

Driving Assistance Provided by Adaptive Cruise Control

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ABSTRACT

This paper discusses the values that Adaptive Cruise Control (ACC) systems can provide to the consumer now and in the future. It contains results from research applicable to understanding ACC behavior in traffic streams. The paper includes findings on (1) non-intrusive means for characterizing ACC behavior, (2) the influence of ACC behavior on the microscopic properties of traffic flow, and (3) prospects for the use of ACC systems to relieve driver frustration in heavy traffic as well as contributing to smoother traffic flow.

INTRODUCTION

Industrial development of adaptive cruise control (ACC) stems from uniting the desire to provide driver assistance with digital control of the time gap between vehicles. The intent of this paper is to describe the driving qualities that ACC systems provide now and those that they could provide in the future.

Results from field operational tests are used to indicate why ACC systems are received favorably by ordinary drivers/consumers operating in their choices of transportation service. The comfort and convenience provided to drivers is discussed in terms of reduced throttle modulation, ease of control in situations involving following other vehicles, and reduced driver workload [1,2].

Results from on going research on desirable ACC behavior in traffic streams are presented next [3,4]. The objectives of that research program are to (1) Evaluate the performance of ACC systems in strings of vehicles as may occur in traffic. (2) Identify ACC system characteristics that influence traffic flow. And (3) Develop a knowledge base that can be used by industry to produce ACC systems that preserve/improve traffic flow in a manner that is acceptable to their customers. The ultimate goal of the research program is to assure that the collective impact of many individual ACC-equipped vehicles or a string of ACC-equipped vehicles will not be a detriment to traffic flow.

ACC'S ROLE IN THE DRIVING PROCESS

Figure 1 illustrates the variables involved in the primary driving situation in which ACC systems control the range clearance and the time gap between vehicles. In addition to sensors, which measure internal vehicle dynamics variables such as velocity V and acceleration A , there are sensors, which look outside of the vehicle to measure the range R and its time rate of change, range rate $Rdot$.

As indicated in figure 1, R is the distance between the ACC-equipped vehicle and its immediately preceding lead-vehicle. The lengths of the vehicles are important in determining the density of vehicles per unit of roadway length. For example, if all of the vehicles were of the same length L and all of them were separated by a range R , the density would be equal to $1/(R + L)$ vehicles per unit length. In terms of global positioning coordinates, where X_p is the location of the front of the preceding vehicle and X is the front of the ACC vehicle, the range is:

$$R = X_p - X - L \quad (1)$$

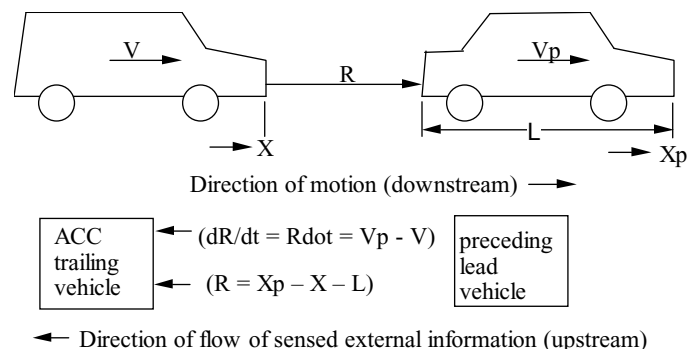


Figure 1. Motion variables and information flow

As indicated in figure 1, $Rdot$ (the relative velocity) is given by the difference between the velocity of the preceding vehicle V_p and the velocity of the ACC vehicle V ; viz.,

$$Rdot = V_p - V \quad (2)$$

Rdot is important in determining the type of control actuation needed to obtain a desired range clearance. If Rdot is less than zero, R is decreasing and the ACC vehicle is closing-in on its preceding vehicle. If $Rdot \approx 0$, the ACC vehicle and the preceding vehicle are travelling at approximately the same speed. If $Rdot \geq 0$, the vehicles are separating in range. The basic control idea for maintaining a desired range is to speed up so that Rdot will be negative if the range is longer than that desired and to slow down so that Rdot will be positive if the range is less than that desired.

R is the accumulating integral of Rdot as either vehicle or both vehicles speed up or slow down. If Rdot is small and its average is approximately zero for an appreciable length of time, R will stay near to a constant value. The control rules used in ACC systems are designed to hold $Rdot \approx 0$ when the range equals the range desired for following a preceding vehicle traveling at approximately a constant speed.

Certain features of ACC design are extensions of conventional cruise control (CCC) in the sense that ACC uses many of the features and sensors associated with CCC. The idea of a set speed V_{set} is directly transferable. If there is not a preceding vehicle within selected bounds of R and Rdot, the ACC vehicle strives for (seeks) $V = V_{set}$. Only when there is a preceding vehicle in reasonable proximity does the ACC system use its control rules to adjust its speed commands and/or its acceleration commands to obtain a desired range. This synergy between CCC and ACC systems has been a major factor contributing to the advancement from CCC to the digital mobility functions of ACC. The new features needed for advancing from CCC to ACC were sensors for measuring the external situation and control algorithms suitable for maintaining an appropriate range clearance.

Figure 2 diagrams the elements of the longitudinal control process as applied to the development of ACC systems. This diagram (figure 2) pertains to the one-on-one situation portrayed in figure 1.

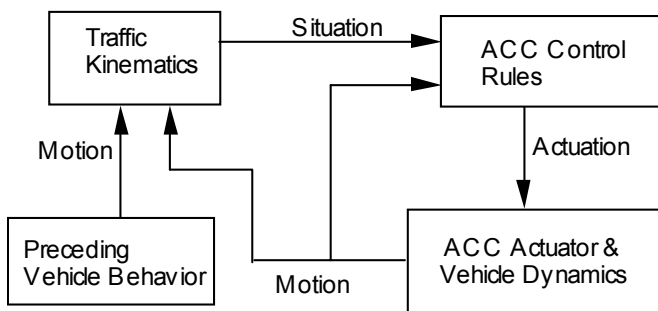


Figure 2. ACC control rules in the driving process

The motions of the preceding vehicle and the ACC vehicle are the inputs to the traffic kinematics block in figure 2. In the analysis or simulation of this block, equation 2 is used to determine Rdot, and Rdot is integrated to obtain the change in R.

As shown, the inputs to the ACC control rules are the driving situation and the motion of the ACC vehicle. For this discussion of ACC, the driving situation is represented by the sensed values of V, R, and Rdot. The output from the control rules is a control command to the actuators of the ACC vehicle.

The nature of ACC control rules will play a major role in discussing the evolution of ACC systems in later sections. However, for now recognize that various organizations have developed rules that will provide longitudinal control of speed and range clearance in a manner that is acceptable to their customers. With few exceptions, the details of these control rules are generally proprietary information. The complexities of these rules will not be treated here. Rather, abstractions, analogies, and aggregation techniques will be used to simplify the equations involved in describing the rules.

In keeping with avoiding detail, the vehicle and its actuators will also be described in terms of simplified concepts appropriate for the high levels of abstraction frequently used in the initial planning stages of designing a system. For example, the control rules for an ACC system used in initial evaluations of performance in field operational tests [1] were based upon using the set speed input available in an existing CCC system as the actuation input for the actuator-vehicle system. This proved to be feasible once all of the electronic checks and gates were programmed to allow access to the input of the CCC control unit. Fortunately the CCC unit had been programmed to work with the vehicle's engine and power train so that equation 3 below provided a working approximation for small changes in the speed of the ACC vehicle; viz.,

$$T_c \dot{V} + V = V_c \quad (3)$$

In (3), T_c is a time constant, the acceleration $\dot{V} = dV/dt = A$, and the velocity command V_c is the actuation signal to the actuator-vehicle block.

Equation 3 is a very simple approximation. It does not account for all of the complicated dynamics of the drive-train, engine, brakes, and the vehicle, and the design choices used in developing the actual actuator-vehicle system. However, the idea that such a simple equation can be used in planning future development is an important part of the process in which past advances can be used as conceptual building blocks in future efforts towards digital mobility.

The control rules for generating V_c (as used in [1]) depended upon R and Rdot and two parameters T_h and T as in shown in equations (4) and (5), which follow.

$$R_h = T \dot{R} + R \quad (4)$$

$$\text{And, } V_c = R_h / T_h \quad (5)$$

Where R_h is the desired range for steady following with $V = V_c$ and $\dot{R} = 0$. In addition to throttle modulation, the ACC system was able to employ a transmission downshift because the transmission was electronically controlled. This provided the mechanism for obtaining greater deceleration than that attainable by dropping the throttle alone.

The ACC system described by equations 3, 4, and 5 was employed in a field operational test aimed at evaluating how well this then new technology could operate under real operating conditions. The results and findings of the operational test showed that drivers would value the driving assistance provided by the ACC system. Part of the success of the system was due to the human-centered design features built into the system. These features were aimed at making the driving characteristics of the ACC system enough like manual driving so that the driver would understand how the ACC system functioned. In that way, when the ACC system was in operation, the task of learning how to supervise the ACC system was apparent to the driver.

For example, the parameters T and T_h in the control rules were selected to fit the preferences of drivers. The role of T in the ACC driving process was to cause the ACC vehicle to close towards steady following in a manner similar to the manner in which drivers close-in on slower moving vehicles in manual driving. The value of T_h was designed to be driver adjustable because it was observed that different drivers had different preferences regarding the time gap used in ACC driving in steady following situations. The value of T_h represents the chosen time gap and consequently determines the desired range R_h when $V = V_c$. The system used in [1] allowed three choices of T_h . The driver could choose $T_h = 1.1$ s (labeled "closer"), 1.5 s (unlabelled), and 2.1 s (labeled "farther"). The results of the field operational test involving 108 different drivers showed the following pattern, which tends to fit common intuitive expectations. The experimental design involved 36 younger drivers, 36 middle-aged drivers, and 36 older drivers. The younger drivers tended to choose "closer" ($T_h = 1.1$ s); the middle aged drivers tended to choose the middle button ($T_h = 1.5$ s); and the older drivers tended to choose "farther" ($T_h = 2.1$ s). The point is that the values T and T_h reflected the influences of driver preferences regarding driving behavior and driving style.

Also, the value of V_{set} was left as a driver adjustable parameter just as it had been during CCC utilization. This means that the drivers were able to interact with the ACC system to obtain driving performance that suited their choices of driving style regarding desired speed. Furthermore, the control algorithm employed switching rules for making the decision between using $V_c = V_{set}$ or using V_c as determined by equations 4 and 5. These switching rules reflected driver concerns with ACC behavior that might tend to slow down the vehicle when it appeared that there was no preceding vehicle close enough to require changing speed. In this sense, the

role of an ACC system is to approach the desired range R_h when there is a preceding vehicle within appropriate conditional relationships involving R and $\dot{R}$.

Another design concern with ACC is its role in situations requiring braking. The ACC used in [1] had limited deceleration capability. The combination of natural retardation due to aerodynamic drag, tire rolling resistance, and engine/driveline drag plus the added retardation due to downshifting the transmission by one gear amounted to a maximum deceleration of approximately 0.07 g at highway speeds. However, this is more than enough to be startling to drivers and passengers if they are not expecting it. On the other hand, the maximum deceleration capability provided by an ACC system determines the boundary for the utility of the system before driver intervention is needed.

The system in [1] did not use the foundation brakes because a "smart" booster that could be installed in the vehicles was not available then. Work in [2] includes the use of a smart booster to control brake pressure as requested by an electrical input signal. In that case, the knowledge that drivers were very sensitive to small amounts of deceleration had an important influence on the rules used to determine the amplitude of the requested pressure/deceleration signal supplied as input to the booster. It had been observed in [1] that dropping the throttle without downshifting provided approximately 0.04 g, and this was enough deceleration to cause everyone in the car to look out front to see what was going on. A compromise between the level of deceleration and the minimum range R encountered during closing was established so that the driver would not be jerked too much nor would the driver feel uncomfortable because of a near encounter at short range [2].

Electronic means for digitally controlling the brakes are generally included in commercially available ACC systems now. The maximum available deceleration may be as high as approximately 0.3 g but the circumstances in which that level of deceleration is used are severely limited. Current topics of discussion and subjects that are frequently addressed by groups developing recommended practices for industry involve how should the brakes be modulated and what are acceptable levels of maximum deceleration. The underlying issue has to do with the appropriate role for ACC systems when higher deceleration levels are required for safety reasons. Perhaps, this issue will become mute if practical and effective collision warning and crash avoidance systems are developed to complement the comfort and convenience values provided by ACC systems. Currently, ACC systems are designed to provide the driver with comfortable assistance in driving. And, even though they provide diligent control of headway as well as deceleration levels that alert the driver to impending difficulties, they are primarily comfort and convenience devices for providing driver assistance in routine longitudinal control activities.

COMFORT AND EASE OF DRIVING

The driver participants in [1] gave high subjective ratings to the ACC system regarding comfort, convenience, and ease of driving. For example, the subjective ratings presented in table 1 indicate that drivers generally expressed a high level of acceptance of the headway control assistance provided by the ACC functionality.

Table 1. Example Subjective Ratings [1]

Comfort:

Using a scale from 1 to 7 where 1 is very uncomfortable and 7 is very comfortable answer the following question:
How comfortable did you feel driving the car using the ACC system?

Statistical evaluation, based upon the responses of all 108 drivers, yielded the following results:
mean value = 5.75, standard deviation = 1.44

Ease of driving:

Using a scale from 1 to 7 where 1 is very difficult and 7 is very easy answer the following question:
How easy did you find it was to drive using the ACC system?

Statistical evaluation, based upon the responses of all 108 drivers, yielded the following results:
mean value = 6.08, standard deviation = 1.02

Reference [1] contains further treatment of subjective ratings. The overall conclusions support the general finding that ACC control is remarkably attractive to most drivers. Furthermore, reference [1] provides information that aids in explaining why ACC driving has a strong attraction compared to manual driving and CCC driving.

Compared to manual driving, ACC driving completely relieves the driver of something that has been named “throttle stress.” Figure 3 illustrates throttle modulation under manual control when the speed of the preceding vehicle is more or less constant. These data are characterized by many more and much greater throttle fluctuations than those observed for ACC driving. Observations of manual driving indicate that there are frequent large excursions in throttle position often reaching dropped throttle. This occurs with a period of approximately 3 seconds. For extended trips this means approximately 1200 throttle modulations per hour. Clearly the driver is relieved of this burden when ACC is modulating the throttle. Interestingly, drivers do not seem to be aware that they are doing this modulation but they appear to recognize the benefits of being relieved of throttle stress, especially on long trips.

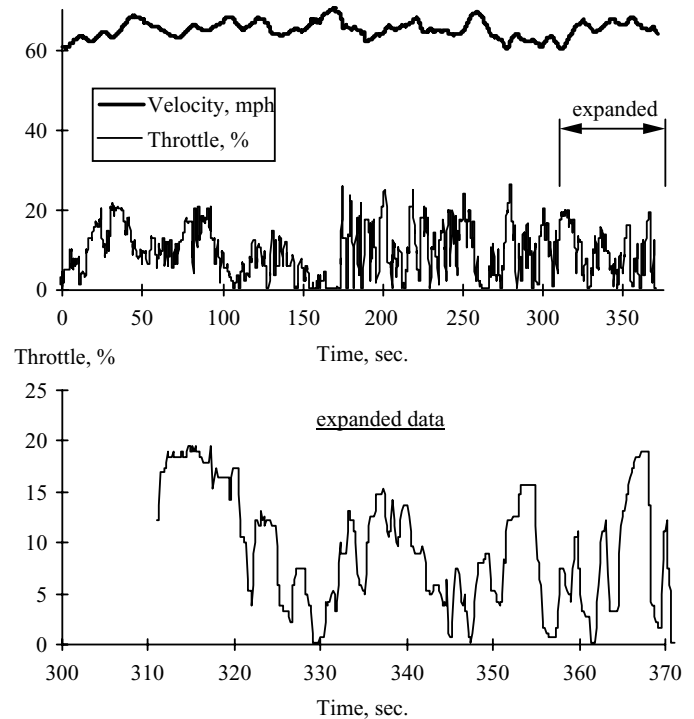


Figure 3. An example of throttle modulation in manual driving

(Incidentally, throttle activity may also have implications with regard to improvements in fuel economy, and that is another matter regarding ACC’s value to the consumer.)

Another type of stress in manual driving has been referred to as “headway stress.” This has been attributed to human visual limitations in perceiving the visual angle subtended by the cross-section of the preceding vehicle and the rate of change of this angle. These are human-centered variables associated with the influences of range R and range rate $R\dot{d}$ on the driver’s perception of the driving situation. The concept involved is that in typical following situations the driver needs to keep making corrections due to difficulties in detecting information related to small values of $R\dot{d}$ and to accurate values of R . The steady following data from manual driving shows a tendency for drivers to vary speed and desired range in a manner that appears as a small limit cycle associated with the effects of limited resolution.

In practice, the search for manual steady following data is a much harder task than one might expect. Experience has shown that drivers seldom follow another vehicle manually for more than 1 minute in their normal driving service. Apparently drivers, who wish to travel faster than the preceding vehicle, find ways to pass the slower moving vehicle. Clearly, there are situations in dense traffic that would require following the preceding vehicle, but once this level of density is reached, stop and go driving may ensue and steady following at approximately constant speed is not characteristic of manual driving. In addition, it appears that many drivers pick where and when they drive so

that they will avoid dense traffic. For example, out of the 108 drivers in [1] 49 of them did not follow another vehicle for one minute or longer in a week of manual driving. The other side of this is that drivers were tolerant of following another vehicle when using ACC. Apparently, ACC driving causes drivers to develop a tolerant attitude towards following a preceding vehicle, because ACC reduces driver workload compared to that involved in manual driving. In this sense, drivers are relieved of headway stress. In any event, when using ACC, drivers are relieved of the stress associated with striving to perceive relatively small variations in the range and relative velocity to the vehicle ahead.

With respect to CCC, ACC provides substantial relief from the frequency of interruption of automatic control normally required under conventional cruise control. The results in [1] show that the period of typical engagements without interruption for ACC driving averaged 75 percent longer than those for CCC driving.

On a scale from 1 to 3 with 1 being the highest preference, ACC compared very favorably with respect to CCC or manual driving. When the driving qualities in question were either enjoyment, convenience, or comfort, the mean subjective rankings given to ACC were between 1.29 and 1.31, compared to mean rankings of 2.06 to 2.12 given to CCC, and 2.56 to 2.62 given to manual driving in highway operations. These results, although obtained with a prototype non-commercial system, support the view that ACC offers great promise for improving the quality of the driving experience. The experience in [1] applies (extrapolates) to current systems in which human-centered design plays a significant role in selecting acceptable system properties.

PERFORMANCE OF ACC IN TRAFFIC

Figure 4 extends the one-on-one situation portrayed in figure 1 to a string of vehicles in which the speed of the lead vehicle is V_p and the speeds of the trailing vehicles are V_1 , V_2 , V_3 , etc. The ranges between each trailing vehicle and its preceding vehicle are symbolized as R_1 , R_2 , R_3 , etc. Figure 4 is an information flow diagram in which R and $Rdot$ values are viewed as flowing upstream from vehicle to vehicle.

The string idea as portrayed here means that the string is made up of a sequence of one-on-one situations in which each trailing vehicle is responding to the motion of the vehicle immediately ahead of it in the string. Clearly, if the amplitude of the motion response grows from vehicle to vehicle going up the string and the string is long enough, there will be a trailing vehicle that will crash into the vehicle ahead of it when the trailing vehicle's range goes to zero. Of course, people do not ordinarily let this happen. (They resort to stop and go driving if they cannot change lanes to avoid the conflict.)

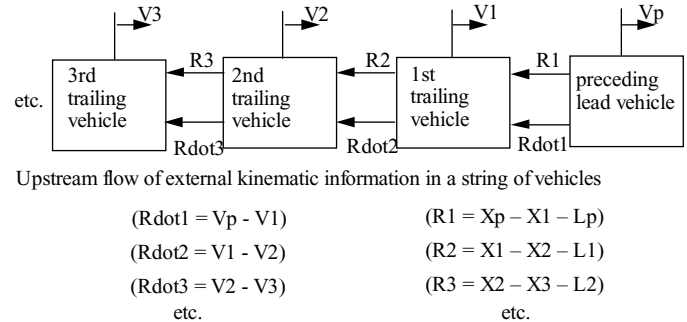


Figure 4. Symbolic representation of a string of vehicles

This string stability issue applies to both manual and ACC driving. In fact, the identical prototypical ACC vehicles used in reference [1] were intentionally driven by test drivers in strings of 4 and 8 vehicles in length to observe their string behavior. These vehicles showed string unstable behavior in response to small changes in lead vehicle speed. The drivers of the trailing vehicles needed to intervene by braking in order to prevent colliding with the vehicle immediately ahead of them in the string.

Although this type of string behavior is not seen as good, drivers can handle these situations as they do now in manual driving. At present with only a small penetration of ACC-equipped vehicles into the overall vehicle fleet, the influence of ACC on traffic flow is not a major issue. However, as the penetration of ACC-equipped vehicles grows, there is need to ensure that ACC tends to preserve or improve traffic flow and does not contribute to increased congestion. Vehicle manufacturers are aware of this issue and they have participated in research to address this issue, for example [3,4].

Another aspect of the concern with traffic flow involves the spacing between vehicles. The parameter Th used earlier in describing ACC systems relates directly to inter-vehicle spacing. If people using ACC were to operate at longer time-gaps and therefore, longer range-clearances as compared to manual driving, it appears that traffic flow would be reduced. However, the situation is more complicated than that. Figure 5 will be used in explaining the fundamental characteristics of traffic flow and issues involved in comparing ACC to manual driving.

The fundamental diagram shown in figure 5 portrays the relationship between flow in vehicles per second on the vertical axis and density in vehicles per unit distance on the horizontal axis. In a sense, this figure pertains to the view of an observer who is standing by the side of the road watching vehicles go by. The relationship between flow and density is represented by segments of two straight lines. These lines represent an aggregation of results for many drivers in the sense that they approximate mean or most likely values for people driving on a particular road.

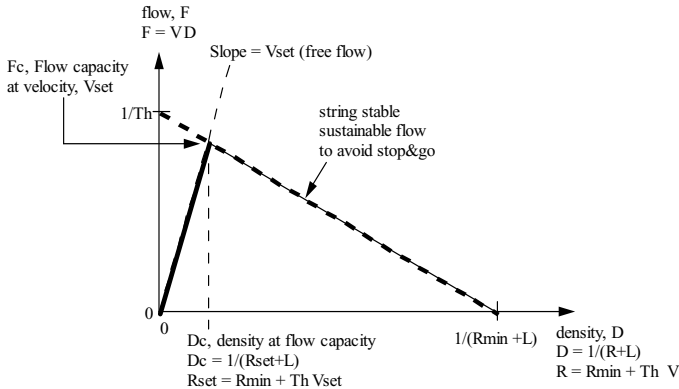


Figure 5. Fundamental diagram, traffic flow

The line with positive slope represents the influence of V_{set} in the case of ACC. In manual driving, the free flow speed chosen by the driver is approximately the same as the set speed that that driver would choose in ACC or CCC driving [1,5]. This phenomenon is associated with the tendency for most people to select a speed that is rather near the speed of prevailing traffic. Since this applies to both ACC and manual driving, it tends to make flow in uncongested freeway situations similar in ACC and manual driving. The drivers who want to travel faster simply pass or change lanes to avoid the drivers who want to travel slower.

The line with negative slope represents the situation when traffic is dense enough that passing is difficult and following rules will apply until there is a chance for faster moving vehicles to pass when a gap opens up in an adjacent lane. This line is dashed because whether or not this represents a sustainable steady-flow condition depends upon whether the manual or ACC control rules are string stable. This discussion has been simplified to apply to what happens in steady flow. However, manual driving is not string stable in high density situations and whether ACC driving is string stable depends upon the parametric values chosen for use in the ACC system. If the ACC system closely emulates driver characteristics, it may lead to string instability as well. (This will be explored later in the paper.)

There are new parameters associated with the dashed line in figure 5. R_{min} represents the average minimum range that drivers achieve when they come to a stop behind a preceding vehicle. D_j is the jam density when all vehicles are stopped. L is the average length of the vehicles involved in the traffic stream. These parameters can be utilized with the following steady-flow equation that includes R_{min} and the desired time gap Th .

$$R = Th V + R_{min} \quad (6)$$

Note that Figure 5 does not include velocity V explicitly on its axes, but V may be related to flow F and density D by the following expressions.

$$F = V D \quad (7)$$

$$D = 1/(R + L) \text{ where } R \text{ is given by (6)} \quad (8)$$

Algebraically combining equations (6), (7), and (8) yields equation (9), which represents the high-density part of the relationship for $D > D_c$.

$$F = (1/Th)(1 - D/D_j), \quad \text{where } D_j = 1/(R_{min} + L) \quad (9)$$

Equation (9) indicates that F would approach $1/Th$ if the density were to approach zero and the vehicle were to travel faster than V_{set} . Although (9) doesn't apply for $F > F_c$, its y-intercept at $F = 1/Th$ indicates the importance of the value of time gap Th in determining maximum flow.

The point where the two straight lines intersect defines the maximum flow at capacity F_c and the density at maximum flow. The velocity at this point is V_{set} , and equations (10) and (11) describe F_c and D_c .

$$D_c = 1/(Th V_{set} + R_{min} + L) \quad (10)$$

$$F_c = D_c V_{set} \quad (11)$$

In this context, the issue of ACC's influence on maximum flow depends upon how the effective value of Th differs between ACC and manual driving. For example, a freeway with a high flow capacity might have a maximum flow of 2100 vehicles/hour (21/36 vehicles per second) at a velocity of approximately 30 m/s for manual driving. Given these conditions, $D_c = 0.0194$ vehicles per meter, and for $R_{min} + L = 6m$, equations (10) and (11) indicate that Th would be approximately 1.5 s. These rough calculations indicate that ACC systems with Th settings averaging higher than 1.5 s might contribute to flow rates that are less than those achieved in manual driving. However, these calculations represent a simplified approach to a very complex matter. The influences of transient dynamics are not included. The distributions of time gaps and free flow speeds utilized by different drivers may not have been properly accounted for. Perhaps the speeds of the slower vehicles set the pace for the others who would like to go faster, but as the density increases, drivers cannot find a gap to use to pass. In light of these uncertainties, the following material addresses research that industrial partners have undertaken to better understand the influence of ACC on traffic flow at capacity and at densities above D_c .

ONE-ON-ONE MEASUREMENTS

Techniques involving microscopic simulation of traffic streams have been chosen to study the influences of ACC behavior on traffic flow. For mixed ACC and manual driving, this involves simulation models that are capable of representing the one-on-one behavior of both ACC vehicles and manually driven vehicles.

Acc driving

Since control rules for ACC systems are proprietary information that manufacturers do not share, special identification methods for characterizing the one-on-one performance of ACC systems have been developed. Industrial partners supplied three ACC vehicles that were already introduced or about to be introduced into the market in 2002 [3]. These were production or pre-production vehicles. The sensors, communication buses, and displays were not to be tapped into to obtain information and data. (In the field studies referenced earlier, the ACC system's units were used to gather data on both ACC and manual driving. In that case, proprietary interests at the component level were observed but the design of the control rules was not a proprietary concern.)

The first step in resolving the proprietary issue was to develop a non-intrusive method for measuring R , $\dot{R}$, and V as needed to obtain pertinent data to be used in characterizing the performance of the ACC vehicle being tested. The data acquisition system developed for this purpose involved two differential global positioning systems (DGPS). One was installed in the car under study. The other was installed in the lead vehicle, which was used to provide the inputs (i.e., V_p and X_p) for exciting the motion response of the ACC vehicle. The DGPS unit in the ACC vehicle measured V and X . See figure 1 to picture these variables. The data from the two DGPS units were synchronized in time using the GPS time signal as recorded by each DGPS system.

The synchronized time histories of X_p and X were processed to obtain the time history of R during testing. V_p and V were similarly processed to obtain $\dot{R}$. See equations (1) and (2). These data were obtained for several maneuvering situations such as closing in from long range, lead vehicle cutting in front of the ACC vehicle (or the ACC vehicle cutting in behind the lead vehicle), lead vehicle decelerating to a lower speed, and lead vehicle accelerating to a higher speed. The data were obtained in sampled data form with a new sample every 0.1 seconds.

Commercially available system identification algorithms were then used to develop response models for use in subsequent simulation work. The identification work indicated that the data could be well represented for small changes in speed by a state space model using the state variables V and R and the input variable V_p . Furthermore, the identification results indicated that one of the identified equations fitted equation (2) (i.e., $\dot{R} = V_p - V$). Hence, the key new pieces of information from the identification process were the coefficients in the equation for $\dot{V}$, which follows in sampled data form using a forward difference approximation for representing the derivative of V .

$$V_{i+1} = a_1 V_i + a_2 R_i + b_1 V_{p_i}, \quad i \text{ is the time index} \quad (12)$$

The values of a_1 , a_2 , and b_1 identify the nature of the control rules used in the ACC system [3,6].

The results of the one-on-one tests for each manufacturer's vehicle were supplied only to the manufacturer of that vehicle thereby protecting the manufacturer's proprietary interests. However, representative parametric values were selected to create a system with characteristics falling within the bounds of commercially available ACC systems. After converting these parameters from digital sampled form to continuous equivalent approximations to equations (2), (3), and (4), the parametric values for the representative system are $T_h = 1.29$ s, $T = 3.92$ s, and $T_c = 20.4$ s. These values provide a reasonable approximation to the average performance of the systems tested. These parameters will be used later to investigate string stability.

Manual driving

Manual driving was found to be much harder to characterize than ACC driving. Even though there are several frequently used driver models incorporated into microscopic simulations of traffic flow, these models appear to encounter difficulties in predicting performance at densities above that at capacity. This situation was examined in [3], and that work led to further study of driver characteristics in [4] using data from [1,2]. Recently, the study of data in [1,7] has led to a better understanding of the modeling of driver behavior [8]. However, the transient aspects of driver behavior and the causes of string instability and stop and go driving will require further study before arriving at an acceptable understanding of human behavior and performance limitations regarding longitudinal control.

Typically, microscopic models are tuned to fit macroscopic observations concerning flow and capacity on particular road sections. This practice suits purposes associated with traffic management, but not those associated with human-centered design of ACC systems and the development of ACC systems that preserve/improve traffic flow.

For now the discussion of manual traffic flow as presented in connection with figure 5 will suffice. The basic idea used hereinafter is that typical values of capacity are known and free flow speeds are known. In addition, manual traffic flow tends to become string unstable (perhaps chaotic) at high densities.

There are further results on manual driving in [4,5]. These provide greater detail concerning the spread of differences from driver-to-driver regarding V_{set} and the non-linear aspects of their time-gap to speed relationship. The later relationship shows shorter time-gaps as speed increases – a characteristic that can lead to dynamic instability for small perturbations as well as string instability. Perhaps, these results will provide

insights that can be used in future studies of the dynamics of the driving process.

TRAFFIC STREAMS AND STRING STABILITY OF ACC

Figure 6 shows the simulated response of a one-on-one situation in which the ACC vehicle is characterized by the representative parameters derived from the testing of commercially available ACC-vehicle products. In this example, the lead vehicle slows from 26.5 m/s to 21 m/s in an exponential fashion.

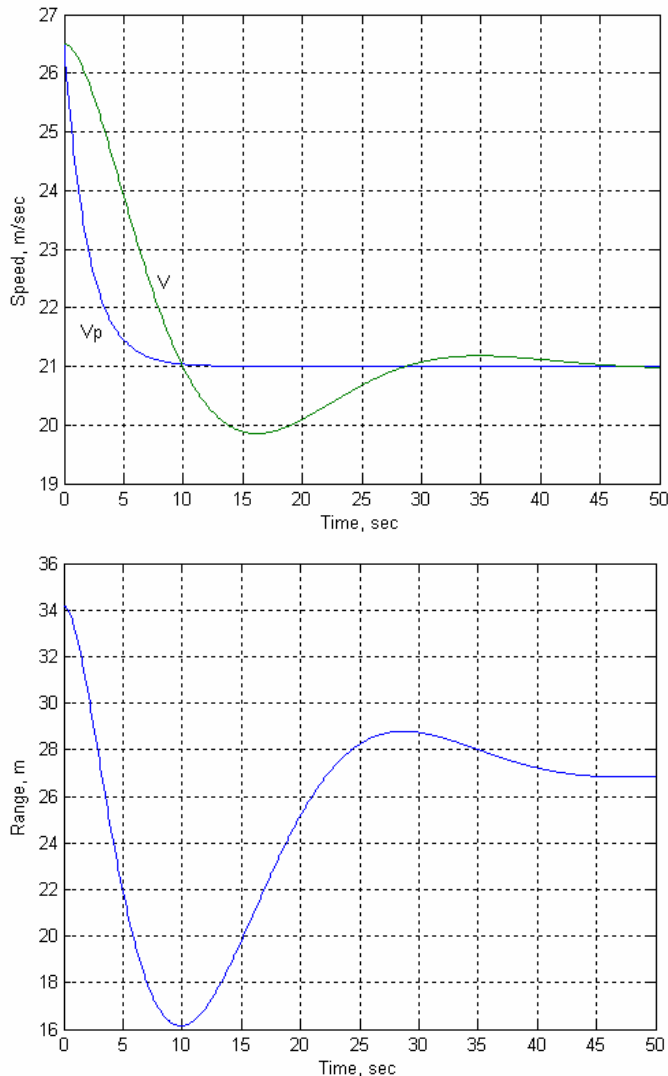


Figure 6. Response of a representative ACC system with $T_h=1.29$ sec., $T=3.92$ sec., and $T_c=20.4$ sec.

As shown in figure 6, the velocity V of the ACC vehicle falls below that of the lead vehicle and then increases to approximately match the velocity V_p of the lead vehicle after about 25 to 35 seconds. The same form of undershoot is exhibited by the range R except the range falls more aggressively than the velocity does. The range reaches a minimum of approximately 16 m before increasing to about 27 m when steady following is achieved. This behavior is not appreciably different from typical results seen in time histories pertaining to manual

driving. This is to be expected when the ACC system emulates typical manual driving behavior.

Figure 7 shows the simulated response of a string of 8 vehicles consisting of a lead vehicle followed by 7 identical ACC vehicles. The lead vehicle slows down as it did in figure 6. The velocity of the lead vehicle is V_p .

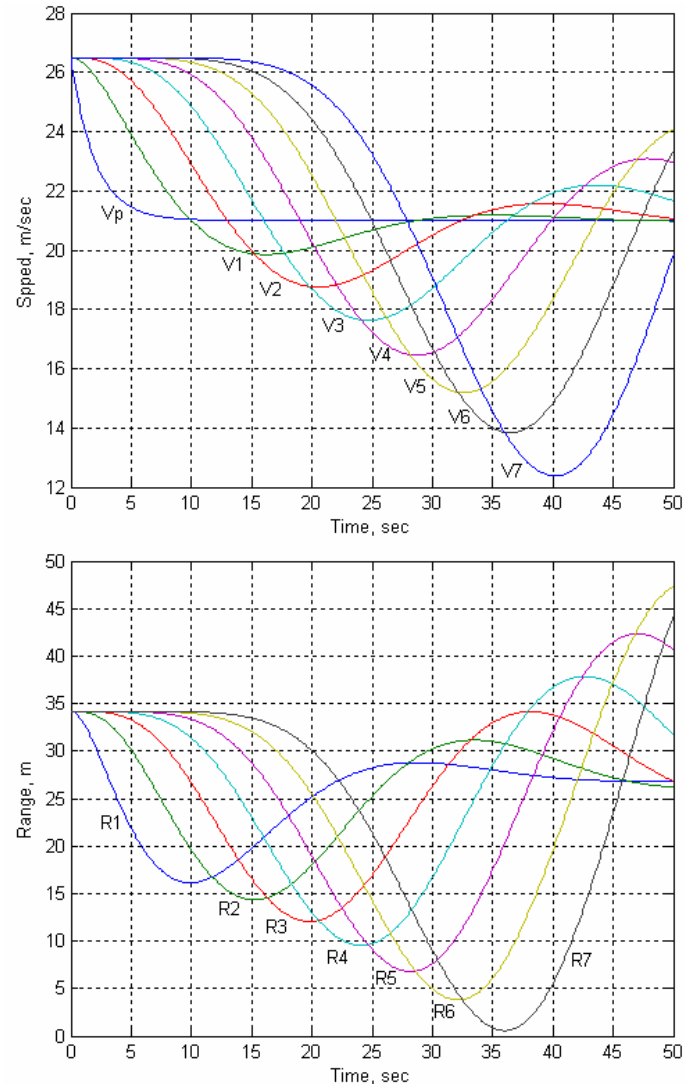


Figure 7. Response of a string of vehicles equipped with a representative ACC system

The trailing vehicles are all identical to the representative ACC vehicle simulated in figure 6. Their velocities are symbolized as V_1 through V_7 and the ranges between each vehicle and its preceding vehicle are symbolized as R_1 through R_7 . In figure 7, V_1 is identical to V in figure 6 and R_1 is identical to R in figure 6. This simulation of a string fits the pattern previously illustrated in figure 4.

As shown in figure 7, the response of each vehicle going upstream to the direction of motion from the front to the back of the string involves more undershoot than that of its immediately preceding vehicle. The situation appears to be more drastic for range than it is for velocity. In fact,

if there had been another ACC vehicle in the string R8 would have reached zero at about 40 seconds after Vp initially started to decrease. This means that a collision would be predicted unless the driver intervened to prevent it.

Although this is not desirable string behavior, it is not likely to cause a collision. In the first place, things like this would happen in manual driving except that the driver intervenes by decelerating so that a collision will not occur. Drivers will interrupt in ACC driving as well. Furthermore, the chance of ACC vehicles forming a string of 8 vehicles will be low until a large percentage of the vehicle population is equipped with ACC systems. Nevertheless, from a traffic flow standpoint this is poor string behavior, and while we may not be able to change driver behavior and manual driving, we may be able to change ACC behavior so that string instability, as demonstrated in figure 7, does not occur.

CONVERGENCE OF DIGITALLY DRIVING AND ADVANCED LONGITUDINAL CONTROL

In this section we address issues associated with advances in ACC technology that have the potential for increasing consumer value by providing improvements in string stability in ACC driving in dense traffic.

Theoretical work has shown that ACC systems using a constant time-gap policy can be made string stable [9]. The general requirement for string stability is formally stated as follows, based on work in [10].

$$|V(s)/V_p(s) \leq 1 \text{ at all frequencies} \quad (13)$$

In (13), the symbol “s” stands for the Laplace transform variable used in linear system theory. For example, (13) indicates that a parameter set with $T_h = 1.29 \text{ s}$, $T = 10 \text{ s}$, and $T_c = 10 \text{ s}$ would make a string stable system using equations (3), (4), and (5). These fundamental ideas provide the basis for broader thinking.

Through the experience gained in studying ACC systems, a generalized procedure for planning and designing advanced systems is envisioned. The basic idea is to write control equations (rules) that are derived directly from a statement of the functional purpose of each driver assistance subsystem. The steps in the generalized procedure will be explained using ACC as an example.

DESIGN STEPS AND THEIR REASONS

For this example, consider ACC driving with an actuator-vehicle system that accepts acceleration commands. This entails an actuator-vehicle system that is more in keeping with general control of braking and accelerating performance than equation (3) is. The form of the actuator-vehicle system is approximated and described for planning purposes by the following differential

equation where T_a is the time constant representing the expected response characteristics of the actuator-vehicle system.

$$T_a \, dA/dt + A = A_c \quad (14)$$

Equation (14) fits into the design procedure in connection with considering each component's role in the driving process.

Step 1, mathematical statement of purpose

The functional purpose of this ACC system is to make $R = T_h V$ when $R_{dot} = 0$ (i.e., $V = V_p$) and $A = 0$ (where $A = V_{dot} = dV/dt$). The constraints on R_{dot} and A mean that $R = T_h V$ is the desired equilibrium situation for steady following. To state this purpose in terms suitable for control work, a special error function is created where the parameter K is a gain factor; viz.,

$$e = R - T_h V - K A \quad (15)$$

If the purpose is being fulfilled, $e = 0$. For $A = 0$ and $e = 0$, $R = T_h V$, which is the functional purpose of the system. For $e \neq 0$, the error value, as determined by substituting measured values of R , V , and A into (15), provides the basis for corrective action.

This means that expression (15) needs to contain all of the state variables, that is, R , V , and A in this case. At first one might be concerned with the number of sensors required, but as more driver assistance functions are incorporated into the vehicle each sensor may serve multiple functions. Sensors for A and V already exist on most vehicles and their outputs can probably be used for more than one purpose.

The acceleration term is needed because the actuator-vehicle system is acceleration based. As will be seen, the error function needs to contain a link to the actuator if the design is to link the actuator-vehicle system's dynamic characteristics into the overall design.

To summarize in a control sense, the functional purpose is now to make $e = 0$ where the value of e is determined by using the state variables to evaluate equation (15).

Step 2, generalized control policy

The aim of the control policy is reduce e to zero. For this purpose a hypothetical sliding surface is created using the following equation that would converge to $e = 0$ in an exponential manner with a time constant T_e .

$$T_e \, de/dt + e = 0 \quad (16)$$

Insight into the meaning of equation (16) can be obtained by differentiating e to obtain de/dt ; viz.,

$$de/dt = R_{dot} - T_h A - K \, dA/dt \quad (17)$$

The variables $\dot{R}$ and A are measured (sensed) quantities in this ACC system. For what is to come in step 3, it is important to observe that dA/dt appears in equation (14) and equation (17). This provides a link between the control policy and the dynamics of the actuator-vehicle system. This means that the control equations (15), (16), and (17) can be solved simultaneously with equation (14) to determine an algebraic expression for the actuator command A_c .

Step 3, actuation command concepts

The following expression for A_c results from a formal algebraic solution using equations (14) through (17), but the underlying consequences of this process are important to understand. The basic control rule follows.

$$A_c = A + (T_a/K) [\dot{R} - T_h A + (e/T_e)] \quad (18)$$

In terms of the overall driving process, equation (18) by itself is not a differential equation. Each term in the equation can be evaluated using the outputs of sensors and the parametric values chosen for T_a , K , T_h , and T_e . This means that the integration operations included in the traffic kinematics and the actuator-vehicle systems are the only integration operations used in the overall dynamics of the driving process for this ACC system. The basic control rule by itself does not include integration operations and in that sense it does not contribute to the dynamic complexity of the system.

Further insight into the meaning of the control rule may be obtained by examining the open-loop transfer function $Y_o(s)$ between $V(s)$ and $\dot{R}(s)$ as shown in figure 8. The closed-loop transfer function, which represents the response of the ACC vehicle to the motion of its preceding vehicle, is also shown in figure 8. The overall importance of these details will become apparent after examining the open loop transfer function, which is as follows.

$$Y_o(s) = (T_e s + 1) / [T_e K s^3 + (T_e T_h + K) s^2 + T_h s] \quad (19)$$

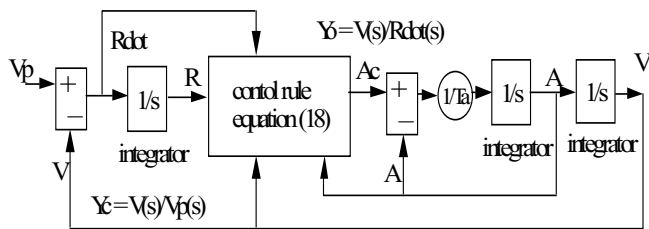


Figure 8. Control diagram for ACC driving

Due to the choice of the form of equation (16), the numerator term in (19) is a factor of the denominator term in equation (19). Although it may not be obvious, this is a consequence of using the control policy described in step 2. In simplified form (19) reduces to equation (20).

$$Y_o(s) = 1/(K s^2 + T_h s) \quad (20)$$

A further consequence of the policy choice in step 2 is that T_a and T_e do not appear in equation (20). Nevertheless, they are still in the control rule. The roles of the parameters T_a and T_e as used in the control rule will be identified with particular aspects of the closed-loop driving process.

Step 4, closed loop features

Based upon equation (20) and the kinematic relationship $\dot{R} = V_p - V$, the closed loop transfer function between $V(s)$ and $V_p(s)$ may be derived; viz.,

$$Y_c(s) = V(s)/V_p(s) = 1/(K s^2 + T_h s + 1) \quad (21)$$

The role of T_h was established when the functional purpose was written in mathematical form in step 1. It establishes the steady-following time gap sought by the ACC system. As discussed earlier, different drivers will prefer different values of T_h . To enhance consumer acceptance and satisfaction, the value of T_h may be left to driver choice over a suitable range of time gaps in future ACC systems.

The role of K in (21) has to do with string stability. Equation (13), which appeared in a previous section, provides the basic relationship regarding string stability. The result of applying (13) to the closed-loop transfer function (21) results in the following relationship regarding K .

$$K \leq T_h^2/2 \quad (22)$$

Since (21) is the equation for a second order system, well known analytical techniques involving natural frequency and damping ratio can be applied. In particular, for a damping ratio equal to one, the following equality between K and T_h applies.

$$K = T_h^2/4 \quad (23)$$

Clearly, if K were chosen by the system designer to be equal to $T_h^2/4$ per equation (23), the system would be string stable per the requirement given by equation (22). Other reasons for using the value of K specified by (23), concern theoretically limiting the amount of over/undershoot during speed changes and the fact that the model and the parameters used here represent an approximation of the practical system, which would be developed through further work. In this sense, the result in (23) provides a safety factor of 2 regarding the string stability limit given in (22). Figure 9 provides simulation results illustrating the orderliness of the theoretical responses of a string of hypothetical vehicles with a value of K perfectly tuned to the desired value. (Compare these results to those given in Figure 7 to obtain an intuitive sense of what might be achieved.)

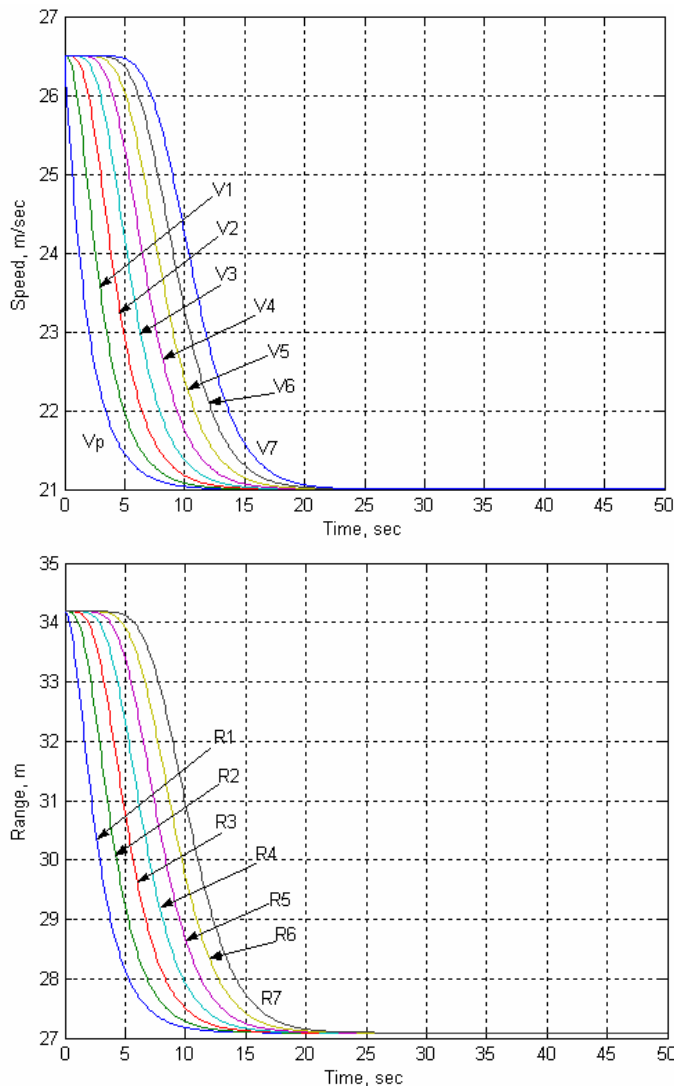


Figure 9. String-stable ACC with $T_e=10$ s, $T_h=1.29$ s, $T_d=T_a=1$ s, $K=T_h^2/4=0.42$ s²

Although T_a and T_e are not included in the open- or closed-loop transfer functions, their values have important influences on the driving process.

The value of T_a , as used in the control rule (18), depends upon knowing how the actuator-vehicle system works. T_a 's role in the control rule (18) is to compensate for the characteristics of the vehicle actuator-vehicle system. If the actuator-vehicle system is not well approximated by a single value of T_a , the designer of the control rule may choose to use a gain factor T_d in place of T_a in equation (18). String stability considerations indicate that T_d should be greater than the maximum expected value of T_a over an appropriate range of speed changes.

T_e 's role is to aid in providing consumer acceptance of the ACC functionality and in making ACC driving less stressful than manual driving. Based upon previous results concerning closing in on a slower moving vehicle, it appears that $T_e \geq 10$ s is a reasonable starting point to use in developing ACC systems of this type. In a control

system sense, T_e provides the predictive qualities of lead associated with the numerator terms in the transfer function. Although the theoretical analysis here indicated that numerator and denominator terms cancel each other, those terms still exist in the system portrayed by figure 8. They will have an influence on transient response as R_{dot} and R vary. In this sense, T_e influences what drivers see and whether drivers like what they see when closing-in on a slower moving vehicle.

RESEARCH AND DEVELOPMENT ACTIVITIES

The steps, as outlined in the previous subsection, illustrate an orderly procedure for proceeding from a functional purpose to a conceptual structure for the design of a driver assistance system. Nevertheless, the completion of a final design requires further development activities including component engineering and physical packaging of the system into the vehicle. In addition, driver assistance systems incorporate new features into the driving process. The influences of these features need to be studied to learn how drivers will react to them. This activity involves a research emphasis that is not typical of routine vehicle development because ACC and other driver assistance systems involve sensing or acquiring information pertaining to situations outside of the vehicle's envelope.

In the case of ACC systems, sensors for measuring R and R_{dot} are used for gathering information about the driving situation outside of the vehicle. Fortunately, the outputs of these sensors have also been saved to provide information about the driving process in both manual and ACC driving [1]. The data acquisition systems employed in previous research have been structured to put information relevant to the driving process (both internal and external) into relational databases. Query structured searches of these relational databases are a powerful tool for extracting knowledge that is pertinent to human-centered design. These capabilities provide the foundation for developing knowledge concerning how people drive and how manual driving compares to ACC driving.

With regard to preserving/improving traffic flow, the previously developed techniques can be applied in studying traffic flow from the perspective of a driver proceeding along with the flow in a traffic stream. This means that microscopic information on conflicts between vehicles in high-density traffic can be observed and processed and used to discover concepts related to the influences of disturbances on congested flow.

For the purpose of research and development work aimed at evaluating the features of ACC control rules, the concept of mobile laboratories has been proposed [4]. In this concept, a mobile laboratory is a vehicle that has all of the data acquisition and processing features used in the previous field operational tests. In addition, it has a computer unit, which has access to the vehicle's

communication busses. This computer unit would receive sensed and communicated information and calculate outputs to the actuator inputs in the actuator-vehicle system. In this manner, research on the influences of the features of the control rules could be studied and evaluated on test facilities and then in naturalistic driving situations.

For example the control rule (18) pertaining to the transfer function (21) using the parametric values given in figure 9, could provide the basis for initial research and development activities. Experience in treating the practical challenges in using real sensors, communication equipment, and actuators would be gained. Human subjective ratings to the decelerations encountered could be evaluated. Increased knowledge concerning the levels of deceleration that people view as appropriate might be forthcoming [11]. Subjective ratings concerning comfort and convenience could be obtained. The values of the parameters in a given set of control rules could be varied. Not only that, the control rules themselves could be changed or new functionalities could be added.

For example, collision-warning features might be considered. In that regard, the system illustrated in figure 9 has interesting features. For $K = Th^2/4$, the transfer function can be written as follows.

$$Y_c = 1/[(Th^2/4)s^2 + Ths + 1] = 1/[(Th/2)s + 1]^2 \quad (24)$$

Inspection of the right side of (24) indicates that the results in figure 9 are those associated with two first order differential equations in series. This means that V will be approximately the same as V_p except that a time delay of approximately Th seconds is involved. (This is what figure 9 illustrates.) In that case, the maximum deceleration of V is approximately equal to that of V_p . The acceleration response of this ACC system is no more drastic than that of the preceding vehicle. If the commanded A_c were less than a predetermined value based upon human-centered criteria, a warning would be given. The mobile laboratory would be a useful tool to use in evaluating this idea (and others like it).

The compelling reasons supporting the use of the mobile-laboratory concept are in developing human-centered knowledge that can be used in assessing driver acceptance and satisfaction, and also, in developing a better understanding of the influences of string-stable vehicles in high density traffic. The ultimate goal would be to develop a driver assistance capability that would be both string stable in dense traffic and provide the consumer with a high degree of assistance and stress relief in dense traffic. In addition, drivers might find or come to understand that this comfortable system has a social benefit concerning improved traffic flow as well as relief from frustration in congested situations.

CONCLUSION

This paper has presented a reasoned structure for designing and developing ACC systems that have the potential for enhancing the value of driver assistance systems to consumers (drivers), who will face the stresses and challenges associated with congested highways. This structure involves the convergence of selected ideas, concepts, and principles from control engineering, vehicle and actuator dynamics, traffic kinematics and flow theory, and knowledge discovery in databases. It utilizes a review of pertinent observations from studies of manual driving data. Practical experience in developing ACC systems has been synthesized and generalized to provide a methodology for developing control rules for driver assistance systems such as ACC. The steps in the methodology involve using the functional purpose of the system along with a generalized control policy to unify the kinematic and dynamic aspects of the driving process in a manner that leads to a human-centered design with features based upon results concerning consumer acceptance and satisfaction.

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REFERENCES

1. Fancher, P., et al., Intelligent Cruise Control (ICC) Field Operational Test, UMTRI, Tech. Rept. DOT-HS-808-849, 1998.
2. Fancher, P., et al., Fostering the Development, Evaluation, and Deployment of Forward Crash-Avoidance Systems (FOCAS), UMTRI, Tech. Rept. UMTRI-2000-27, 2000.
3. Fancher, P., et al., Research on Desirable Adaptive Cruise Control Behavior in Traffic Streams, UMTRI, Tech. Rept. UMTRI-2002-16, (Phase I) 2002.
4. Fancher, P., et al., Research on Desirable Adaptive Cruise Control Behavior in Traffic Streams, UMTRI, Tech. Rept. UMTRI-2003-14 (Phase 2), 2003.
5. Fancher, P., et al., "Relationships between Manual Driving and Driving with Adaptive Cruise Control," to be presented in the upcoming 7th International

Symposium on Advanced Vehicle Control (AVEC'04), 23-27 August 2004.

6. Bareket, Z., et al., "Methodology for Assessing Adaptive Cruise Control Behavior," IEEE Transactions in Intelligent Transportation Systems, Vol. 4, No. 3, September 2003.
7. Ervin, R. et al., "System for Assessment of the Vehicle Motion Environment (SAVME)," University of Michigan Transportation Research Institute, UMTRI-2000-21-1, August 2000.
8. Lee, Kangwon, "Longitudinal Driver Model and Collision Warning and Avoidance Algorithms Based on Human Driving Databases", Doctoral Dissertation, Mechanical Engineering, University of Michigan, 2004
9. Ioannou, P.A., and Chien, C.C., "*Intelligent Cruise Control*," IEEE Trans. Veh. Technol., vol. 42, no. 4, pp. 657-672, Nov. 1993.
10. Sheikholeslam, S., and Desoer, C., "A System-Level Study of the Longitudinal Control of a Platoon of Vehicles," ASME J. Dyn. Syst. Meas. Contr., 1991.

11. LeBlanc, D., et al, "Forward Collision Warning: Preliminary Requirements for Crash Alert Timing", SAE paper 2001-01-0462, March 2001.

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