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Evaluating the Influences of Adaptive Cruise Control Systems on the Longitudinal Dynamics of Strings of Highway Vehicles

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SUMMARY

This paper presents experimental results, analytical findings, and simulation evaluations pertaining to the longitudinal dynamics and headway performance of strings of vehicles with and without adaptive cruise control (ACC) systems. It focuses on the amplification of speed disturbances along a string of vehicles, i.e., the stability of string behavior. The work describes measurement, analysis, and simulation tools that are suitable for use in evaluating the impact of ACC system characteristics on traffic flow.

1. INTRODUCTION

ACC systems are currently being introduced into the consumer market by vehicle manufacturers. These systems have been tuned to gain high levels of acceptance from the individual consumers. Results from initial operational tests [1] indicate that drivers generally like the comfort and convenience provided by systems that control the time gap between vehicles. However, there is concern that the aggregate dynamic effects from many such vehicles in a string could act to disrupt traffic flow.

The paper includes analytical results indicating system characteristics yielding good string performance, practical means for measuring system characteristics related to string performance, and the use of simulations for evaluating string performance in staged driving situations. The emphasis of this work is on systems involving an inner loop for controlling vehicle speed and an outer process-control loop for determining appropriate velocity commands to the inner control loop. This type of system architecture is used in modeling both ACC-system and driver control of speed and time gap. Issues associated with representing and simulating traffic flow in order to evaluate string performance are discussed. Statements concerning the application of this work to the practical evaluation of string performance appear at the end of the paper.

2. BASIC EXPERIMENTAL EVIDENCE SHOWING STRING INSTABILITY

Initial operational experiments [1] involving testing of strings with 4 to 8 ACC-equipped vehicles in a row have shown that string instability can occur, depending upon the particular ACC system used. Figure 1 provides an example showing time histories of velocity (V) in response to a variation in the lead-vehicle velocity (Vp). In this particular case, the range (R) between the vehicles in the string became small enough to cause the drivers in the third and fourth cars to intervene by braking toward a stop. The potential for introducing stop-and-go driving is demonstrated by these results.

The ACC system whose test results are shown in Figure 1 used an inner-loop that responded to velocity commands (V_c) and an outer-loop for determining V_c. The intended functional purpose of this ACC system is to seek and maintain a desired range (R_h) between the ACC vehicle and the preceding vehicle. Figure 2 illustrates the overall functional concept and shows the information flow between primary elements of the ACC system architecture.

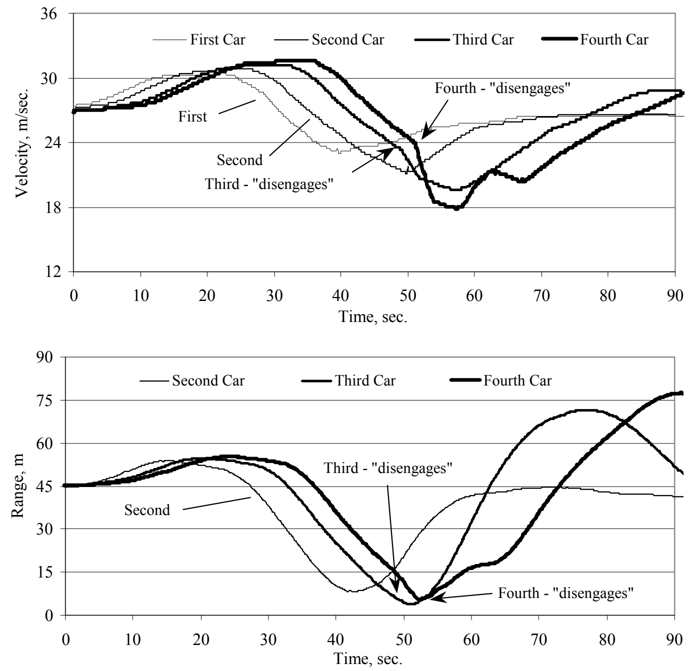

Figure 1. String Instability Exhibited by a String of 4 ACC Vehicles

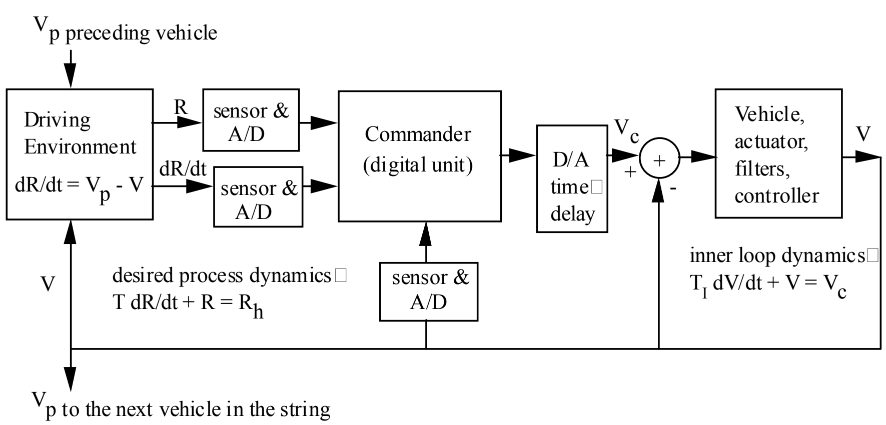

Figure 2. A Functional Concept for the Longitudinal Aspects of the Driving Process.

In this system, the desired clearance range (R_h) is equal to $T_h \cdot Vp$ where T_h is selected and set by the driver. For the case shown in figure 1, T_h was set at 1.5 seconds. The design of the system was based on observations of driver behavior. The design goal was to make the operation of the ACC system compatible with the rules and skills that drivers appear to use in manual driving. In this regard, the velocity command (V_c) was determined using observations of range, range rate, and velocity. The time parameter *T* in the desired process dynamics equation shown in Figure 1 was set equal to 11 sec to be representative of driver behavior in closing towards the desired clearance range R_h .

The representation of the inner-loop is a first order system with time constant T_i . For the speed control loop used in field testing, the time constant was greater than 4 sec. The ACC system with T_h = 1.1, 1.5, or 2.1 sec; *T* = 11 sec; and $T_i \approx 4$ sec performed satisfactorily in obtaining a comfortable process-control behavior between a preceding and a following vehicle in one-on-one situations. However, as already indicated by Figure 1, the string performance was poor.

3. SOME ANALYTICAL RESULTS CONCERNING STRING STABILITY

The term string stability refers to the propagation of a vehicle speed perturbation from one end toward the other end of a string of vehicles. In the literature, it is common to say that a vehicle is “string unstable”, when an imaginary string of this vehicle exhibits amplified responses to a lead-vehicle speed perturbation.

String stability is influenced by the control strategies involved. The control gains, the controller structure, and even headway policy will all affect the string stability behavior of a vehicle. Often linear assumptions are made in deriving speed transfer functions based on the propagation of a vehicle speed perturbation. It has been widely accepted that for a vehicle to be string stable, it needs to satisfy $|G(s)| \leq 1$, where *G(s)* is the vehicle speed propagation transfer function.

The following material will present analytical results pertaining to the string stability of vehicles fitting the structure illustrated in Figure 2. It will be shown that in order to become string-stable, the parameters of the ACC control algorithm have to satisfy a set of inequality constraints. It is worthwhile to point out that the inequality constraints will change with the structure and policy of the control algorithm. For example, the constraints to be presented below are very different from the ones presented in [2].

For this analysis, the commander-vehicle closed-loop system is described by the following equations:

Outer-loop:
$$V_c = V_p + \frac{R - T_h V}{T_o} + c\dot{R} \tag{1}$$

Inner-loop:
$$T_i \dot{V} + V = V_c \tag{2}$$

The equation for the outer-loop combines three control objectives: the desired speed should be the same as the lead vehicle speed, plus a small proportional feedback gain on a range error factor, and a proportional gain on range rate. The time constant To is the inverse of the proportional gain on the range error factor. A large To implies the designer is willing to tolerate a slower convergence to the desired range. The constant "c" can be used to compensate the responsiveness of the main-loop. Large c will result in a more agile outer-loop, which will be shown below to improve the vehicle's string stability characteristics.

By noting that $\dot{R} = Vp - V$, the following two transfer functions can be derived from (1) and (2):

$$G(s) \equiv \frac{V(s)}{V_p(s)} = \frac{T_o(1+c)s+1}{T_iT_os^2 + [(1+c)T_o + T_h]s + 1} \tag{3}$$

and

$$\frac{R(s)}{V_p(s)} = \frac{T_iT_os + T_h}{T_iT_os^2 + [(1+c)T_o + T_h]s + 1} \tag{4}$$

Eq.(3) shows the vehicle speed transfer function from which string stability behavior is determined. This transfer function has two function poles, and one function zero. Examination of Eq.(3) indicates that there will be a pole-zero cancellation if $T_i = T_h(1+c)$. In that case, $V(s)/Vp(s) = 1/(T_hs+1)$ which is string stable since $|G(s)| \le 1$.

To better understand this result, imagine that the ACC design problem is done sequentially, with the outer-loop control parameters (To, c, and T_h) already selected, and the inner-loop control parameter (T_i) needs to be designed to result in a string stable vehicle. From Eq.(3), it can be seen that the transfer function zero is fixed at $-1/(To(1+c))$ while the poles are influenced by the magnitude of T_i. The pole locations, as functions of the variable T_i are shown in the root-locus diagram shown in Figure 3 (assuming $To > T_h$).

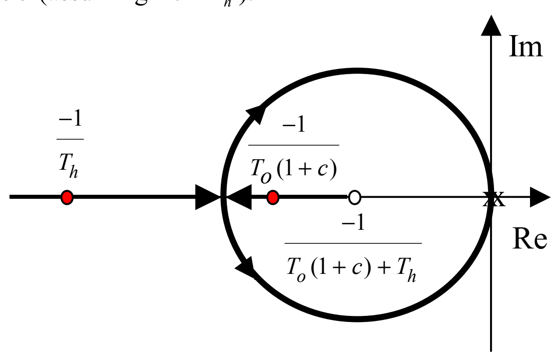

Figure 3. Root-locus diagram of the poles of Eq.(3) (assuming $T_O > T_h$, arrows indicate increasing T_i)

Figure 3 shows that when the inner-loop dynamics is infinitely fast ($T_i = 0$), the two poles are located at $-1/(To(1+c)+T_h)$ and $-\infty$. As the time constant of the inner-loop dynamics T_i increases, the slower pole becomes closer to the transfer function zero. When the slow pole is exactly equal to the transfer function zero ($T_i = T_h(1+c)$), the other (faster) pole is located at $-1/T_h$. When the inner-loop dynamics is even slower ($T_i > T_h(1+c)$), the slower pole becomes faster than the transfer function zero, and thus the frequency response magnitude will be larger than

1 at least between the frequency range governed by the zero and the faster pole, in other words, the vehicle becomes string unstable. As the inner-loop dynamics keep slowing down (increasing T_i), the poles will become complex conjugate, before their magnitude reduces. Therefore, even though the natural frequency of the poles will become smaller than the magnitude of the transfer zero as T_i approaches ∞, the vehicle string will remain string unstable due to the fact the poles are under-damped.

The necessary and sufficient condition for the above ACC algorithm to be string stable is summarized in the following theorem.

Theorem 1: For the ACC algorithm described by Eqs.(1) and (2), if $T_o > T_h$ the vehicle becomes string unstable when $T_i > T_h(1+c)$. If $T_o < T_h$, the vehicle becomes string unstable when $T_i > [To(1+c)+T_h]^2/4To$, i.e., when the poles of Eq.(3) become under-damped. (The case $T_o < T_h$ is not likely to occur for real designs but it is listed here for the completeness of the theorem.)

From an evaluation perspective, Theorem 1 may be used in estimating the amount of compensation needed to make an existing system approach string-stable performance for a particular disturbance.

4. MEASUREMENT AND CHARACTERIZATION OF ACC PERFORMANCE

Global positioning systems (GPS) provide a convenient means for measuring the response of an ACC-equipped vehicle to speed perturbations of a confederate-preceding vehicle. Each vehicle needs to be equipped with a GPS unit. These units provide the positions and velocities of each vehicle as functions of time. Range and relative velocity between vehicles are readily computed using the positions (Xp and X) and the velocities (Vp and V), viz.,

$$\dot{R} = Vp - V \;\; and \;\; R = Xp - X \tag{5}$$

Hence, the basic variables needed for evaluating headway control (R, $\dot{R}$, and V) can be measured without using the sensors and communication busses installed in the vehicle. In this manner the evaluation can be made that is independent of the equipment used in the vehicle. Using differential GPS systems of modest cost, range information within 0.5 m can be obtained at a rate of 10 Hz.

Measurements of R, $\dot{R}$, and V provide the data needed for characterizing the performance characteristics of the response of an ACC vehicle to changes in the speed of a confederate preceding vehicle. System identification techniques can be used to obtain an approximate linear model by fitting the observed data.

However, experience has shown that the proper selection of parameters in Eqs. (3) and (4) can be used to obtain a good fit to specific test results with rms error measures comparable to those obtained using system identification techniques. The reason for this is that data from distinctive operating conditions can be used to solve for suitable parametric values. The minimums of the velocity and range variables, which occur when $\dot{V}$ and $\dot{R}$ equal zero, should be employed in estimating the parametric values. The parameter T_h is readily obtained by examining steady following situations at constant values of Vp. The parameter T_i and its relation to $(1+c)$ is best obtained from data points near $R = T_h V$ during deceleration. The point is that the data from one-on-one driving situations can be used to deduce system models that predict pertinent string performance measures such as minimum V and R with good accuracy.

In general, the goal of system characterization is to determine the amount that the system response exceeds the final value of Vp at the end of a particular disturbance. As will be seen in the next section, the range response is more sensitive than the velocity response. Furthermore, improper range, rather than improper speed, relates directly to perceived safety. Hence, the amount that the range response exceeds R_h is useful in assessing string performance.

5. SIMULATIONS OF STAGED STRINGS

In this section, simulations of strings of vehicles are presented. Results are given for the following types of strings: (1) identical vehicles with specified values of T_i, T_h, To, and c; (2) vehicles with switching rules creating nonlinear behavior; (3) models of manually driven vehicles; and (4) manually driven vehicles with interspersed ACC vehicles.

The computation of V_c includes an approximation for the time delay associated with the sensors plus the analog-to-digital converters (A/D) and digital-to-analog converters (D/A) shown in Figure 2. This delay is equal to ½ of the cycle time. This means that the delay used for ACC systems is 0.05 s, for typical ACC systems that have 0.1 second cycle time. The cycle time representative of manual driving is not readily determined from field observations. It varies from one driver to another and from time to time for an individual driver. As a basis for comparison with ACC driving, a one second time delay has been chosen for use in simulating manual driving.

Figure 4 is an example illustrating simulated results for a string of 8 vehicles consisting of a lead vehicle followed by seven ACC-equipped vehicles. The lead vehicle makes a sudden speed change from 30 m/s to 20 m/s as shown. The parametric values for these ACC vehicles are such that theorem 1 indicates string instability (even without 0.05 seconds of time delay). Inspection of the figure indicates that the velocities reach successively smaller values for vehicles that are positioned further back in the string. The results for the ranges show a similar trend. The range between the seventh and eighth vehicle reduces to less than 5 meters. In a case like this, drivers would be expected to intervene by braking, thereby breaking the string and putting their ACC systems on standby until they are re-engaged.

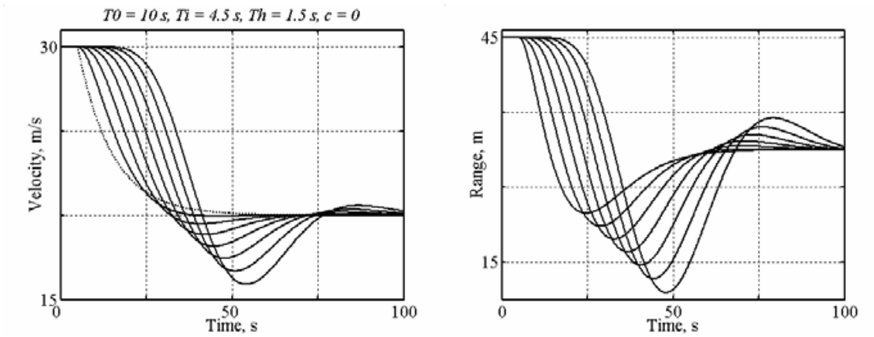

Figure 4. String Performance Uncompensated

Application of theorem 1 indicates that the system used in making Figure 4 would become string stable if c were changed from 0 to 2. The results shown in Figure 5 confirm this prediction. In this case, the minimum velocity and range is practically the same as the final values of Vp and R_h respectively.

The results shown in Figures 4 and 5 indicate a technique for rating string performance. That is, the value of the compensation parameter (c) needed to produce string stability is a measure for comparing the performance of the system represented by Figure 4 to an ideally compensated system such as that demonstrated in Figure5. (Experience has shown that the parameters for fitting the response of a given ACC system may include a value of c that is less than zero. In this case the performance measure for rating the system should be the change in c from its negative value to the positive value that would be needed for string stability.)

Given the system structure shown in Figure 2, the method for computing V_c can easily incorporate switching rules allowing the calculation of V_c to depend upon operating conditions. Detailed examination of driver braking data indicates that drivers apparently tend to make $\dot{R}$ approach zero during braking situations. In the context of Figure 2, this would mean that they would use $V_c = Vp$ during braking. Only when $\dot{R}$ gets rather close to zero would the typical driver attempt to make R = R_h. Figure 6 illustrates a set of switching boundaries that are employed in making $V_c = Vp$ in braking situations. In other situations, the model reverts to the rules described by Eqs. (1) and (2).

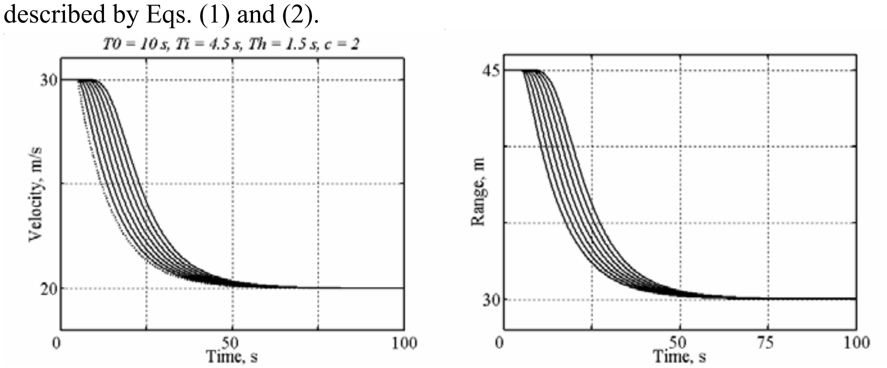

Figure 5. String Performance Compensated)

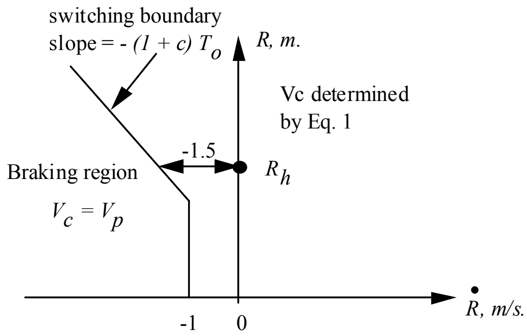

Figure 6. Nonlinear Switching Rules

Physical reasoning supports the choice of making $V_c = Vp$. Neglecting the influence of any time delay, the system reduces to $T_i\dot{V} + V = Vp$, when $V_c = Vp$. Since $\dot{R} = Vp - V$, this means that $\dot{R} = T_i\dot{V}$. Integrating with respect to time indicates that the change in range ΔR = T_i ΔV, where ΔV is the change in velocity. If this amount of change in R is equal to T_h (Δ *Vp*), the change in range will be ideal for achieving the desired range. If *Ti* is set equal to *Th*, the ideal condition will be achieved in a coordinated manner as the speed of the preceding vehicle changes.

Computed results for an ACC algorithm using the switching rules described above indicate that there will be a very small amount of overshoot such that R decreases to less than R_h in response to a transient change in Vp. This is due to the effect of the time delay of 0.05 seconds included in the simulation. This may be compensated for by making *c* greater than zero. A value of *c* = 0.5 provides satisfactory compensation. However, if the time delay is one second long, corresponding to a prototypical manual-driving situation, the effect of the delay is substantial. See Figure 7 for an example of simplified, human-controlled response. In this case, the minimum velocity for each vehicle is smaller than that achieved by the preceding vehicle in the string. String performance is not good. (Since drivers have difficulty in maintaining good string performance in the real world, of course, poor simulated performance is expected.)

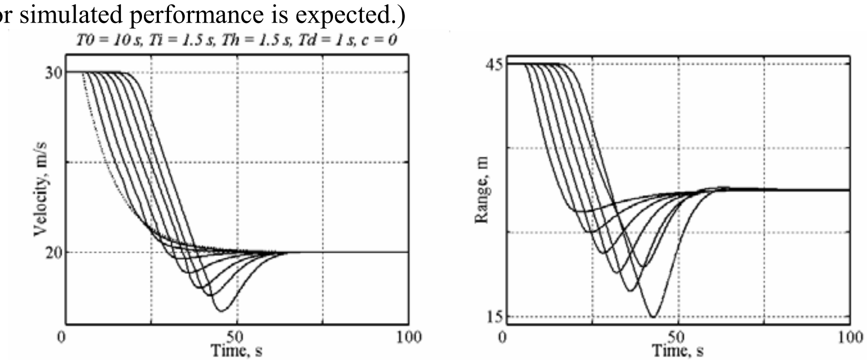

Figure 7. String Performance, Driver Model Uncompensated

The difference between the adjacent traces in the velocity plot is equal to $\dot{R}$, which is the time rate of change of the range from a following vehicle to its preceding vehicle. Hence the area between the curves, up to the point where $Vp = V$

is the change in R from its initial value. Inspection of the velocity traces in Figure 7 indicates that these areas differ slightly between vehicle pairs. The influence of this difference is apparent in the range traces for which the minimum range occurs when $Vp = V$, that is when $\dot{R} = 0$ for each follower-preceding vehicle combination. Interestingly in this case (Figure 7), the minimum range for the sixth ACC vehicle is not as small as that for the fifth or seventh ACC vehicle. Clearly, the non-linear switching behavior introduces results that can confuse string stability issues associated with range behavior. Just because one vehicle appears to be doing better than its preceding vehicle does not mean that the next vehicle will perform better.

The representation of the driver using $Vc = Vp$ can be related to a classical form of traffic flow analysis. t. As indicated before if $T_i = T_h$, then $\dot{R} = T_i \dot{V}$. As described in [2], this is the form that Pipes used to model driver behavior. A time delay (*td*) was incorporated into Pipes' work such that $T_i \dot{V}(t) = \dot{R}(t-td)$. The length of the time delay has been a subject of study with Pipes suggesting 2 s. and Chandler suggesting 1.5 s. as a representative value. In the calculations presented in Figure 7, 1.0 second is used to represent an alert driver who is concentrating on the driving task. The purpose in this paper is to provide a basis for comparing ACC performance to manual driving performance. Clearly, the difficult part of this comparison is to determine what represents manual driving in a realistic and useful manner.

Interestingly, the manual driver model with 1.0-second delay can be compensated to get good string performance. The results in Figure 8 show this. This change in performance is due to changing c from zero to 0.5. Although c was introduced in the context of linear systems, its power in improving string performance applies to non-linear systems as well. Based upon these results, the representative driver's compensation rating for string performance is given by $c = 0.5$.

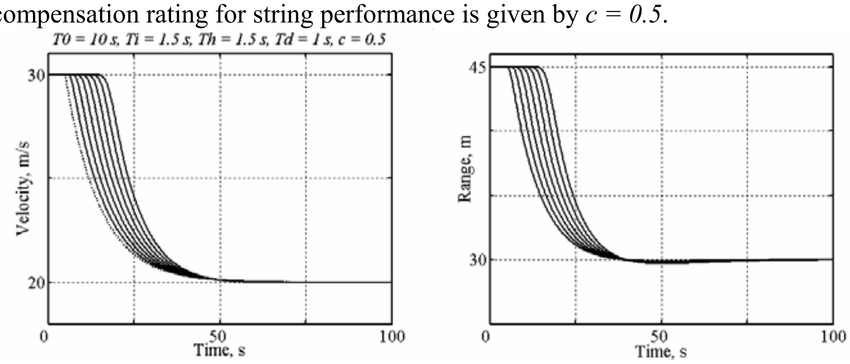

Figure 8. String Performance, Driver Model Compensated

As a lead into the next section, which discusses traffic, flow simulation, consider a string with ACC vehicles interspersed between manually driven vehicles. This string consists of a lead vehicle followed by a manually driven vehicle and then an ACC vehicle, etc. such that there are four manually driven vehicles and three ACC vehicles following the lead vehicle. This example is included to provide insight into whether string-stable ACC vehicles might help to stabilize mixed traffic. The results are shown in Figure 9.

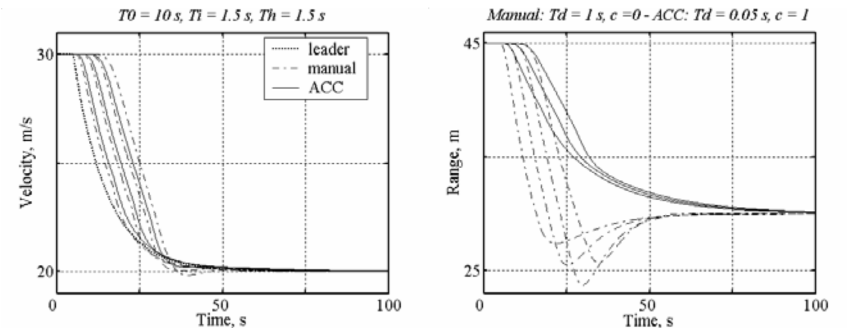

Figure 9. Mixed Manual and ACC String

In Figure 9, a dotted line represents the lead vehicle, the dashed lines are manually driven vehicles, and the solid lines represent ACC vehicles. Observe that due to the smaller time delay for ACC vehicles, the separations between the velocity traces for the ACC vehicles and their preceding vehicle are much smaller than the separations from the manually driven vehicles to their preceding vehicle. These differences mean that the change in range during this driving situation will be much larger for the manually driven vehicles than it is for the ACC vehicles.

The differences between the range responses of the manually driven and the ACC vehicles are graphically portrayed in the range versus range-rate diagram shown in Figure 9. At any range, the value of $\dot{R}$ is much smaller for the ACC cars than that for the manually driven cars. Since $\dot{R}$ is larger for the manually driven cars, R is changing more quickly for these cars, which might be appraised as more responsive if it did not lead to going well below the desired range. On the other hand, the responses of the ACC cars appear to be well damped. In this case c was chosen to be more than enough to obtain string stability in the hopes of improving performance for the whole mixed string. To a certain extent this was achieved with reasonable range and velocity performance during the 100 seconds simulated for this string of 8 vehicles. The situation portrayed in Figure 9 involves a compromise concerning speed of response. It is possible that some drivers will be impatient with the rate that this ACC system closes in towards the desired range.

6. EVALUATING THE INFLUENCE OF ACC ON TRAFFIC FLOW

In recent years, the number of microscopic models and simulation tools has increased dramatically. The SMARTEST project that was completed recently by a consortium led by the Institute for Transport Studies of the University of Leeds identified 58 microscopic simulation models of which 32 were analyzed. Examples of these microscopic models include AIMSUN[3], SmartAHS [4], TRANSIMS [5], and CORSIM [6].

One of the key benefits of these microscopic models over fluid-based macroscopic models is the possibility to recognize each vehicle/driver's "personality". Therefore, more accurate evaluation of individual vehicle's response under realistic traffic conditions is possible. Drivers' behavior and ACC system characteristics can be described either by certain car-following/lane change models or by a set of if-then rules. These models or rules generally dictate the lane location, forward speed or acceleration of each vehicle at each sampling time, based on predetermined driver and vehicle parameters. Proper linking (pairing) between vehicles is then necessary to calculate important variables such as range, time gap, and relative speed. Depending on the purpose of the simulator, additional variables may be computed.

Key performance metrics for ACC systems include microscopic measures (range, range rate, time to collision, frequency of emergency braking, etc.) as well as macroscopic measures (aggregate flow, average speed, formation of shock waves, etc.) Microscopic simulations are important tools for use in predicting and evaluating the potential influences of ACC system properties on traffic flow.

A microscopic simulator (UM-ACCSIM) has been developed specifically for the evaluation of ACC performance [7]. This software tool simulates and records the motions of an extensive set of vehicles operating on a 2-lane circular track, and can produce all the important microscopic and macroscopic outputs stated above. The car-following headway, average speed and lane change models are all constructed based on a statistical analysis of human drivers' characteristics from field measurement work [2].

Experience operating this simulator has shown that, due to the existence of two lanes, numerous lane changes into gaps between vehicles will occur. This, in turn, will cause many velocity perturbations to occur. This is ideal for analyzing the performance of ACC vehicles operating in a naturalistic environment.

7. CONCLUDING STATEMENTS

Evaluation of string performance has been the theme of this paper. Various aspects of the evaluation process have been considered. A theorem concerning the string stability of linear approximations to ACC systems has been presented. This theorem provides a basis for assessing the extent to which a given ACC system satisfies a combined requirement for string performance as well as headway control. As a basis for comparative evaluations, a driver model has been introduced to provide a means for comparing ACC performance to manual driving.

Techniques for measuring ACC system performance have been described. This measurement capability provides the data needed to simulate strings of vehicles using measured one-on-one responses to velocity perturbations. Examples involving linear and non-linear simulations have been presented. These examples illustrate how the predicted string performance of ACC controlled vehicles can be compared to that of an ideal ACC system or that of manually controlled vehicles.

The use of microscopic models and simulation tools for studying traffic flow has been described in the context of incorporating selected driver models and ACC system representations into a two-lane traffic simulator. This type of simulator can be used to assess string performance in a naturalistic environment. In addition, the simulator can be used to estimate the likelihood for various lengths of strings to develop. These matters can be studied as a function of traffic density.

The primary conclusion of this paper is that analytical findings, measurement and characterization methods, and simulation tools are now ready to support field operational tests involving ACC-equipped vehicles. The ability to measure and assess one-on-one performance indicates the potential for developing industry and government standards concerning the influence of ACC system performance on string behavior.

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