying car following situations have been made. Six of them are presented here.

(1) Suppose that V = 80 kph, V_l = 90 kph, from the climate and vehicle condition $\mu = 0.7$, the vehicle is just in transition stage, the spacing between the front car and the follower is initiated at 20 meters. The model result is illustrated in Figure 3(a). It shows that

there is extra length over the minimum separated spacing when at first 2 seconds. Through soft acceleration, after about 3 seconds the follower's speed catches up with its leader, and no more extra spacing exists.

(2) Suppose the same situation as (1), but the spacing between the front car and the follower is initiated at 8 meters. The response result is illustrated in Figure 3(b). Although the initial spacing is unsafe, fortunately the leader is faster than the follower. Though acceleration following soft deceleration, only 1.5 seconds all situation turns safe and stable.

(3) Suppose that $V = 100$ kph, $V_l = 80$ kph, from the climate and vehicle condition $\mu = 0.7$. Figure 3(c) shows the result of the model response of the vehicle just traveling in transition when the spacing from the front car is initiated at 56 meters. It's lucky because the initial spacing is enough to brake for avoiding rear-end collision. After 2 seconds, the situation turns normal.

(4) Similarly, $V = 100$ kph, $V_l = 80$ kph, and $\mu = 0.7$ are given. But, the spacing is just measured at 36 meters. Figure 3(d) reveals the time response result. Both since the initial spacing drops in unsafe range, and the leader moves slower than the follower about 20kph, the follower needs 4.5 seconds to brake; it turns safe, then.

(5) Suppose that $V = 120$ kph, $V_l = 115$ kph, and $\mu = 0.7$. A speed cruising situation when the spacing between the front car and the follower is initiated at 16.5 meters is simulated here. The result is illustrated in Figure 4(a). At beginning, there is a little bit of unsafe condition. But, after smooth decelerating, it is safe.

(6)The conditions are the same as (5) except the spacing between the front car and the follower is initiated at 4.4 meters. The time response result is illustrated in Figure 4(b). Because the speeds of them are rather closed, it is soon to become stable.

Case (1) is simulated 5 minutes long with variation of the speed of the leading car. Figure 5 shows the details. We find that the follower is quite good in following. No violation happens.

5. Conclusions

Traffic problem is gradually getting serious in Taiwan. On account of less usable land for new highway construction, how to use the existing road in efficiency becomes a highlight of researches. Project ADVANCE-F counters to accomplish an ameliorative technology for traffic. The dominant subject of this project is to develop an auto pilot vehicle. One of the key issues is to determine a suitable car-following model. In this paper, a car-following model is successively derived, which is based on the two functions of the minimum separated spacing for speed cruise or transition. The model's objective is selected to minimize both of the differences of the front car's speed vs. the follower's speed and the real spacing vs. the minimum separated distance. The model is comprehensive according to the optimal control theory, and the feedback gain is solved by the Reccati equation. The solution is evaluated with several cases and simulations. All show the model satisfactory and potential for implementation.

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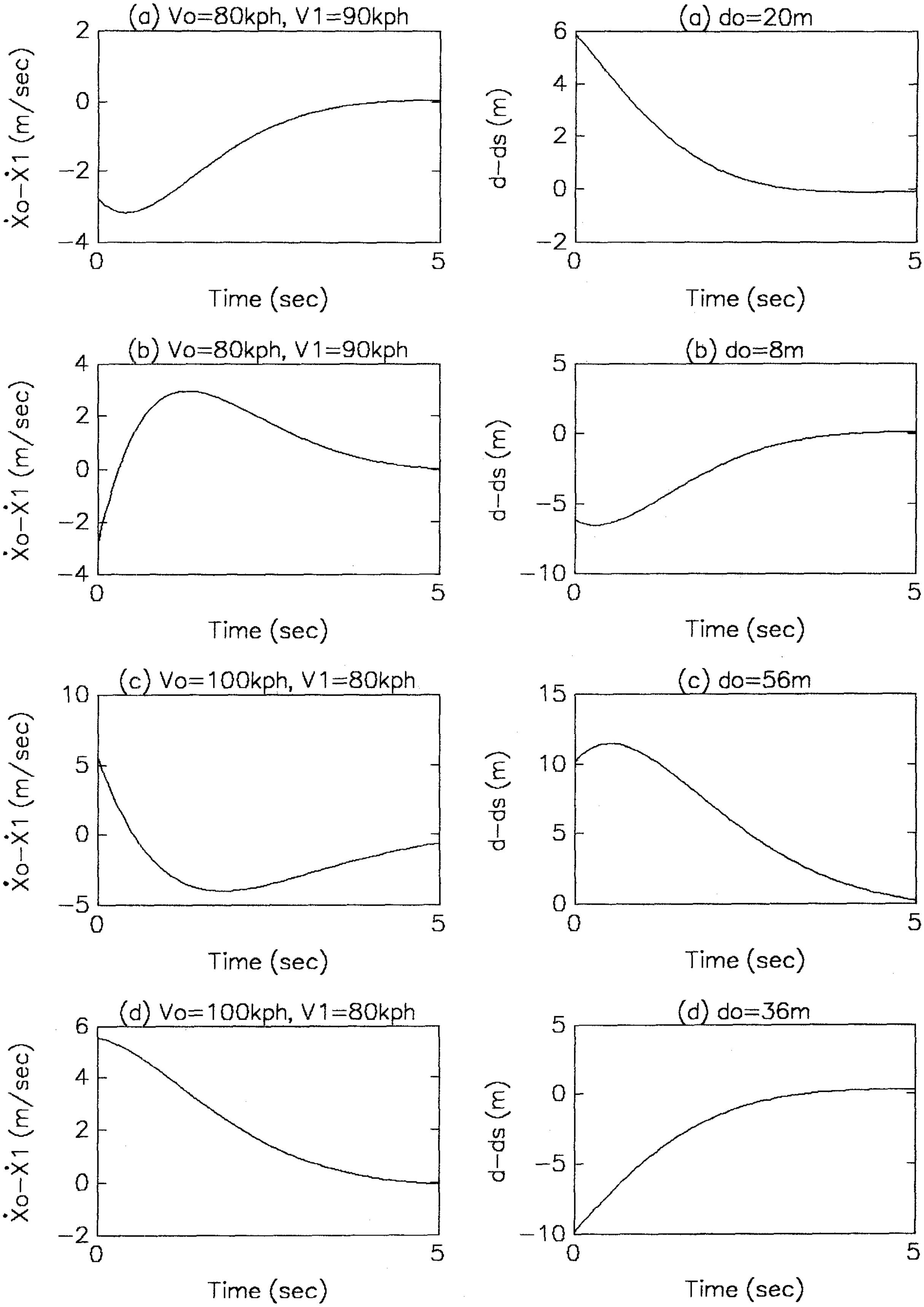

Figure 3. System Response at Transition (Vo=initial follower's speed, V1=leader's speed, do=inital spacing)

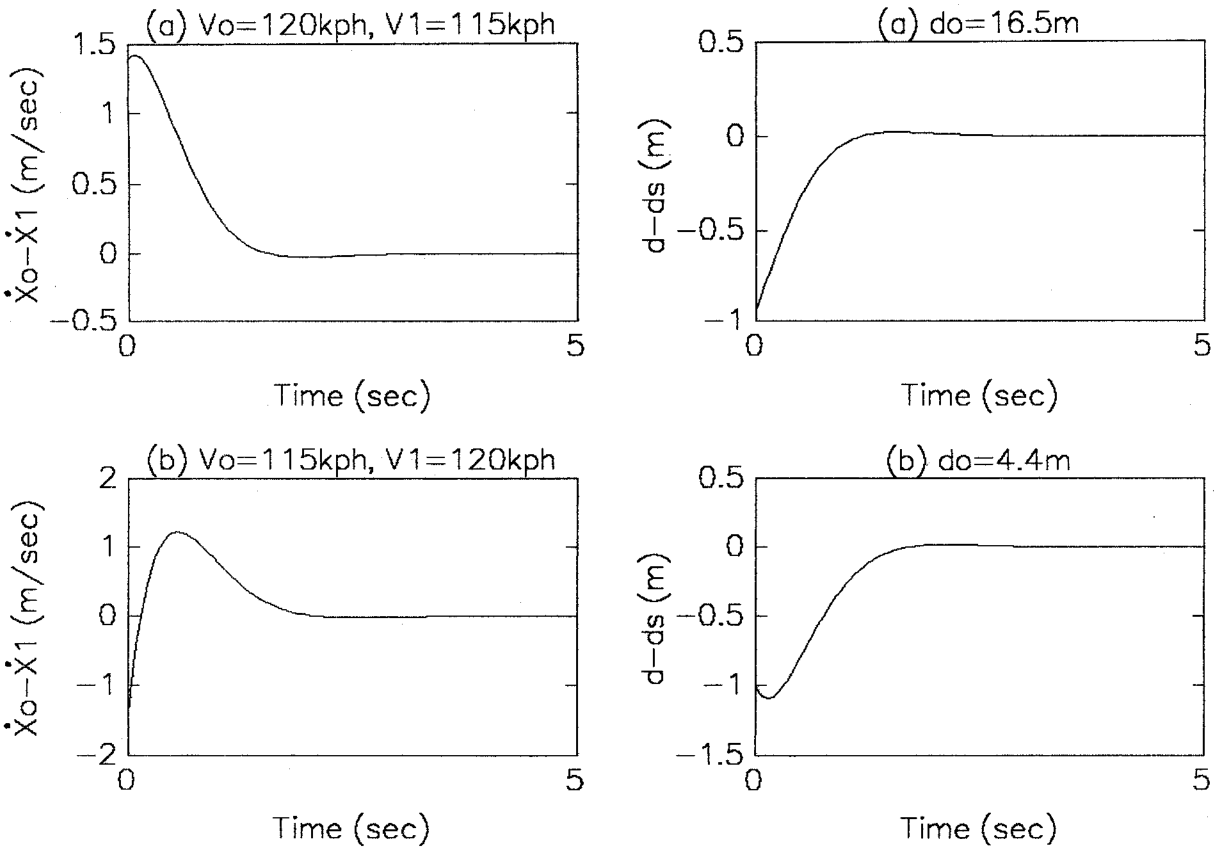

Figure 4. System Response at Cruising (Vo=initial follower's speed, V1=leader's speed, do=inital spacing)

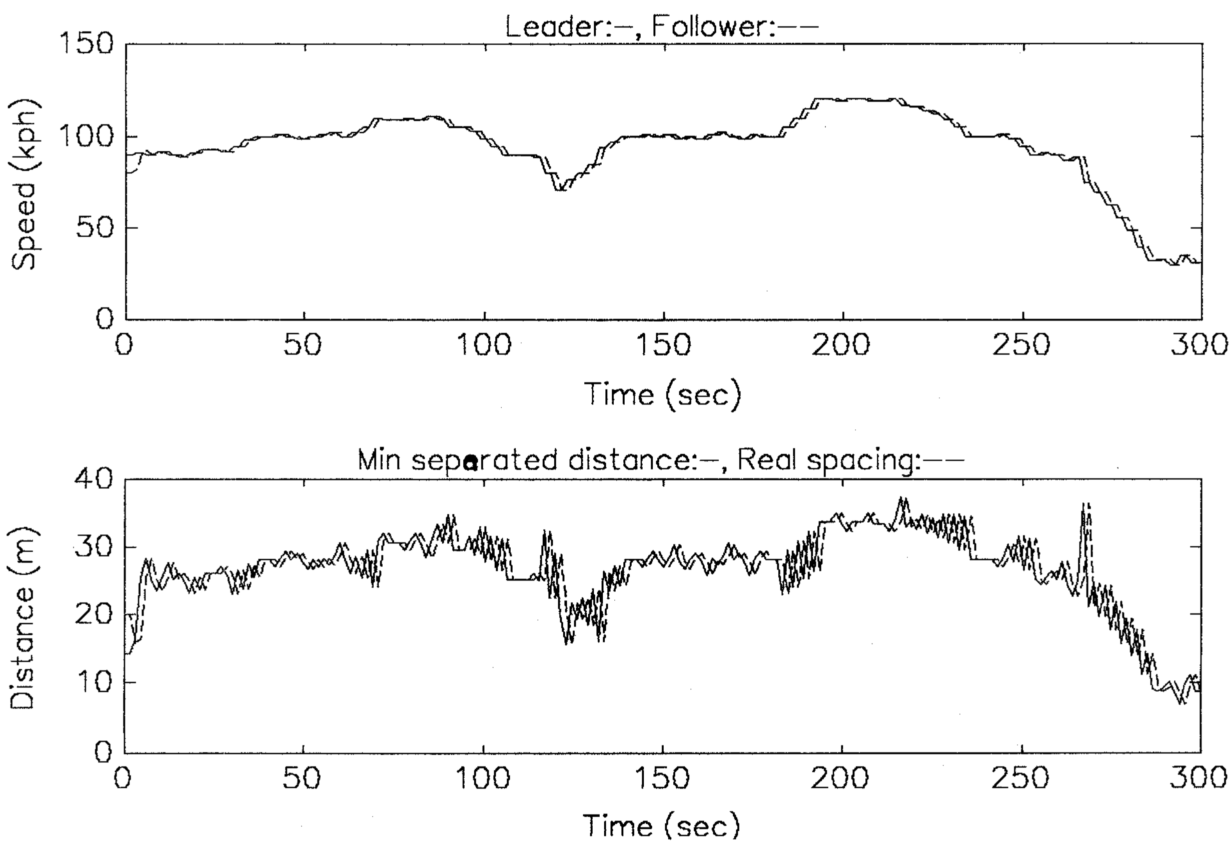

Figure 5. Car Following Simulation