AUTOMOBILE CRUISE CONTROL SYSTEMS USING MATLAB/SIMULINK

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ABSTRACT

Basic theory behind how automobile cruise control systems operate is presented in this paper. Cruise control, developed in America in the 1940s and 50s, first appeared on production vehicles in 1959. Today’s systems are much more complex, and often utilize computerized PID control to achieve optimal operation of keeping speed steady and smooth. A demonstration of the basic control principles behind cruise control systems is given, starting with an open loop system, moving on to a closed loop system, and then analyzing how a PID controller can help fine-tune the system to make the cruise control operate smoothly and quickly. A complex real-world system is then looked at and compared to the simple PID control system.

1. INTRODUCTION

CRUISE Control systems on automobiles allow people to drive long distances with ease. While driving long distances can be a very tiring experience, it was made much less tiring with the creation of cruise control. Cruise control allows a driver to set his vehicle to a desired speed and have it stay at that speed until he tells it to change—it eliminates the need to control the speed with the gas pedal.

This document examines the relationships between the physics of an automobile and the operation of cruise control systems. It gives a brief history of the early development of cruise control, and then examines the technical side of the systems. It analyzes a simplified model of a cruise control system, and then looks at where other factors could be included to improve the usefulness of the system. It then explores a real world cruise control system from an actual modern
production car to see how much more complex an actual system is compared to the simplified model. It also looks to what is currently being developed with adaptive cruise control, and how this technology could be beneficial now and in the future.

2. TECHNICAL WORK PREPARATION

2.1 HISTORY

The idea for the first cruise control device is credited to Ralph Teetor, who was a mechanical engineer. Teetor came from a family that seemed to be rich in engineering knowledge—he worked for an automotive parts company that his family had founded. With his invention of cruise control, he certainly didn't disappoint the rest of his innovative family.

Teetor, who was blind for most of his life, had a major interest in automobiles since a young age; he had actually built his own car already by the age of 12. Apparently, his idea for cruise control came after an uncomfortable ride with his lawyer, who was not good at keeping a constant driving speed while conversing with passengers. Teetor figured that he could fix this problem by inventing some kind of device that controlled the speed of an automobile, and by 1945, he had his invention patented.

The first implementation of cruise control in production automobiles didn't occur until the late 1950s. In 1958, Chrysler, known for being an upscale automaker, installed cruise control in 3 of its models: the New Yorker, the Imperial, and the Windsor. Not to be outdone by one of its rivals, Cadillac offered cruise control across its entire model line by 1960. Today, every automaker offers cruise control on models across the board, from luxury cruisers to sports cars to trucks to econo-cars. According to Ward’s AutoWorld, an automotive publication, it is estimated that for the 2003 model year, 87% of the new cars and trucks sold in the U.S. were equipped with cruise control.

It is thought that cruise control was quicker to develop in America than in Europe due to the nature of the way people drive here. Americans tend to take long trips more frequently, and these trips are done on a highway system that requires monotonous use of constant speed over many miles; in Europe, trips tend to be shorter, and the speeds on the roads tend to be less
constant.

The same can be said for the Japanese market. According to an article found in Business Week in 1997, when Honda was developing a new generation of their top selling Honda Accord, they decided to design it very differently for the different markets around the world in which it would be sold. Some hints in this article show how differently the American and Japanese markets treat cruise control technology. Concerning the new redesign, the article states that “this time around, the Japanese Accord won't be burdened with features dictated by American tastes.” It then specifically mentions that cruise control would not even be offered on the Japanese version, citing that “there’s not as much driving on the open highway in Japan.” This points out an interesting exception to how the world often views the development of automotive technology—despite many electronically controlled automotive advancements having their roots in Japan and Europe, cruise control was initially developed in America, and still holds the most popularity in the American market.

Interestingly, even though early cruise control systems were developed in America, the developments in adaptive cruise control technology have their roots in Europe with Mercedes-Benz and TRW. It is fitting then that adaptive cruise control is currently offered primarily on luxury vehicles—five models from Mercedes-Benz offer it, as well as a handful of vehicles from Audi, Cadillac, Lexus, BMW, Volkswagen, and Jaguar. The only automaker to this point to offer it on a non-luxury platform has been Toyota, offering it on the latest Sienna minivan, though it is only offered on the top-of-the-line version. At this point, the cost of the technology keeps it from becoming an option on more mainstream vehicles, very similar to situation faced by the first cruise control systems of the late 1950s. Like those systems, it is expected that the adaptive systems will improve and become more widely available in just a matter of years.

3. SYSTEM COMPONENTS

A cruise control system basically consists of the following devices: vehicle speed sensor, control computer, actuator to set throttle, cancellation switches, and control buttons for the driver. Obviously, real systems in today’s vehicles are extremely complex, but they still consist of devices that perform these necessary functions that allow a cruise control system to exist. The following
paragraphs give a quick summary of the purpose of each component.

Vehicle speed sensor: the vehicle speed sensor measures how fast the vehicle is traveling. This is central to the control of speed, because in order to maintain a constant speed, the actual desired speed of the car must be known. When a cruise control system is activated, the vehicle speed sensor sends data of how fast the car is traveling to a computer where the value is stored as a reference. Most vehicles use a rotating mechanism connected to the transaxle shaft to create a pulse signal that changes proportional to the vehicle speed. Some vehicles also utilize the actual speedometer itself to sense the vehicle speed.

The control computer is where the brains of the cruise control system are located. The control computer receives signals from the vehicle speed sensor, and then sends signals out that adjust the throttle to maintain the desired speed that is determined when the system is first activated. The computer uses control logic to continually adjust the throttle as the forces acting on the car attempt to change the vehicle’s speed. The computer is also responsible for receiving input from the driver that allows the cruise control to increase or decrease the vehicle speed, as well as receiving signals that turn the cruise control off.

The actuator receives electronic signals from the computer and turns them into mechanical motion that controls how much the throttle is open. The actuator is attached to a linkage that pushes the throttle farther open or closed, depending on what the computer tells it to do. Most actuators are operated by vacuum pumps. The electronic signals from the control computer are sent to small motors that control the vacuum pump. The vacuum pump sucks air out of a chamber to create a low pressure chamber; the greater the amount of power supplied to the motors, the more the vacuum pump sucks, and the lower the pressure becomes in this chamber. As the pressure lowers, a diaphragm at one end of the chamber is pulled farther into the chamber. This diaphragm is linked to the throttle cable, and thus pulls the throttle farther open as it slides into the chamber.

Cancellation switches turn the cruise control system off. A switch is always installed on the brake pedal that breaks the cruise control circuit when the brake is depressed; likewise, for cars with manual transmission, a switch of the
same sort is installed on the clutch pedal. The reasons for this are obvious—it would be very dangerous and harmful for the cruise control system to stay activated while the driver is trying to stop or slow down the car. These switches allow the cruise control system to shut off as soon as the driver desires to slow down without the driver actually having to consciously turn it off.

The user control buttons allow the driver to turn the cruise control on and off. Furthermore, most modern systems allow the driver to change the speed of the vehicle one the cruise control is on through use of accelerate and decelerate buttons. These buttons each send a signal to the control computer.

4. THE PHYSICS BEHIND CRUISE CONTROL SYSTEMS

Early cruise control systems lacked the fancy computer programming that modern systems utilize. As a result, early systems were not as good at actually keeping the speed of the car constant; the throttle was held in position, but as other forces on the vehicle varied, the vehicle speed fluctuated some. The logic of modern control systems in cruise control comes out of the need to compensate for the physical forces that act on a car and try to change its speed.

In a simplified ideal situation, only two forces would be present in the movement of a car—the friction between the wheels and the road, and the force with which the engine pulls the car. In such a situation, the control system would be very simple. A simple proportional controller could control the speed by simply having set throttle positions for each possible speed setting. However, this idealized situation is far from reality. Cars have varying drag forces due to wind, varying mechanical component friction due to speed and temperature, varying gravitational forces due to inclines, and varying engine force due to hydraulically activated steering pumps.

For the sake of understanding the basics of how the controls work, the simplest case mentioned is a good starting point. Only forces are the engine force and the wheel friction are considered, so the main goal of a cruise control system will be to get the car to the desired speed, like what happens does when a driver hits the resume button. Once this resume speed is achieved, the forces on the car will not be changing, so no logic will be needed for maintaining the speed.
The logic instead will deal with making the car accelerate up to the desired speed rapidly without overshooting that desired speed by very much. Calling the mass of the car $m$, the velocity $v$, the force from the engine $F$, and the friction coefficient $f$, the model for the car becomes:

$$F = m\dot{v} + bv$$  \hspace{1cm} (1)

The goal is to create a simple transfer function from this equation that can be used in an open loop system. This transfer function will be the ratio of the velocity over the engine force. Performing a Laplace transform to the physical equation makes this possible:

$$F(s) = msV(s) + bV(s)$$  \hspace{1cm} (2)

The transfer function then becomes:

$$\frac{V(s)}{U(s)} = \frac{1}{ms + b}$$  \hspace{1cm} (3)

Since we actually want to track the velocity of the car, this can also be looked at the following way:

$$V(s) = \frac{U(s)}{ms + b}$$  \hspace{1cm} (4)

5. SIMPLE BLOCK DIAGRAM SIMULATIONS

To test to see how this system responds, some values must be assumed for the mass, friction, and speed. SI units tend to work the best in this type of model, because they all convert well between each other. Assume that the car is 1400 kg (about 3000 lbs), the desired speed to resume to is 30 m/s (about 65 mph), and that friction $b$ is 50 Nsec/m. To reach this speed, the engine needs to apply 1500 N of force. This situation can be tested in the following Simulink simulation (Figure 1):

**Figure 1**: Simple open loop cruise control block diagram

The output of this simulation with a step input of 1 looks like this (Figure 2):

**Figure 2**: Open loop cruise control system response

This system is simple because it takes a
step input of 1 and then just continues to grow until it reaches its maximum possible speed of 30 m/s. Clearly, this system needs much improving though, because no one would want a cruise control system that takes a few minutes to accelerate to 65 mph! A quick improvement that can be made is to add a harmony feedback loop (Figure 3):

![Figure 3: Simple closed loop cruise control block diagram](image)

The output of this system is the following (Figure 4):

![Figure 4: Closed loop cruise control system response, step input of 1](image)

The feedback loop causes the output to try to equal the input of the initial step function. Since the step function was still set at 1 for this simulation, the output tries to go to 1 m/s instead of the desired 30 m/s. With a feedback loop, the input to the system must be equal to the desired output. This is basically saying that when the driver hits the resume button, the input to the system is the stored value for the speed that the cruise control had previously been set at. With the step function set at 30, the output is the following (Figure 5):

![Figure 5: Closed loop cruise control system response, step input of 30](image)

Clearly, the feedback loop works well in speeding up the response time. In fact, the 5 second response time is rather unrealistic for a car accelerating to 65 mph. This is partly due to the assumption that the engine is providing a constant 1500 N force; this is not a realistic assumption, because the amount of force the engine can provide will fluctuate up and down as the car accelerates, and a driver generally does not wish to make a car accelerate as fast as it can. A realistic target response time
for accelerating to 65 mph is probably about 15 seconds under real world driving conditions (most cars can do so in under 10 seconds if held at full throttle, but full throttle acceleration is generally not ideal for real world driving conditions with surrounding traffic, nor for fuel economy). Another shortcoming of the feedback system is the steady state error—the car is actually only traveling at 29 m/s instead of the desired 30 m/s. The solution is to introduce a PID controller, which is just what most real cruise control systems utilize today.

6. PID CONTROLLED CRUISE CONTROL

PID stands for Proportional Integral Derivative. It uses 3 types of controls that can each be fine tuned to get the perfect response. Adding a PID makes the system look like this (Figure 6):

![Figure 6: Simple PID controlled closed loop cruise control block diagram](image)

If a PID controller simply has the Proportional component set at 1, it does nothing, and the output of the system is identical to that of the previously looked at feedback loop with the steady state error of 1 m/s. Adding an integral component set at 1 introduces some undesirable overshoot to the system and also increases the response time, but does solve the steady state error problem—the output is now at the desired 30 m/s (Figure 7):

![Figure 7: PID controlled closed loop cruise control system response; P=1, I=1, D=0](image)

Adding the derivative component set at 1 makes the oscillations ever wilder at the beginning, both increasing the overshoot and increasing the response time. However, what it does do is get rid of and of the long term oscillations seen in the previous response (Figure 8):

![Figure 8: PID controlled closed loop cruise control system response; P=1, I=1, D=1](image)
Now the response must be fine tuned by tinkering with the different values of the PID. As it is right now, the settling time is reasonable for the 15 second acceleration target, and the rise time is probably even a bit fast. The big problem that must be fixed is the large overshoot. Imagine pressing a button that you thought would make your car accelerate to 65 mph and having the car shoot all the way up to over 80 mph first! This would simply not be allowed to happen in a real automobile.

It should be mentioned that it is not necessary to utilize all three components of a PID in all cases. In situations where a very fast rise time is needed, all three components can be very important, in order to control the settling time and overshoot. However, in a slow rise time situation such as this one, it is possible to control the overshoot, steady state error, and response time with just two of the components. This is because of the general effects each of the components has on the response. The proportional controller has a huge effect on rise time—the higher it is set, the quicker the response. However, increasing the proportional component also introduces some steady state error and often a fair degree of overshoot too. The integral controller also speeds of response time, and has potential to increase the overshoot too; however, its most useful attribute is that it helps to eliminate steady state error. The purpose of the derivative controller then becomes cutting down on the overshoot caused by the proportional and integral.

With these factors in mind, let's now revisit the cruise control response starting again with just the proportional response. Recall that with the proportional controller set to 1, the car accelerated to the desired speed in about 5 seconds, but also had a steady state error the left the final speed slightly below the desired level. Since 5 seconds is too quick for average driving conditions, decreasing the proportional controller should help slow the response. With the proportional controller set to 0.3, the response becomes the following (Figure 9):

![Figure 9: PID controlled closed loop cruise control system response; P=0.3, I=0, D=0](image)

This has a nearly perfect acceleration
time of about 15 seconds. However, the steady state error has increased negatively again, and the car now is traveling significantly slower than desired. Adding the integral controller should help fix this steady state error. However, we know that using too high of a value for the integral controller can create much overshoot and an undesirable level of oscillation, so the integral value must be set very small to find the optimum point of eliminating steady state error while not created any overshoot. A value of 0.01 appears to do this very nicely (Figure 10):

![Figure 10: PID controlled closed loop cruise control system response; P=0.3, I=0.01, D=0](image)

This shows a reasonably desirable acceleration of an average car. This appears to exactly fulfill what the design specifications wanted without even using a derivative controller. The derivative is not needed here simply because the slow response time means that neither the proportional nor the integral controllers need to be set at a level that creates any overshoot.

Through this demonstration of how a PID can be used to tune a cruise control system, one can see how the system could then be tuned for different vehicles that drive in different ways. This 15 second response might be good for a minivan or family sedan, but a driver of a sports car might wish for a much quicker response time from the cruise control system. Setting the proportional and integral controllers to values of 0.6 and 0.02, respectively, creates such an output (Figure 11):

![Figure 11: PID controlled closed loop cruise control system response; P=0.6, I=0.02, D=0](image)

This shows a reasonably desirable acceleration of a sports car. It is easy to see from this how a PID is extremely versatile for tuning a cruise control system exactly to the desired automobile specifications.

### 6.1 DISTURBANCE

In real world driving conditions, a cruise
control system generally has to work at maintaining a constant speed as well as accelerating to the correct speed. In fact, the ability to maintain the proper speed is probably more important to the customer's satisfaction with the cruise control system than the ability to accelerate well. Factors like wind, hills, varying road friction, drafts from other vehicles, or steering forces all work against the speed of the vehicle—some work to speed it up, and some work to slow it down. This sort of idea could probably be modeled with some sort of random signal generator disturbance input in the system, but a more complicated would need to be created to actually show how the system would operate. To do this topic justice, a whole separate paper would need to be devoted to it. This paper will stick more with the fundamentals.

6.2 REAL WORLD SYSTEMS

Real world cruise control systems, while built around many of the basic principles already discussed, are vastly more complicated than just a PID controller feedback loop. While this type of control unit might actually still be utilized somewhere in the cruise control logic, there likely exists a much more complicated logic system with multiple loops feeding back to various points in the system.

To compare the way a real world system is set up, some technical diagrams from a cruise control system in a 1991 Dodge Stealth were found. While these diagrams are not from a new car of the last few years, they still effectively can give a glimpse into both the complexity and the fundamentals of a real world system (it even could be argued that these are a better starting point for analyzing real world systems, because new cruise control systems grow more complex with each new redesign).

To start with, a diagram of the component structure of the Stealth cruise control system is shown in Figure 12. Since the beginning of the paper discussed the physical components that make cruise control work, this is a good place to start for looking at a real world system. In the diagram, all of the inputs to the system are shown above the control computer, and all of the outputs are shown below. Every component discussed previously in Section B is present in this system, and this diagram makes it very easy to see how each component fits into the system.
The top half of the system (above the dotted zigzag line) is referred to as the control system, because its job is to work to actually tell the car what to do. One interesting part to note in the control system is the Throttle Position Sensor. This sensor, which is not mentioned in section B, monitors how far open the throttle is.

By using both this and the vehicle speed as inputs, the computer is able to make better decisions about how aggressively to open or close the throttle in order to make the car travel at the desired speed; it allows for smoother operation of the system.

If the car is losing speed, the computer needs to send the message to open the throttle wider. Having a sensor on the throttle allows for this to be done smoothly—rather than opening the throttle very rapidly and creating a jerky ride (the exact problem that led Teetor to invent cruise control in the first place), the throttle position sensor lets the computer know to ease onto the throttle to maintain a more steady response of the vehicle.
Two other control components worth noting are the overdrive switch (OD switch) and the ELC-4A/T control unit. One worry that exists in a car with overdrive is that the overdrive gear, which is usually the gear being used while cruise control is on, will not allow the car to have enough power to climb hills. Depending on gearing and engine output, some cars are not able to maintain speed on a hill with overdrive engaged. In a car with a manual transmission, it would be up to the driver to shift out of overdrive and into a lower gear; on a car with an automatic transmission, it is possible for the cruise control system to monitor when this needs to be done, and actually do it.

The OD switch simply senses whether overdrive is engaged; if the computer senses a significant decrease vehicle speed sensor's speed reading (4 mph), it will send a signal to the transmission control unit to shift out of overdrive and into third gear.

To avoid a gear hunting problem, which would mean the transmission continually is shifting back and forth between third and overdrive, the computer tells the transmission to hold third gear for a fixed amount of time to assure that the vehicle has time to get back to speed rather than having the transmission quickly shift back to overdrive as soon as the speed begins to increase.

The bottom half of the system (below the dotted zigzag line) is called the actuator system. This part of the system takes an output signal from the control computer and turns it into mechanical motion through a series of actuators and linkages that connect to the throttle. The actuator system found in this Stealth has no significant differences compared to the one described in Section B.

One area that is still very grey in this Dodge Stealth cruise control system in this is control computer. To help clear up somewhat how it works, a logic diagram is shown in Figure 13.
Unfortunately, this diagram still does not dig into the actual logic process used inside the computer, but rather just gives a much more detailed look at how the inputs and outputs are integrated into the computer. However, it does show some of the feedback loops that are present in the overall system.

The way Figure 12 was arranged, one might think that the system operated like an open loop system; the vehicle speed sensor and the throttle position sensor both fed inputs into the computer, but
nothing on the output side of the computer was shown to be monitored and fed back into the computer. However, a careful look at this logic diagram in Figure 13 shows that there is some feedback monitoring taking place with the control computer. Both the micro-computer monitor circuit and the actuator drive circuit send information back into the computer. The purpose of the loop on the micro-computer monitor appears to simply be to keep checking to make sure the power supply to the micro-computer is working properly. The feedback loop on the actuator drive circuit appears to actually function similar to the way the feedback Fig. 13. Dodge Stealth Cruise Control Logic Diagram loop in the simulink simulations worked; that is, it monitors what the controller is doing, and uses this data to decide what else needs to be done. Unfortunately, as mentioned already, there is really no further information on the nature of the control computer in this system.

7. CONCLUSIONS

Cruise control technology has come a long way since the first systems invented by Teetor or installed on the late 50’s Chryslers. With the glimpse into the real world Dodge Stealth system from 1991, it is easy to see just how much computerized control play a role in controlling the speed of vehicles today. As computerized control technology continues to expand, it is expected that adaptive cruise control will begin to become more widespread. The possibilities of what such a system can do seem nearly limitless. If every car on the road could one day be equipped with adaptive cruise control, we could live in a world with drastically fewer traffic accidents than we ever have thought possible. While cruise control was invented as a comfort or convenience item, it could eventually begin to double as a safety feature that changes the way we drive our cars.

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