
Performance, Robustness, and Durability of an Automatic Brake System for Vehicle Adaptive Cruise Control

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ABSTRACT

Adaptive Cruise Control (ACC) technology is presently emerging in the automotive market as a convenience function intended to reduce driver workload. It allows the host vehicle to maintain a set speed and distance from preceding vehicles by a forward object detection sensor. The forward object detection sensor is the focal point of the ACC control system, which determines and regulates vehicle acceleration and deceleration through a powertrain torque control system and an automatic brake control system. This paper presents a design of an automatic braking system that utilizes a microprocessor-controlled brake hydraulic modulator. The alternatively qualified automatic braking means is reviewed first. The product level requirements of the performance, robustness, and durability for an automatic brake system are addressed. A brief overview of the presented system architecture is described. The control methodology of generating brake pressure via a hydraulic modulator to achieve the vehicle deceleration requested by ACC controller is then introduced. The paper includes a description of two Pulse Width Modulated (PWM) solenoid control designs and applications as an important technology to ensure the automatic braking performance. The implementation of moding the automatic brake system with ABS, Traction Control, and Vehicle Stability Control is revealed at the vehicle system level. Vehicle test data will be presented as insight to the braking performance and robustness. The control-related system durability will also be examined and discussed under vehicle testing profiles. Vehicle integration system test data summarizes and concludes the practice and value of the presented automatic brake system for vehicle adaptive cruise control.

INTRODUCTION

ACC is a system that uses a forward radar sensor to determine the distance between the host vehicle and a target vehicle. The system is intended to match the speed of the target vehicle by reducing the throttle and/or applying the brakes without requiring the driver to adjust the cruise control settings. Figure 1 shows the

components and subsystems required to implement ACC.

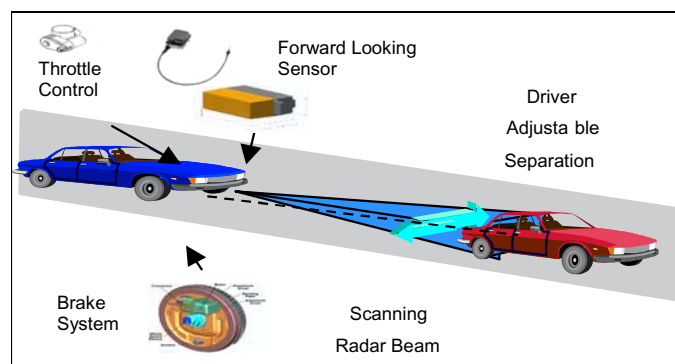


Figure 1 The Components of the ACC System

There are several ways to implement ACC on a vehicle and this paper will discuss some typical implementation schemes. The automatic braking function can be achieved by various means; some methods include an intelligent brake booster, electric calipers, stored hydraulic fluid pressure, etc. This paper details implementation based upon stored hydraulic fluid pressure; however, brief descriptions of other methods are given first. One method to regulate wheel brake pressure utilizes an intelligent/smart booster. Wheel pressure is regulated by a solenoid valve that controls air flow into the booster air chamber, which generates differential pressure across the booster's diaphragm. This method generates little audible noise and is also very smooth; however, there is additional risk of mechanical failure plus the brake pedal drops during an autobraking event. One prior method of generating brake pressure with the hydraulic modulator is the traditional operation of traction control. When the pump, Prime Valve and Isolation Valve are energized together, brake fluid is delivered under pressure to the wheel brakes. The fluid flow from the master cylinder into the pump is regulated by the Prime Valves. The Isolation Valve is located on the high pressure side of the pump to prevent the fluid from returning to the master cylinder. The wheel brake pressure is regulated by the Apply Valves and Release Valves. The Apply valves are energized to block the in-flow of fluid to the brake to control the rate of the

pressure increase, while the Release Valves are energized to control the rate of the pressure decrease. This method of controlling the wheel brake pressure is suitable for traction control and vehicle stability where noise and harshness are less of a concern. In the automatic braking mode of ACC, the noise and harshness would typically be unacceptable.

An alternate method to regulate the wheel brake pressure is through ON/OFF control of the Prime and Isolation Valves. Wheel pressure is increased by regulating the fluid supply to the pump through Prime Valve modulation and pressure is decreased by releasing fluid through the Isolation Valves. This method generates much less noise, but it is not as smooth as required for auto braking.

The chosen method to control the wheel brake pressure is through the use of a hydraulic pump (modulator), prime valve, and Variable Isolation Valve (VIV). The VIV operates as a pressure regulating valve where the blow-off pressure is proportional to the applied PWM duty cycle. To increase wheel brake pressure, the Prime Valve and pump are energized, and the PWM signal to control the VIV is set appropriately to hold/build the desired pressure. To release pressure, the VIV PWM duty cycle is reduced. This modulator control method is smoother, quieter, and more cost effective than the prior methods. The remainder of this paper gives some insight to the implementation, performance, robustness, and durability of this chosen method.

THE PRESENTED SYSTEM OVERVIEW

Hydraulic Mechanization

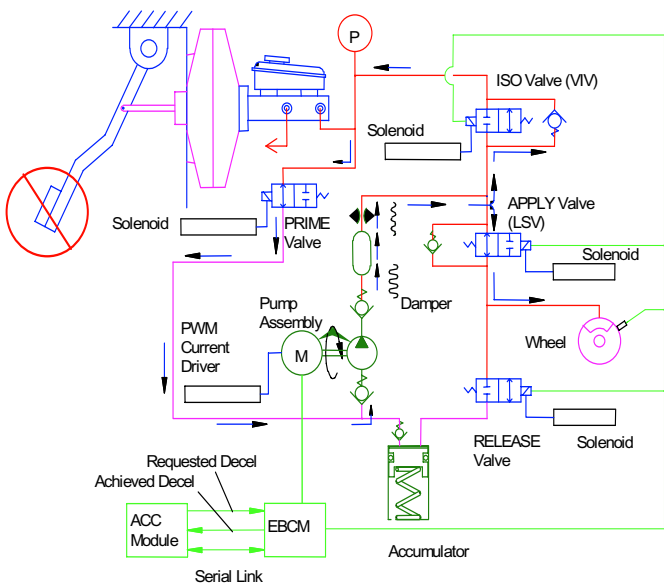


Figure 2 The Mechanization of Hydraulic Modulator

Figure 2 depicts the mechanization of the ABS/TCS/VSE controlled brake system capable of performing ACC Automatic Braking without driver input on the braking pedal. The ABS Controller commands the motor in the modulator to pump brake fluid from the master cylinder into the wheel brake lines through the energized and opened PRIME solenoid valves. ACC Automatic Brake utilizes PWM-driven variable isolation valves (VIV) to regulate the pressure level on the wheel brake hydraulic lines. Delphi VIV technology provides the characteristic of throttling the braking flow through the orifice of the solenoid valve with extremely low-pressure jumps. The result achieves smooth, uniform, and low-vibration vehicle deceleration. The VIV provides an attractive linear flow control of the solenoid valves where the blow-off pressure is proportional to the applied current. That overcomes the technologic limitations of conventional ON/OFF style solenoid valves, which are used in most of today's industrial market. Additional key features of the VIV hardware are the capabilities to match the deceleration control stability requirements of ACC automatic brake through synchronizing pressure control with ABS/TCS/VSE subsystems which basically utilize APPLY and RELEASE valves for wheel brake pressure regulation. To meet the low noise requirement, a PWM-driven motor control circuit is equipped to effectively minimize the noise level from pump piston impact.

Vehicle System Integration

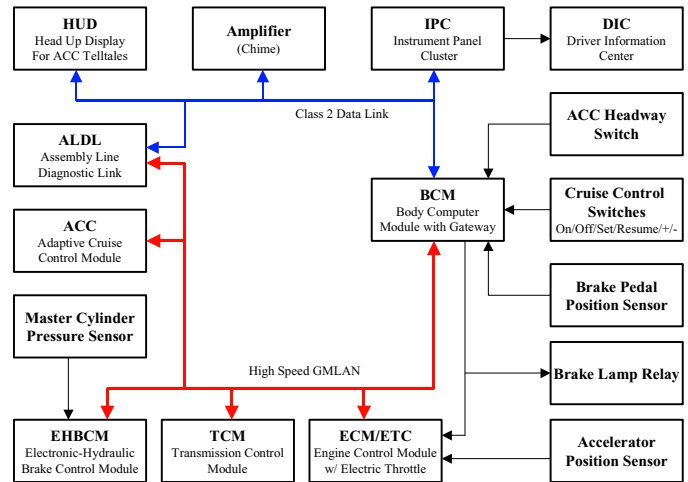


Figure 3 The Architecture of Vehicle System Integration

Figure 3 indicates the block diagram of implementing the ACC vehicle integration system. To maintain the vehicle headway and cruise speed, the ACC controller issues the requested deceleration or acceleration commands through a high-speed serial link to the EHCMB and ECM. The ACC Automatic Brake System is assigned to fulfill the task of achieving the desired deceleration level beyond the maximum decelerating capability available

from the powertrain system. In ACC autobraking mode, when the driver applies the brake pedal, the automatic braking action is phased out. This transition is done and secured by monitoring the signals from brake pedal position sensor and master cylinder pressure sensor. Input to the electric throttle from the driver and the ACC module for speed maintenance is differentiated within the ECM. The ECM reports the driver's throttle input during ACC autobraking activation to the EHBCM via the high-speed serial link. When the ECM reports the driver's throttle input, ACC autobraking phases out. If the decel request from the ACC module persists once the driver's throttle input goes away, then ACC autobraking resumes. A brake lamp relay is included in the system for the purpose of signaling the tail brake warning light in the ACC automatic braking events.

AUTOBRAKING SYSTEM PERFORMANCE

Control Design

The key control design of the Automatic Brake system is to achieve the required performance through vehicle deceleration tracking control. The vehicle deceleration, which is derived from the fusion of wheel speed signals subject to possible wheel slips/spins or active brake control, is used as the feedback to guide the tracking schemes. To match the product requirements, a sequence of control sessions is adopted to take advantage of the dedicated hardware technologies, VIV and PWM Motor, to regulate the braking pressures at all 4 wheels. Figure 4 cascades the high-level flow of the wheel brake pressure control.

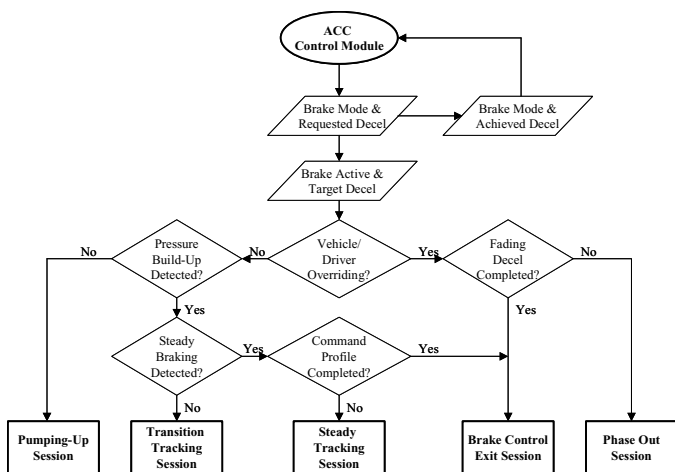


Figure 4 The Cascade of the Wheel Pressure Control

The pressure control scheme starts with a pumping up session that applies a temperature compensation based open-loop command to the VIVs and PWM Motor to maximize response time. After the detection of the pressure buildup, a closed-loop transient tracking

session takes over to pilot the VIV blow-off pressure to achieve the vehicle deceleration target with minimum overshoot. Next, a steady tracking session with learning process follows to generate smooth, quiet, and low-vibration deceleration, which also helps to avoid misleading feedback due to rough road disturbances or emergency braking cycles. In the event of a driver's override or system failure, an open-loop phase out session is used to fade out the wheel brake pressures to satisfy the requirement for a smooth transition. In addition, a brake control exit session is executed to remove any residual upstream vacuum or downstream pressure relative to the modulator to ensure repeatable performance.

Vehicle Testing and Responses

The Automatic Brake control design is validated in the target production vehicle, which is equipped with Delphi's Adaptive Cruise Control Module with Forward Detection Sensor and Delphi's DBC7.2 brake system. The DBC7.2 brake system for the target production vehicle has capabilities for Antilock Braking (ABS), Traction Control (TCS), Electronic Stability Control (ESC) and Adaptive Cruise Control Automatic Braking. A variety of tests and evaluations were performed to achieve the production requirements on automatic braking deceleration – responsive, precise, smooth, low-noise, low-vibration, decent transition, uniform/stable, and robust. Fundamental tests, such as Rubber-Band Cruising, Lane Changes, Lane Cut-in, Tailing Stopping, Ride and Handling Cruise, Brake Overriding, Throttle Overriding, etc., were executed on proving ground tracks. Public Road Tests were done to verify the integrated system performance and to monitor the brake thermal reaction. The vehicles were exposed to low temperature and winter surfaces to confirm the response time and subsystem moding (ABS/ESC) with the Automatic Braking. Figure 5 shows data collected through a CAN Analyzer. The graph demonstrates the decel tracking response and precision during lane-cut-in tailing. It also displays the Automatic Braking capability to track the deceleration commands after transition from speed control mode (acceleration in this case) to braking mode.

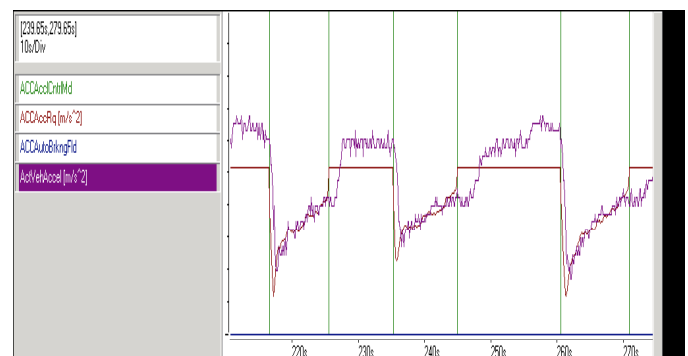


Figure 5 The Deceleration Tracking in Event of Lane-Cut-In Tailing.

AUTOBRAKING SYSTEM ROBUSTNESS

Modeling and Simulation Technology

The simulation of this system was run using a co-simulation between Matlab, Simulink, AMESim and CarSim. The brake control algorithm was generated using an s-function, in Simulink, which was created using Visual C++. This s-function derives the modulator commands based on the requested deceleration and the vehicle's behavior.

AMESim offers an environment for simulating mechanical, fluid and thermo-fluid systems. In this simulation, the pressure on each brake caliper was derived based on modulator commands, which are developed within the Simulink model. The AMESim model contains two pumps, one to run each side of the diagonally split braking system. The volumetric efficiency of each of these pumps was varied to understand the vehicle yaw and stability effects.

CarSim can be used for simulating and animating the behavior of four-wheel vehicles. The user may define a three-dimensional environment for the vehicle to travel in and various parameters of the vehicle. It can provide graphical outputs of specified parameters, a data file, or an animation of the vehicle in its environment. AMESim and CarSim generate s-functions when they are compiled; these s-functions are put into Simulink to interface with the brake control algorithm.

Simulation Results

When the model is run, CarSim allows the user to define the friction of the surface upon which the vehicle is traveling. Using this feature the simulated vehicle was driven on a straight path with a high coefficient of friction surface, to simulate a dry surface. It was run again with a split coefficient of friction surface, to simulate a vehicle that had its left wheels on a dry surface while its right wheels were on an icy surface.

CarSim also allows the user to vary the amount of steering. The tests were first run with a fixed steering wheel angle input. Then they were each run a second time with a simulated driver corrected steering. This simulated the driver having a one second preview. In each of the tests, the volumetric efficiency on the two pumps was varied to the most extreme case that is typically seen. After each condition had been tested, the yaw of the vehicle for each run was plotted. This shows the severity of changes in the pump efficiency based on yaw in a diagonally split braking application.

The yaw for a high coefficient of friction surface is shown in Figure 6.

The simulation was run for five seconds and the deceleration rate was requested when the time was equal to one second until the end of the simulation. The

lower volumetric efficiency was on the pump that drives fluid to the left front and right rear brake corners, this explains the vehicle's movement to the right without the driver correcting the steering. The dark line depicts the case in which the simulated driver tried to correct steering. The driver over steers slightly, but is able to maintain the straight path with little effort. The lighter line is the case when the steering angle is fixed. This level of yaw is very minimal and could easily be corrected by a driver with very little effort.

This same test was run on a surface with a split coefficient of friction. The yaw in each case was again measured and plotted with respect to time. This plot is shown in Figure 7.

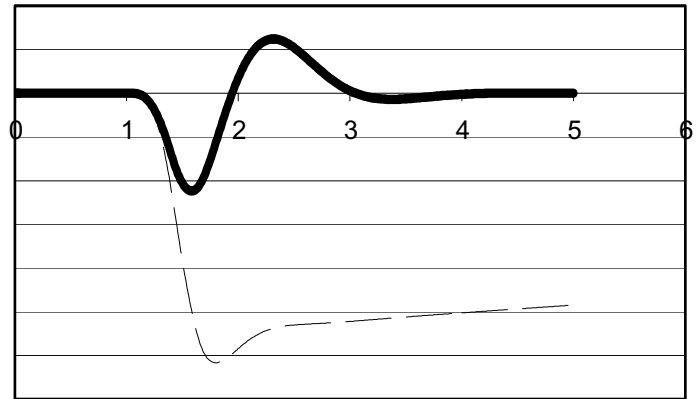


Figure 6 Yaw vs. Time on a Surface with High Coefficient of Friction.

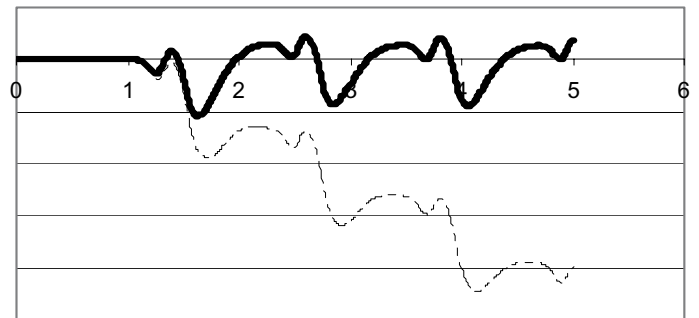


Figure 7 Yaw vs. Time on a Surface with Split Coefficient of Friction.

It is important to note that the right wheels of the vehicle are on a surface that is very slippery; this causes the vehicle to enter an antilock braking event when braking is requested. It is continually entering and exiting an antilock braking event for the remainder of the simulation. This causes the waves that are shown in Figure 7. Once again the right front and left rear brake corners are run by the greater pump efficiency. The dark line is the case in which the driver corrects the

steering, while the lighter line is the instance in which the steering wheel is fixed. With the driver corrected steering the yaw is still very minimal, without the driver's correction the yaw is still within a safe range. Based on this simulation Delphi feels very confident in their brake control algorithm in this application.

AUTOBRAKING SYSTEM DURABILITY

Usage Profile Study

A question arose regarding what should be a reasonable hardware usage profile to be defined in the production specification for the presented ACC Automatic Brake System. This issue affects the system durability testing to meet the product platform requirements. Though a thought was to induct the profile by interpolating the conventional cruise control brake usage envelope based on SAE or an OEM data inventory, the deviations of driver's overriding projection and system turned-on acceptance ruled out using this method. There is also the complication of trying to estimate how many of the base brake applications that are required to disengage the conventional cruise control system will be inherited by the ACC system. Another plot was to refer the automatic braking profile to the existing market vehicles equipped with ACC systems, which use intelligent boosters as the automatic braking mechanisms. However, the discrepancies of the deceleration command limitation, speed range availability, powertrain braking capability, headway setting sensibility (sensitivity?), forwarding defense algorithm, and of course commercial secret obstacles this direct importing door.

Therefore a customer-supplier joint effort was initiated to study the usage profile in a development car equipped with the targeted product ACC system. The test vehicle was driven in a variety of situations and road conditions. There were 86 separate test drives completed, which resulted in 3,246 test miles of ACC activation being logged. A total of 847 Automatic Braking events were recorded during the 3,246 miles. The data was taken at different daily timing, at different speeds by different drivers in an attempt to simulate as many different driving situations as possible. The drive routes ranged from heavy urban street traffic in and around Detroit

Metro, Michigan and Dayton Metro, Ohio to high-speed rural interstate travels. Figure 8 shows the automatic event percentage and the deceleration request bands, which was from extrapolating the data across the standard 100,000 miles vehicle life cycle.

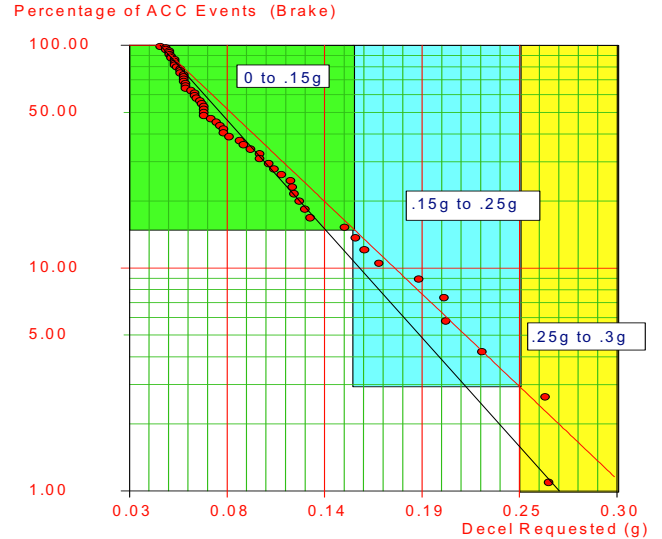


Figure 8 Autobraking Events vs Requested Decel

Component Durability Verification (DV)

In process of the presented Automatic Braking component Development Verification, the real-time vehicle control data corresponding to requested commands in the above study were broken down into 3 event-cycle-equivalent time domain profiles to fit practically for feasible chamber testing. Figure 9 displays the VIV valve input profiles which have linearly ramp-up and ramp-down signals to respectively represent the average energizing durations of pressure control. These 3 profiles were run in a chamber at four season temperatures evenly with the individually equivalent event cycle numbers and pre-set trigger waiting times. To minimize the hydraulic modulator noise, similar profiles with PWM commands proportional to these VIV signal levels were utilized to drive the hydraulic motor for the DV testing. The specification-met cycle numbers were accomplished in the chamber.

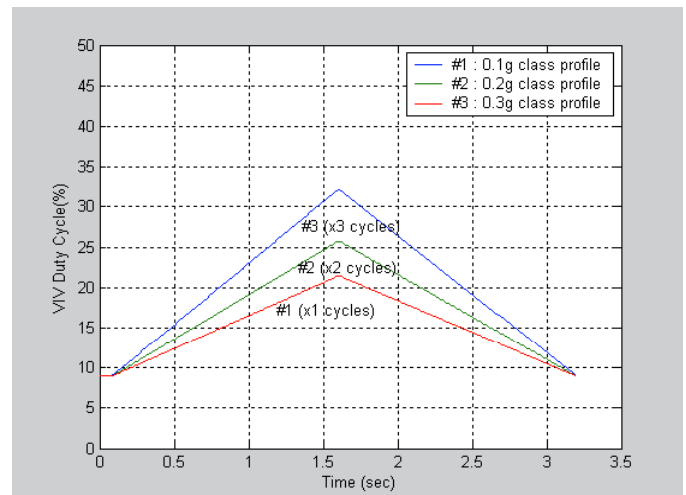


Figure 9 The VIV PWM Signals for the HCU DV Testing

CONCLUSION

There are several ways to implement an ACC automatic brake system for vehicle adaptive cruise control. The hydraulic-modulator-based implementation was examined here. The vehicle integration system testing verifies the presented automatic brake system performance. The component testing reveals its durability under brake life usage profiles. The simulation technology proves the automatic braking control robustness subject to driver, environment and manufacturer related disturbances.

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DEFINITIONS, ACRONYMS, ABBREVIATIONS

ACC	Adaptive Cruise Control
ABS	Anti-lock Brake System
TCS	Traction Control System
ESC	Electronic Stability Control
EBCM	Electronic Brake Control Module
PWM	Pulse Width Module
VIV	Variable Isolation Valve
LSV	Linear Solenoid Valve