WP5-6 6:00

Proceedings of the 1999 IEEE
International Conference on Control Applications
Kohala Coast-Island of Hawai'i, Hawai'i, USA • August 22-27, 1999

# Stop & Go Controller for Adaptive Cruise Control

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**Abstract**

In the field of vehicle control, conventional cruise control systems have been available on the market for many years. During the last years, modern cars include more and more electronic systems. These systems are often governed by a computer or a network of computers programmed with powerful software. One of those new services is Adaptive Cruise Control (ACC) (or Autonomous Intelligent Cruise Control (AICC)), which extends the conventional cruise control system to include automated car following when the preceding car is driving at a lower speed than the desired set-speed. The focus of ACC has mainly been directed towards high-speed highway application, but to improve the comfort to the driver also low-speed situations must be considered. This paper presents an ACC system that is capable of car following in low-speed situations, e.g. in suburban areas, as well as in high-speed situations. The system is implemented in a test car and the result is evaluated.

**Keywords:** Vehicle Control, Automotive Systems, Motion Control, Adaptive Control

## Introduction

In a conventional cruise control system, the driver can set a desired speed and the car will maintain this speed as soon as it has been established. This is done independently of the environment, e.g. other vehicles on the road. When the vehicle ahead is traveling slower than the desired speed, the driver must at some point intervene with the brake pedal to avoid a collision. Alternatively, he must overtake the vehicle. The ACC concept extends the conventional cruise control system to include car following. In the scenario above, the ACC would have automatically lowered the speed of the car to match the speed of the vehicle ahead and to maintain an appropriate distance. If the preceding vehicle would have later on increased its speed, the ACC system would have automatically increased the speed (thereby following the car), unless it becomes greater than the desired speed set by the driver.

Devices of ACC are currently being introduced by several car manufacturers in their latest car models. These systems consist of a sensor, mounted in the front of the car, that measures the preceding vehicle's velocity and distance. The sensor could either be of optical or radar type, but the radar sensor is often preferred since it is much less influenced by the weather conditions than the optical sensor. The sensor information is transmitted to an ACC controller (a computer) that controls the engine and brake systems. The first generation of ACC will only allow gentle acceleration and deceleration. A major reason for this is that the driver should never be surprised by the actions of the ACC system and the driver should always be able to intervene if the system does not comply with the driver's intentions. These systems will only work in highway traffic, where the needed speed changes are moderate. The second generation of ACC will allow a greater acceleration and deceleration, which is necessary in suburban areas where the speed and distance is relatively low, but where the relative speed may be rather high. It is important to remember that the ACC is only a service to help the driver, not a replacement of the driver. The driver is still in charge of the car at any moment, regardless if the ACC system is active or not.

A difficulty that arises in suburban areas is that it might be hard to find a model of the car dynamics that is good enough. Since the controller must be able to accelerate and decelerate quite hard, it must be carefully designed so it does not behave in an inconvenient manner which causes discomfort to the driver. There must not be any big overshoots and also if the acceleration is hard, it must be smooth. Hence, the design of the controller requires a good model of the car dynamics. But even if a good model

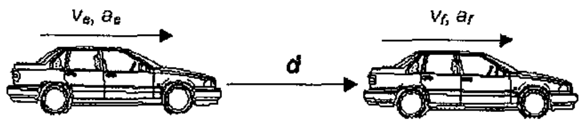


**Figure 1:** A car is following another car at a distance **d**.

is known, it still might be hard to design a suitable controller.

A more practical difficulty is that the radar must have good resolution, also at small distances. The relative speed must also be measured with high resolution. Figure 1 shows a situation where one car is following another one. The speed of the preceding and following vehicle are denoted $v_f$ and $v_e$, respectively. The corresponding accelerations are denoted $a_f$ and $a_e$ and the distance between the vehicles is denoted $\mathbf{d}$. The relative speed is defined as:

$$\Delta v = v_f - v_e = \frac{d}{dt}\mathbf{d} \tag{1}$$

We consider a vehicle that should follow the vehicle ahead at a preferred distance which is denoted $\mathbf{d}_{set}$. If only $v$ or $a$ is written, i.e. without subscript, it is equivalent to $v_e$ respectively $a_e$.

## 1 System overview

### 1.1 The coordination

The ACC system must be coordinated with the ordinary cruise control system in some way. Both systems generate a desired acceleration of the vehicle, but only one value can be passed on to the accelerator controller. The coordination chosen is that if a target vehicle is existing, the overall desired acceleration equal the minimum of the desired accelerations generated by the two systems. In the absence of a target, the acceleration of the conventional cruise control is selected.

### 1.2 The ACC system

The ACC system should control the car in a safe and comfortable way and ensure that the desired distance to the vehicle ahead is maintained. The overall control problem can be divided into two separate parts (Fig. 2). The outer control loop generates a desired acceleration $a_{set}$, given the speed of the car ($v_e$) and the distance $\mathbf{d}$ and relative speed ($\Delta v$) to the vehicle ahead. It is assumed that the desired acceleration is a static function of these inputs without any dynamics included. Several investigations supports this assumption [2]. The inner control loop should control the brake pressure (by using $u_{brk}$) and the throttle position (by using $u_{thr}$) in such a way that the desired acceleration is obtained quickly and with little overshoot.

The major advantage with this separation into two loops is that the loops are independent of each other in the following sense: The outer loop represents the driver behavior and is independent of the vehicle to be controlled. The inner loop, on the other hand, is highly dependent of the vehicle dynamics, but is independent of the driver behavior (*i.e.*, the outer loop). This separation makes it possible to change the algorithm in the outer loop without having to change the algorithm in the inner loop. If a car with different dynamics is to be controlled, only the inner loop has to be changed. It is though important that the inner loop is well designed—*i.e.*, that the desired acceleration is obtained quickly and with little overshoot. Otherwise, it is hard to evaluate the performance of the outer loop.

## 2 Car Modeling

To be able to design a good accelerator controller, a good model of the car behavior must be determined. The true car dynamics is unfortunately complex and includes many nonlinearities. The relevant car behavior is how the throttle angle and brake pressure influence the acceleration of the car. The throttle angle and the brake pressure can be regarded as inputs and the acceleration of the car as the output of a system. The speed of the car will further be noted $v$, the acceleration with $a$, the throttle position with $u_{thr}$ and the brake pressure with $u_{brk}$.

### 2.1 Static analysis

The first analysis of the data was a simple static correlation analysis.

The leftmost diagram in Fig. 3 shows some data from a brake experiment. The rightmost diagram in Fig. 3 depicts the correspondence between the acceleration and the brake pressure. After an initial transient (corresponding mainly to the data points where the pressure is above 25), the acceleration is close to proportional to the brake pressure. The leftmost diagram in Fig. 3 shows that the deceleration is as good as proportional to the brake pressure, except for an initial transient. The rightmost diagram, on the other hand, depicts the fact that there is not a simple linear static relationship between the throttle position and the acceleration.

The major difference between the throttle position signal and the brake pressure signal, is that the brake pressure affects the wheels in an almost di-

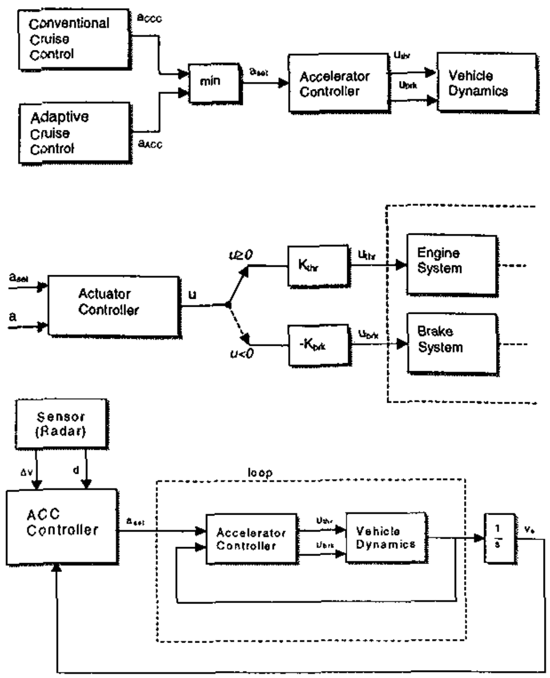


**Figure 2:** The coordination of the conventional and adaptive cruise control systems. The minimum acceleration is chosen (upper); The overall control problem is divided into two separate parts (lower); The actuator controller either controls the throttle position or the brake pressure, but not both at the same time (middle).

rect manner, whereas the throttle position only affects an air stream. This air stream affects in turn an engine combustion, which in turn affects a transmission system, which finally affects the wheels (all this simplified speaking). Since these systems include dynamics, there is no simple static linear relationship between the throttle position and the acceleration.

### 2.2 Dynamic analysis

As indicated in the previous section, there are dynamics involved in the relationship between the inputs ($u_{brk}$ and $u_{thr}$) and the output $a$. Therefore, assume that the relation between the inputs and the output is described with a dynamic linear system, i.e. that the following relation holds:

$$a(k) = H'_{thr}(q)u_{thr}(k) + H'_{brk}(q)u_{brk}(k) \qquad (2)$$

Since $v$ is the actual measured signal and not $a$ and to reduce the influence of the noise, the following relation is analyzed instead:

$$v(k) = H_{thr}(q)u_{thr}(k) + H_{brk}(q)u_{brk}(k) \qquad (3)$$

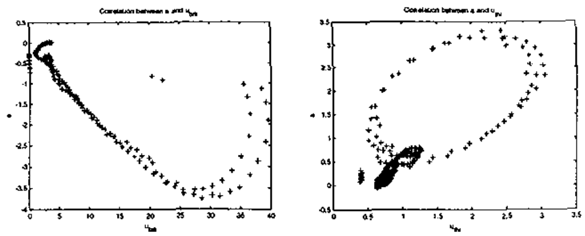

**Figure 3:** Diagram showing the static correlation between $u_{brk}$ (left) and $u_{thr}$ (right) and acceleration $a$.

The transfer functions $H_{thr}$ and $H_{brk}$ were estimated using a prediction-error method [3]. Identification verifies that the pulse-transfer function $H_{thr}$ has low-pass properties without any complicating zero dynamics whereas $H_{brk}$ exhibits integrator-like dynamics.

### 2.3 Conclusion

The derived car model reflects the actual system in many aspects. The model does not describe the system well when different gears are used, due to the fact that each gear has an individual static gain. This shortcoming does not have to be severe, because an integrator in the control loop could take care of this error well. The model does not either describe the nonlinearities that inherently exist, e.g. that the engine torque is a nonlinear function of the throttle position and the engine speed. The nonlinear function of the converter is not described.

## 3 Actuator control

The innermost control loop is the actuator control loop. The actuator controller should control the acceleration $a$ of the car to match the desired acceleration $a_{set}$. This should be accomplished by using two control signals: $u_{brk}$, which controls the brake pressure, and $u_{thr}$, which controls the throttle position.

### 3.1 Design overview

It is clear that $u_{thr}$ and $u_{brk}$ never should be both non-zero at the same time (you do not want to step on the gas and brake pedal at the same time). The general idea is therefore to calculate a single control signal u and then let $u_{thr}$ and $u_{brk}$ be a function of $u$. If u is positive, $u_{thr}$ should be non-zero and $u_{brk}$ should equal zero, and if $u$ is negative, $u_{thr}$ should equal zero and $u_{brk}$ should be non-zero. Figure 2 shows an overview of the controller, the controller gains $K_{thr}$ and $K_{brk}$ being positive constants introduced to allow scaling of $u$. The calculation of $u$ may be done using ordinary methods of control theory.

### 3.2 Controller design

Since the true car dynamics are not known in detail, the controller must be reliable and robust. Therefore, a simple PI-controller was the starting point in designing a suitable controller. Experiments and simulations have shown that the noise in the acceleration signal was of that great magnitude that a proportional part in the PI-controller was impossible. A pure I-controller removes stationary errors, but it cannot provide the required system speed. The closed system must be well damped so $K_i$ cannot be too large. To acquire the desired speed, the I-controller was complemented with a feed-forward term, resulting in:

$$u(k) = K_{ff}a_{set}(k) + \frac{K_i h}{q-1}(a_{set}(k) - a(k)) \qquad (4)$$

where $h$ is the sample period.

As the dynamics from $u_{thr}$ to acceleration $a$ are quite different from the dynamics from $u_{brk}$ to $a$, it is not reasonable to use the same control law in the entire scope of operation. The scope of operation is therefore divided into two parts: one when $u$ is positive ($u_{thr}$ is non-zero) and one when $u$ is negative ($u_{brk}$ is non-zero). Different values on $K_{ff}$ and $K_i$ are used in the two parts.

Since the deceleration is almost proportional to the brake pressure, it is reasonable to use a fairly high feedforward action and a rather small integral part when $u$ is negative. When $u$ is positive, the situation becomes quite different since there are more dynamics involved. Therefore, a smaller feed-forward term and a greater integral term was used in that case.

### 3.3 Conclusion

Several experiments have shown that the controller behaves in a comfortable and fast way, but it is in no way perfect. A better controller could have been designed if information on the engine speed and the current gear were available. Unfortunately, that was not the case with the test car used for the experiments. Unknown model errors, e.g. nonlinearities, also debase the performance of the controller. In particular, when the car should accelerate from a zero-speed condition—*i.e.*, from a position at rest ($v = 0$)—the performance is poor as compared to other situations.

## 4 Driver Modeling

For safe operation, it is important to have a an adequate driver model the model the real driver behavior in a satisfactory way. The model must conform to the safety requirements of real driver experience—*e.g.*, keeping an appropriate distance to the vehicle ahead. It is also very important that the model conforms to the need of comfort, so that the overall system performs smoothly and well. Small deviations from the desired position should not lead to big reactions (*e.g.*, huge brake pressures), but rather to reaction in such way that the desired distance be obtained slowly and smoothly. The acceleration and deceleration of the car must conform to a real driver's behavior in every situation. The fundamental approach is that a driver's desired acceleration is a static function of $v$, $\mathbf{d}$ and $\Delta v$.

### 4.1 Linear regression

The first approach was to find a simple linear relationship between the desired acceleration $a_{set}$, and the speed of the following car ($v = v_e$), distance ($\mathbf{d}$) and relative speed ($\Delta v = v_f - v_e$):

$$a_{set} = k_0 + k_1 v + k_2 d + k_3 \Delta v \qquad (5)$$

The coefficients were estimated using a least-squares method, given data of a real driver's behavior. The desired distance could then be written as:

$$d_{set} = T_q v_e + d_0, \text{ or } d_{set} = T_g v_f + d_0 \qquad (6)$$

where $T_g$ is the desired time gap and $\mathbf{d}_0$ is the desired zero-speed distance, the actual choice being a matter of viewpoint. Using cross-validation data, it was verified that there ws good agreement between simulated mode behavior and measured data.

The correspondence is fairly good when the magnitude of the acceleration is small, but is less accurate for large magnitude.

### 4.2 Approaching situations (negative $\Delta v$)

Since a real driver often brakes with a rather constant deceleration during the brake procedure [5], the model should generate a rather constant $a_{set}$ when $\Delta v$ is large negative (fast approaching). For large negative $\Delta v$ the desired acceleration should approximately equal:

$$a_{set} \approx -\frac{\Delta v^2}{2(d - d_{set})}, \quad \Delta v < 0, d > d_{set} \qquad (7)$$

This is not achieved with the linear regression model. The model was therefore expanded with another variable $F$ that had the property that if the linear regression model were multiplied with $F$, the relationship of Eq. (7) would be approximately achieved. Other modifications were also made. Figure 4 shows a simulation of an approach situation with these modifications included.

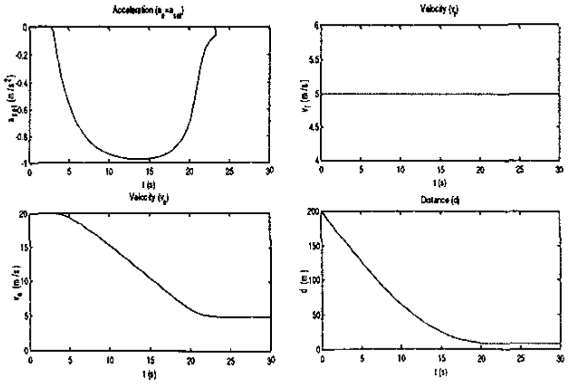

**Figure 4:** Simulation of a fast approach situation. The deceleration is fairly constant during the brake procedure.

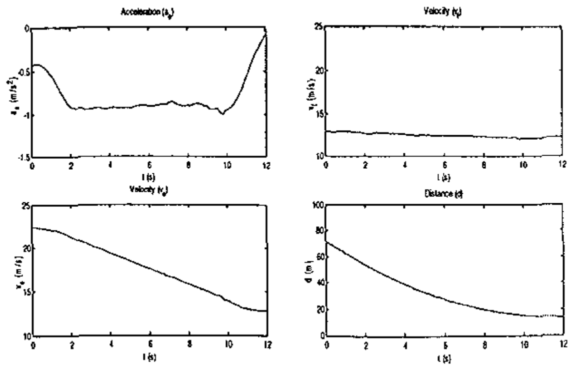

**Figure 5:** The ACC system will brake with a constant deceleration (1 m/s2). The dotted lines are the desired values.

Even though the previous model behaves satisfactory in the approach situation, it behaves unsatisfactory in many other situations. In non-dangerous situations, the magnitude of the acceleration is generally too high. Therefore, a new variable $Q$ was introduced that is a function of the danger of a situation. For instance, such a measure of danger could be the time to collision if both vehicles are continuing with the current speed. Typically, $Q$ should be less than 1 for non-dangerous situations and greater than 1 for dangerous situations. Then, this variable may enter the model as a factor.

### 4.3 Separating situations (positive $\Delta v$)

Situations with positive $\Delta v$ is quite different from situations with negative $\Delta v$. The major difference is that there is no imminent danger for collision, since the vehicle ahead is moving away from the vehicle behind. Whereas the problem with negative $\Delta v$ is to avoid a collision, the problem with positive $\Delta v$ is to avoid that the distance becomes much higher than the desired one, i.e. to avoid that the following vehicle lag behind. Whereas $F$ was introduced to make the deceleration fairly constant during an approach, there is no such analogous situation when $\Delta v$ is positive. Hence, $F$ may be assigned to $F = 1$. Since there is no imminent risk for collision, $Q$ is also modified. The desired acceleration is instead magnified if the relative speed is huge positive.

When the vehicle ahead is accelerating from a position at rest, the acceleration is quickly approaching the acceleration of the preceding vehicle ($1.0 \mathrm{m/s}^2$) and the distance is close to the desired one.

### 4.4 Conclusion

The driver model is derived step by step. Starting with a simple linear relation, the model is modified and expanded piece by piece. The changes are driven by unacceptable behavior in certain situations of the current model. The proposed changes are often a result of intuitive reasoning and engineering judgement. The final driver model includes several design parameters. A favorable property is that the model could be tuned to fit a desired behavior very well. A problem is that it might be difficult to understand the model and the influence of the different parts. Most effort has been made on situations when the relative speed is negative.

## 5 Implementation and validation

The driver model in the previous section was derived using many intuitive reasoning and simulation results. It is therefore very important that the results are verified in practise. The driver model must be compared to the behavior of real drivers. One must though remember that there will seldom be a perfect match between the behavior of the driver model and the real driver. A real driver can react in several acceptable ways in the same situation. The actual behavior might change from time to time and from driver to driver. Hence, the driver's perception of the driver model must also be further considered.

### 5.1 Typical situations

First, the driver model was implemented and tested during normal driving. The behavior was tested in normal traffic with no special preparations. The car was driving in both urban and sub-urban traffic. The behavior was tested in many typical traffic situations that required a fairly low acceleration or deceleration (Fig. 5).

The general conclusion was that the driver model

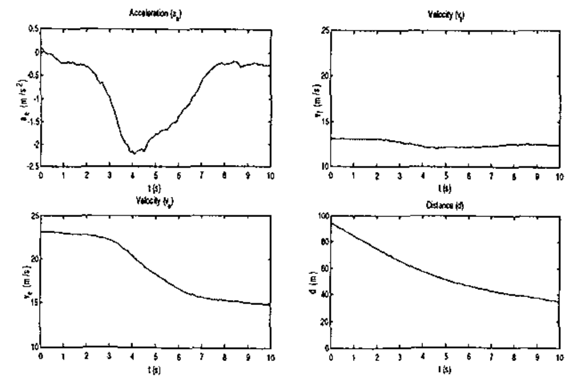

**Figure 6:** The behavior of a real driver. In this case, deceleration is not quite constant, but other tests have shown a more steady deceleration.

conforms very well to the behavior of a real driver. This conclusion was drawn by observing how many situations that felt uncomfortable or unnatural. Most situations felt very comfortable and natural, whereas some few felt only fairly comfortable and natural. The behavior was in no case unacceptable. The evaluation of the behavior was here done very qualitative, but since the result was so good no further investigations were made.

### 5.2 Special situations

The behavior in typical situations is very important, but other situations must be examined as well. Typical situations are often simple situations because the required reaction is often limited. To examine the behavior in untypical situations—*e.g.*, dangerous situations, special arrangements were made. Firstly, the tests were not performed in real traffic, but rather at a non-public piece of road. Secondly, the driver of the vehicle ahead was instructed to drive in a certain way depending on test case. Each test case was performed twice. One with the ACC system activated and one with the ACC system deactivated—*i.e.*, manual driving. In this way, the behavior of the ACC system could be compared with the behavior of a real driver. The first test case was an approach scenario. The vehicle ahead should drive with a constant speed of 40 km/h (= 11.1 m/s) and the following vehicle should use a set-speed of 80 km/h (= 16.7 m/s). Figure 6 shows the deceleration behavior when the following car approaches the car ahead. The deceleration is as expected constant during the brake procedure and has a magnitude close to the desired one (in this case 1 $m/s^2$). The behavior of a real driver in a similar situation is shown in Fig. 6. As compared to the behavior of the driver model, deceleration is not kept constant. and its magnitude is higher. Even though the behavior of the driver model is different than the behavior of the real driver, it does not make the driver model unacceptable. Tests have shown that most manual brake procedures of an approach situation either shows a constant deceleration or a slowly declining deceleration. Both are found acceptable to a driver. The driver model includes parameters that determine the level of deceleration and they could also easily be chosen so that the deceleration is not constant, but rather conforms to the deceleration in the Fig. 6. Other, more dangerous situations were also tested with good results. Most problems could be solved by tuning the parameters of the driver model.

## 6 Conclusions

The general conclusion of the driver model is that it behaves in a comfortable and safe way in most situations. The driver model is complex with many parameters, but most parameters have a clear intuitive meaning such as desired deceleration etc. The model complexity and the number of parameters are sufficient to permit the driver model to be tuned to fit the behavior of a real driver quite well. In implementation, the driver model has proved to be quite robust—*i.e.*, even if the desired acceleration is not achieved quickly by the actuator controller, the desired distance is achieved rather comfortably.

### Acknowledgements

This work was a joint project with partners of Volvo Technological Development Corporation and the Department of Automatic Control, Lund University. The authors thank for financial support from NUTEK.

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