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Range Policy of Adaptive Cruise Control for Improved Flow Stability and String Stability

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Abstract - *This paper presents the problem of designing a range policy for Adaptive Cruise Control systems and a companion control algorithm for improved traffic flow stability and string stability. A nonlinear range policy is proposed and its performance is compared against a Constant Time-Headway policy and the range policy employed by human drivers, with special attention on traffic flow stability. The proposed range policy is obtained from the solution of an optimization problem under traffic flow requirements. A sliding mode controller is then designed to work with the range policy. Simulation results show that higher and sustainable (stable) traffic flow is achieved by the proposed method.*

Keywords: Adaptive Cruise Control, range policy, traffic flow stability, string stability, sliding mode control.

1 Introduction

Adaptive Cruise Control (ACC) has been proposed as a driver assistance system to provide significantly enhanced driver convenience and reduced workload. In addition to the speed-regulation function like a conventional Cruise Control, an ACC vehicle detects the presence of any preceding vehicle and measures the distance (range) and the relative speed (range rate) by using a forward-looking sensor. An ACC vehicle automatically adjusts the speed to keep a proper range when a preceding vehicle is detected.

Recently, ACC became available in the high-end automotive market, on models from Lexus, BMW, Jaguar, Infiniti, Cadillac, etc. ACC systems may improve highway safety, efficiency and capacity because of their more consistent behavior. To implement ACC vehicles on a large scale, their string behavior and flow characteristics need to be carefully designed. Otherwise, traffic congestion may be aggravated instead of being relieved. While ACC systems are designed mainly for highway applications with relatively homogeneous traffic behavior, Stop-and-go Cruise Control system have been designed to reduce driver workload under congested highway traffic and dense urban traffic [8]. In those applications, vehicle speed is low and frequent gear shifts result in widely varied traction behavior.

Two important issues for ACC designs are traffic flow stability and string stability. Traffic flow stability [7] defines the evolution of aggregate traffic density and velocity in response to small variation in traffic density. This is especially important for areas upstream of the point where the traffic density perturbation is introduced. A traffic flow is said to be stable (or unstable) when the traffic flow Q goes up (or down) as the traffic density ρ is increased. In other words, in the fundamental diagram, when the density-flow chart demonstrates a positive slope for $\partial Q/\partial \rho$, the traffic is said to be stable. A typical reason of density disturbance is the merging of vehicles from an entrance ramp into the main lanes of a highway. If the traffic flow is unstable, such density disturbance will affect sections upstream of the disturbance source because less flow can go through. The density will go even higher than flow goes lower, and eventually causes a complete jam. When ACC vehicles are introduced, it will be desirable to design their headway policy so that the traffic flow stability is improved. This can be achieved by ensuring that the slope $\partial Q/\partial \rho$ remains positive until a higher traffic density. This obviously needs to be done carefully without compromising safety.

The string stability problem of vehicles has been studied since the late 1970's [1]. The term "string stability" refers to the non-amplifying upstream propagation of vehicle speed perturbation through a string of vehicles. This property guarantees that variation of leading vehicle speed will not result in collision for any following vehicles, even if a string contains an infinite number of vehicles.

Both traffic flow stability and string stability are influenced by the vehicle range policy. In addition, string stability is influenced by the ACC control algorithm. Determining a proper range policy is thus an important first step, which then needs to be complemented by a proper design of the servo-loop control algorithm.

2 Range policy requirements

Range policy [2] refers to the selection of the desired following distance as a function of vehicle operating parameters, especially forward speed. There are two kinds of range policies: constant range and variable range

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policies. In a constant range policy, the separating distance is independent of the velocity of the controlled vehicle and the implementation of such a range policy requires intervehicular communication [6]. This range policy is used primarily in automated highway research when traffic flow is of utmost importance. No ACC designs had been designed using constant range policy. In this paper we will limit our discussion to variable range policies because requiring vehicle-to-vehicle communication is not an attractive path for ACC implementation.

It is recognized that an ACC range policy should satisfy the following attributes as much as possible:

1. The range policy should lead to a high traffic capacity and a stable traffic flow [5];
2. The selected range policy should have a companion ACC servo-controller which ensures string stability without communicating with neighboring vehicles or the infrastructure. In the meantime, the control effort should be within vehicle's physical limit;
3. It should be kept close to human drivers' natural behavior as much as possible.

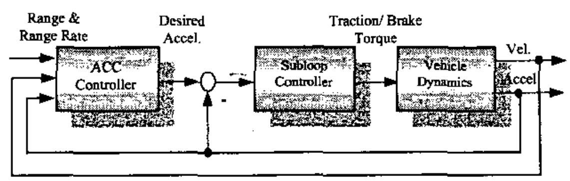

Figure 1. Dual-loop structure of an ACC system

The overall ACC design can be divided into two steps: (i) specify a range policy; and (ii) design a controller for the range-following loop. In this paper, the ACC range controller is modeled as a dual-loop structure (see Figure 1). A main loop controller determines the proper acceleration based on measured range, range rate, speed and/or acceleration signals. A sub-loop controller then manipulates engine and brake inputs to achieve the desired acceleration. Since the emphasis of this study is on the range policy and outer-loop controller, the sub-loop is assumed to be approximated by a first-order system:

$$\tau \cdot \dot{a}_i + a_i = a_{i,des} \tag{1}$$

where a_i is the vehicle's actual acceleration, $a_{i,des}$ is the acceleration command and τ is the time constant.

3 Constant time-headway policy

The desired intervehicular range given by a constant time-headway (CTH) policy is: $R_d = A + T_h \cdot v_i$, where A is the separation distance when the vehicle is at standstill, T_h is the time-headway and v_i is the host vehicle velocity. CTH policy is commonly suggested as a safe practice for human drivers and is frequently used in ACC designs. Prototype ACC vehicles commonly offer selectable time headway between 1-2 seconds. For CTH policy, a sliding mode control technique can be designed to guarantee string stability [10]:

$$a_{i,des} = (K/T_h) \cdot e_i + (1/T_h) \cdot \dot{R}_i \tag{2}$$

where K is the convergence rate of the sliding surface, range error e_i is defined as the difference between the actual range and the desired range, and range rate is equal to the difference between the lead vehicle speed and the following vehicle speed: $\dot{R}_i \equiv v_{i-1} - v_i$. The desired acceleration is inversely proportional to T_h, i.e., short time-headway necessitates aggressive control effort.

To ensure string stability, a necessary lower bound on T_h is $T_h \geq 2\tau$ [4], where τ is the time constant of the sub-loop (see Eq.(1)). Typically τ is between 0.5~1 sec, and could depend on vehicle speed and vehicle power-to-weight ratio. When the vehicle response is sluggish (e.g., at very low or very high speed), the time headway becomes large. Therefore, the time-headway needs to increase to ensure string stability. In other words, flow rate will reduce. The example above clearly shows the importance of the main-loop control design.

To relax the time-headway requirement ($T_h \geq 2\tau$), a better control algorithm needs to be designed. If measurement of the ACC vehicle's acceleration is available for feedback, an augmented sliding mode controller can be synthesized [10]:

$$a_{i,des} = (1 - \tau T_h / T_a) \cdot a_i + (\tau / T_a) \cdot \dot{R}_i + (\tau K / T_a) \cdot \varepsilon_i \tag{3}$$

For this controller a compound range error is defined as: $\varepsilon_i = R_i - T_h \cdot v_i - T_a \cdot a_i$, where T_a is a positive parameter which can be chosen to achieve string stability. It can be shown that if the time constant τ is perfectly known, the string stability condition becomes $T_h^2 \geq 2T_a > 0$, which effectively eliminates the dependence of T_h on τ. In practice an accurate knowledge of τ is hard to obtain. However string stability can be maintained even if the actual time constant is twice as long as the estimated value [10]. The details are omitted here.

The influence of range policy on traffic flow can be analyzed using the fundamental diagram (see Figure 2). By assuming a uniform vehicle length L, the traffic density at steady state is given by $\rho = 1/(L + A + T_h \cdot v)$. When the traffic flow is constrained (i.e., vehicles can no longer drive at their free flow speeds), the flow rate is $Q = \rho v = 1/T_h - (L + A) \cdot \rho / T_h$. Since the separation distance A must be positive (else collision happens), the slope $dQ/d\rho$ is always negative. Therefore the traffic flow is always unstable when the traffic density is in the constrained flow section.

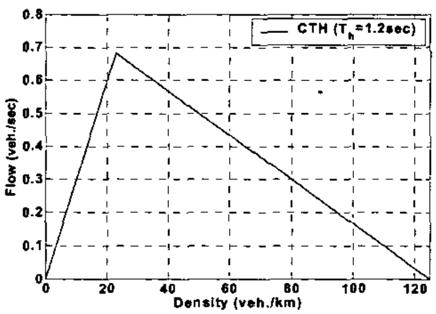

Figure 2. Fundamental diagram of Constant Time Headway (CTH) policy (T_h=1.2sec)

Although constant time-headway policy is easy to implement and a servo controller can be easily designed to ensure string stability, it has poor traffic flow stability in the constrained flow region. In other words, it is prone to traffic congestion given any traffic density disturbance. For this reason, we believe that CTH range policy is suitable for free-flow car following, but is a poor choice for stop-and-go ACC, which is designed to work under (locally) congested conditions.

4 Range policy used by human drivers

Even though driver behavior varies widely, aggregate driving data could be used to identify an averaged human range policy. One such averaged driver behavior was recently extracted from the data collected in UMTRI's ICCFOT database [2]. In the ICCFOT project, driving data of 107 test subjects was recorded, including a large quantity of manual driving data. The steady state data was collected and the human range behavior is identified. The human range policy was found to be in the form of a quadratic curve:

$$R = A + T \cdot v + G \cdot v^2 \qquad (4)$$

where A is the separating distance at standstill, T and G are the coefficients identified from the test data. The parameter T for individual drivers was found to be mostly between 1.0 and 2.5 (sec). The parameter G was found to be strongly correlated to T by the equation $G = -0.0246 \cdot T + 0.018$ (see Figure 3). Surprisingly, all human drivers in the ICCFOT database exhibit a negative value of 'G', i.e., at higher vehicle forward speed, the effective "time headway" reduces.

Another curve fitting result of human driver behavior was reported in [9]. It takes the form of a power function: $R = 2 + 6.33 \cdot v^{0.48}$. The comparison of these two reported human driver range policies is shown in Figure 4. Despite notable mismatch in the specific range values, they are similar qualitatively., In addition both models indicate that human drivers use a smaller effective time-headway at higher vehicle speed.

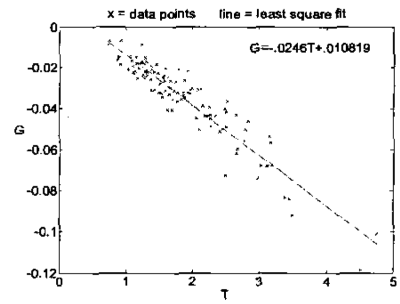

Figure 3. Relation between Coefficients T and G

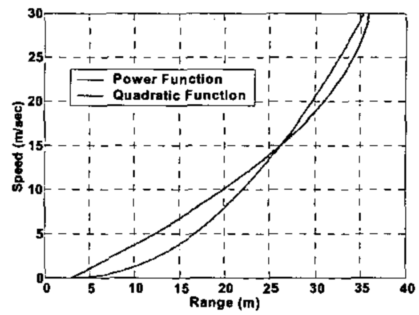

Figure 4. Range policies employed by human driver

The traffic flow characteristics of these two policies (quadratic and power) are evaluated below. In the following, details of only the quadratic range policy will be shown. At steady state, the traffic density becomes $\rho = 1/(L + A + T \cdot v + G \cdot v^2)$. Flow rate can then be formulated as a function of ρ: $Q = \rho \cdot v$ $= \rho \cdot \frac{\sqrt{T^2 - 4G(L + A - 1/\rho)} - T}{2G}$. Take the derivative and set it to zero: $dQ/d\rho = 0 \Rightarrow$

$$\sqrt{T^2 - 4G(L + A - 1/\rho)} - \frac{2G}{\rho \cdot \sqrt{T^2 - 4G(L + A - 1/\rho)}} - T = 0 \qquad (5)$$

Solve Eq.(5) and accept the positive solution only:

$$\rho_{cr} = \frac{1}{2(L + A) + T \cdot \sqrt{(L + A)/G}} \qquad (6)$$

The critical density ρ_{cr} corresponds to the density when the maximum traffic flow is obtained, which also marks the boundary between stable traffic flow and unstable traffic flow. Solution for Eq.(6) exists only when G is positive—when G is negative, the slope $dQ/d\rho$ is discontinuous and is never equal to zero.

The fundamental diagrams of the above two nonlinear range policies are shown in Figure 5. The maximum traffic flow of both policies is achieved when the vehicles are at the boundary between free flow and constrained conditions. As soon as the traffic becomes constrained, flow rate starts to reduce with increased flow density. Like the constant time-headway policy, the traffic flow is always unstable in the constrained region due to the negative-definiteness of $\partial Q/\partial \rho$. For human drivers,

G is always negative (see Figure 3), which indicates that vehicle strings formed by human drivers are "more unstable" than ACC vehicles using the CTH range policy. In other words, if we design ACC range policies to be closer to human driver's natural behavior, the resulting traffic flow stability will be even worse than vehicles using CTH range policy. Requirement 4 (human-like) listed in section 2 is thus conflicting with the requirements 1 and 2 (higher and more stable traffic flow).

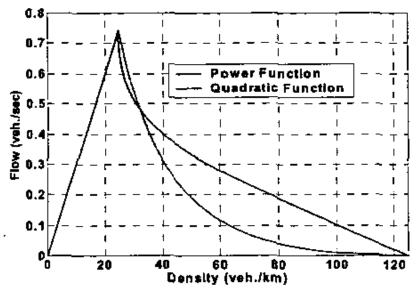

Figure 5. Fundamental diagram of the range policies employed by human driver

5 Synthesis of a range policy for traffic flow stability and string stability

The main goal of this section is to identify a range policy to achieve stable traffic flow up to a higher density than both human and CTH range policies. This new range policy will thus achieve a higher and sustainable flow through the roadway systems. The following facts can be seen from Eq. (6):

1. The quadratic range policy has a local maximum in the constrained flow section only when G is positive;
2. If $A=-L$, ρ_{cr} does not exist (goes to infinity), In other words, $\partial Q/\partial \rho$ is always positive and thus the traffic flow is always stable;
3. If A, T, G are all positive, the critical density is upper bounded: $\rho_{cr} < 1/[2(L+A)]$.

The proposed range policy takes advantage of the above facts. We will still use a quadratic policy $R=A+T\cdot v+G\cdot v^2$. For traffic flow stability, G is selected to be positive and A is fixed to be equal to $-L$. Obviously this range law is practical only when the vehicle speed is sufficiently high. At low speeds, the range may become too small or even negative. To remedy this problem, the range policy switches to another parabola form when vehicle speed is lower than a threshold speed (v_{th}). At v_{th} the transition is made smooth—both the value and the first derivative are constrained to be the same (i.e., C_1 continuous). To specify these two segments, there are two sets of parameters to manipulate: A_1, T_1, G_1 and A_2, T_2, G_2. Two of them are fixed: A_1 is equal to the separating distance at standstill and A_2 is equal to $-L$. Therefore we have four freedom parameters to determine the complete range policy subject to a set of requirements. Hence it can be formulated as a constrained optimization problem:

Design (free) variables: T_1, G_1, T_2, G_2, v_{th}
Objective: to maximize flow capacity.
Subject to the following constraints:
1. The range should be a non-decreasing function of forward speed, i.e., $dR/dv \geq 0$;
2. $G_1 > 0$ and $G_2 > 0$ to guarantee stable traffic flow;
3. Critical density ρ_{cr} should be maintained close to its upper limit $1/[2(L+A_1)]$;
4. The transition of range at the threshold speed (v_{th}) should be C_1 continuous;
5. At the boundary point between free flow and constrained flow, the flow rate should not be lower than that of the CTH policy ($T_h=1.2$ sec);
6. Since the control effort is inversely proportional to time-headway, the slope of range policy dR/dv should be lower bounded (e.g., ≥ 0.6sec).

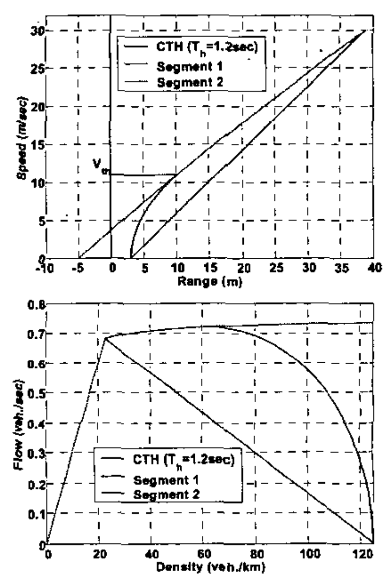

Figure 6. The proposed range policy and its traffic flow characteristics

This optimization problem is converted into the negative null form and solved by using the Matlab Optimization Toolbox. Two range segments are obtained: for speed below the threshold: $R_1 = 3 + 0.002\cdot v + 0.06\cdot v^2$, for speed above the threshold: $R_2 = -5 + 1.333\cdot v + 0.0045\cdot v^2$, and the threshold velocity v_{th} is 12.03 *m/sec*. This nonlinear range policy and its traffic flow characteristics are shown in Figure 6 together with a CTH policy for comparison. The critical density of the suggested range policy is considerably higher than that of the CTH policy. While CTH policy achieves a maximum capacity of 0.68 Veh./sec at the density of 22.7 Veh/km, the proposed range policy maintains a stable flow up to 62.4 Veh./km and results in a higher capacity of 0.72

Veh./sec, thus the traffic flow stability region is significantly extended.

6 Controller for nonlinear range policy

A sliding mode control algorithm is designed for the ACC system with the nonlinear range policy proposed in the previous section. First define a compound range error for the new range policy:

$$\varepsilon_i = R_i - (A + T \cdot v_i + G \cdot v_i^2) - T_a \cdot a_i \qquad (7)$$

where T_a is a positive parameter to be determined later. The sliding surface is then selected to be: $S = \varepsilon_i$. In order to ensure sliding motion, impose the relation $\dot{S} = \dot{\varepsilon}_i = -\lambda S$. Substitute the simplified sub-loop dynamics Eq.(1) into sliding motion condition:

$$\dot{R}_i - T_v \cdot a_i - T_a \cdot (a_{i,des} - a_i)/\tau = -\lambda \varepsilon_i \qquad (8)$$

where the equivalent time-headway $T_v \equiv dR/dv = T + 2Gv_i$, as a result the acceleration command is synthesized as:

$$a_{i,des} = (1 - \tau T_v/T_a) \cdot a_i + (\tau/T_a) \cdot \dot{R}_i + (\tau\lambda/T_a) \cdot \varepsilon_i \qquad (9)$$

The sliding mode control guarantees the stability of individual vehicles, namely range error and velocity difference will converge to zero asymptotically. In order to investigate its string stability characteristics, the ACC system is linearized around a nominal vehicle velocity. Suppose initially the string is at steady state: $v_{0,i} = v_{0,i+1} = v_0$ and corresponding $R_{0,i} = R_{0,i+1} = R_0$. At certain moment the lead vehicle begins to change its speed, thus introducing perturbation to the trailing vehicles. Let $v_i = v_0 + \Delta v_i$, $\dot{v}_i = \Delta\dot{v}_i$ and $R_i = R_0 + \Delta R_i$, $\dot{R}_i = \Delta\dot{R}_i$. It can be shown [4] that for linear systems the range error propagation transfer function is the same as that of the velocity variation TF, i.e.,

$$G(s) = e_i(s)/e_{i-1}(s) = \Delta v_i(s)/\Delta v_{i-1}(s) \qquad (10)$$

Therefore, the study on string stability boils down to checking the maximum magnitude of the transfer function of the velocity variation. Based on the results from linear range policy, we choose T_a to be $T_a = T_v^2/k$ $= (T + 2Gv_i)^2/k$, where k is a scaling factor. Under the assumption that deviations from the nominal range and vehicle velocity are small, by combining Eq.(1) and Eq.(9), the transfer function of velocity variation is:

$$\frac{\Delta v_i}{\Delta v_{i-1}}(s) = \frac{k\tau \cdot s + k\tau\lambda}{\tau T_v^2 \cdot s^3 + (k\tau T_v \cdot s^2 + \tau\lambda T_v^2 \cdot s^2) + (k\tau \cdot s + k\tau\lambda T_v \cdot s) + k\tau\lambda} \qquad (11)$$

In order to ensure string stability, the magnitude inequality $\|\Delta v_i(s)/\Delta v_{i-1}(s)\| \le 1$ must hold, the requirement of which can be reduced to:

$$T_v^2 \cdot \omega^4 + (k^2 - 2k + \lambda^2 T_v^2) \cdot \omega^2 + (k^2 - 2k) \cdot \lambda^2 \ge 0 \quad (12)$$

After some analysis, it was found that this inequality constraint is always satisfied if $k > 2$, i.e. string stability is guaranteed. The control law in Eq.(9) together with the condition $k > 2$ ensure the desired nonlinear range policy (which is traffic flow stable under steady-state condition) is tracked in a string stable fashion (under transient).

7 Simulation results

The effectiveness of the nonlinear controller to maintain the proposed range policy is verified by simulations. The scenario is as follows: the vehicles on the main lane are limited to travel in a straight section of the highway. An on-ramp is located at 500m downstream from the entrance (see Figure 7). As soon as the average position of Veh. 2 and 4 crosses the end of the ramp, Veh. 3 enters the main lane. It is assumed that at this moment the velocity of Veh. 3 matches that of Veh. 2, however its actual range may deviate from the desired one. At this instant the predecessor of Veh. 4 switches from Veh. 2 to 3 and it causes abrupt change of the measured range. Although only 5 vehicles are show in Figure 7, this merging process can be repeated forever as long as the vehicles on highway are still moving. In the following simulation, the cruising speed on the highway is 25m/sec, each merging vehicle is introduced for every four vehicles on the main lane. All of the vehicles adopt the range policy proposed in Section 5 and are equipped with the ACC controller of Eq.(9). To ensure that the acceleration and deceleration efforts are within practical range, the limits on acceleration are taken from human driving data: $a_{max} = 0.7764$, $a_{min} = -3.5388$ (m/s^2) [3].

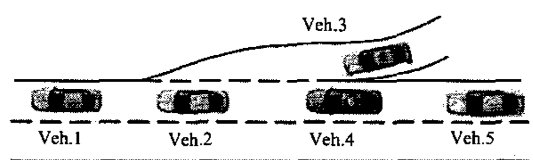

Figure 7. Merging simulation scenario

Figure 8-10 show the position, velocity and acceleration histories of selected vehicles during a merging simulation (solid line for merging vehicles and dashed line for original main-lane vehicles). Although vehicles merging into the traffic continually induce density perturbation to the traffic flow on the main lane, the traffic density is recovered at some distance downstream and the traffic flow remains stable. In Figure 9 the hard braking is caused by the sudden change of measured range. However, it is evident that the velocities are lower-bounded and no vehicle will come to a stop. Figure 10 shows that string stability is maintained after the vehicles leave the ramp intersection, since the peaks of the acceleration get decreased upstream.

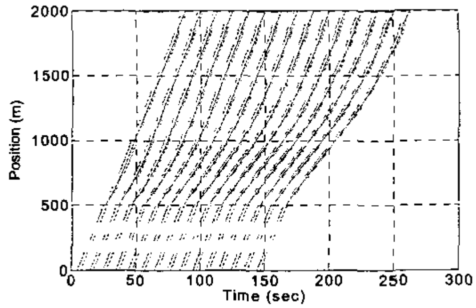

Figure 8. Traffic-space-time chart for ACC vehicles

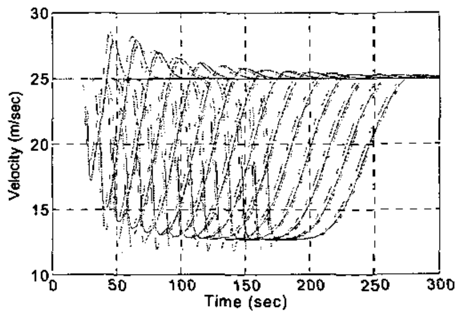

Figure 9. Velocity of ACC vehicles in merging simulation

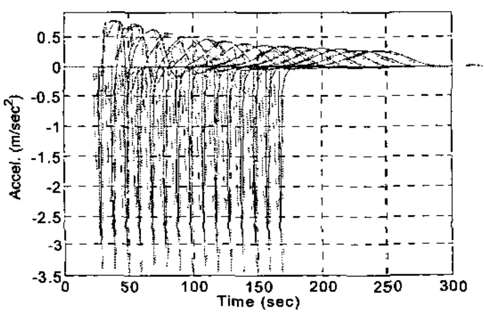

Figure 10. Accel. of ACC vehicles in merging simulation

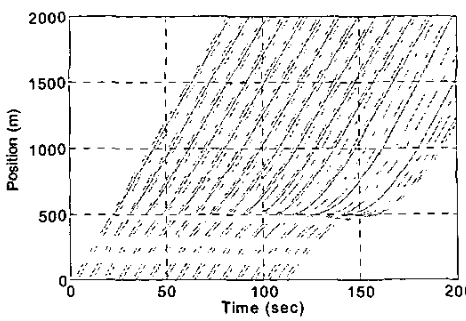

Figure 11. Traffic-space-time chart for human drivers

By comparison, modified Gipps model [3] is used to predict how human will behave in the same merging maneuver. The following parameters are used: $a_n = 0.7664$ (m/s^2), $V_F = 30$ (m/s), $b_n = -3.5388$ (m/s^2), $\hat{b} = -4$ (m/s^2), $R_{min} = 3.5094$ (m), $\tau = 0.67$ (s) [3]. Figure 11 shows that after some time certain vehicles stop near the ramp intersection which leads to traffic accumulation, thus the traffic flow stability is lost.

8 Conclusions

The design of a flow stable and string stable ACC is presented in this paper. The new range policy is designed based on an optimization procedure. The final result consists of two quadratic segments to meet those requirements, especially the extension of traffic flow stability region. A nonlinear controller based on sliding mode technique was used to keep the desired range while maintaining string stability. A merging simulation is set up to validate the proposed ACC system. Both traffic flow stability and vehicle string stability are retained.

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