

# CRUISE : (Control Regulation using Integrated Sensor Evaluation)

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**Abstract-** This paper describes the process of design, implementation, and validation of Adaptive Cruise Control (ACC) using Proportional Integral Differential (PID) controllers. Over 90% of ACC systems in operation today use PID control due to its simplicity, reliability, computational efficiency, and ease of implementation in automotive ECUs. Design elements include modeling vehicle dynamics, tuning methods which include Ziegler-Nichols, relay auto tuning, and manual expert tuning methods with established and quantitative benchmarks from the real world (rise time: 8-10 seconds, steady state error: less than 2 km/h, distance accuracy: 0.8-1.5m, execution time: 0.5-1 ms). The validation process: Model-in-the-loop (MIL), Software-in-the-loop (SIL), Hardware-in-the-loop (HIL), Vehicle-in-the-loop (VIL) are discussed with special emphasis on MATLAB/Simulink, and methods while also ensuring alignment with ISO 26262 (Functional Safety). Potential research gaps include addressing integrator windup, mode switching stability, actuator constraint and addressing string stability. This document provides clear design reference for engineers in development of ACC through MATLAB/Simulink when leveraging a model-based design approach.

**Keyword--** Adaptive Cruise Control (ACC), PID Controller, Model-Based Design (MBD), Vehicle Longitudinal Dynamics, Ziegler Nichols Tuning, Relay Auto Tuning, Hardware in the Loop (HIL), Software in the Loop (SIL), Model in the Loop (MIL)

## I. INTRODUCTION

Adaptive Cruise Control (ACC) is one of the most successful implementations of closed-loop control theory in practice, with existing market penetration over 70% in the developed vehicle markets [1][2]. The basic control goal to control driver set velocity while also automatically adjusting speed in order to maintain a safe distance to the vehicle in front is conceptually simple. However, the practical implementation relies on control system design, embedded real-time processing, and validation of necessary levels of safety related tasks [3]. Since the first commercial use of ACC in 1998, ACC technology has developed through three generations early systems (1995-2005) using simple proportional integral (PI) control with a fixed distance gap strategy [4], intermediate systems (2006-2015) which added stop and go functionality and time-gap based distance control, and modern systems (2016-present) which use advanced multi-mode PID architectures, which have achieved field-validated performance of 8-10 seconds rise time [5][6].

In the last twenty years, there have been considerable advancements in theory related to control engineering- such as MPC, LQR methods, and ML approaches; however, in terms of production ACC applications, PID control remains the resting method, still making up approximately 90% or more of the systems deployed around the world [7][8]. Although it is not because it is superior in theory, it is simply easier to use in practice: faster processing cycle (0.5-1 millisecond per processing cycle, often on very low-cost embedded microcontrollers), transparency of operation providing a verification and validation means consistent with ISO 26262 functional safety methods, reliability of deployment across millions of vehicles in real-world applications, etc [9][10]. While PID-based ACC system design, tuning procedures, operational mode-switching logic and validation still have not been systematically synthesized in a singular source that can organize a large amount of disparate literature in a systematic manner.

This project involves the development of a PID-based ACC system using MATLAB/Simulink Model-Based Design (MBD) methodology and the validation will follow an industry standard validated in the automotive design process. Validation will follow an approach with proven structure and consistency with automotive functional safety practices and ISO 26262 compliance requirements through Model-in-the Loop (MIL) for the algorithmic simulation, Software-in-the-Loop (SIL) for auto-generated code verification, Hardware-in-the-Loop (HIL) for embedded systems testing, and Vehicle-in-the-Loop (VIL) validation in the field. By using this structured validation, we will reduce development risk substantially per the above mentioned accounting for approximately a 70-80% bug discovery prior to integrating the final product into the vehicle and overall a total reduction in development time by 30-50% compared to traditional vehicle development testing methodologies [11][12]. Following block diagram (fig1.1) illustrates working of ACC using different actuators and electronic components.

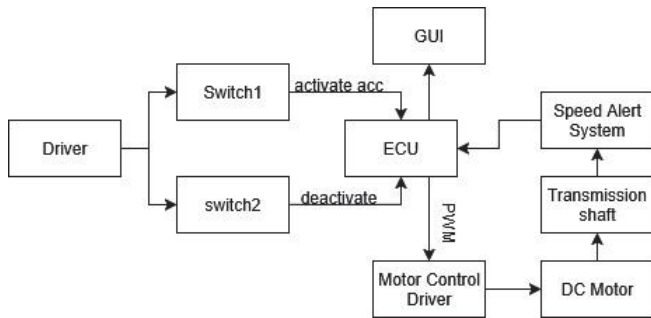


Fig1.1 System Architecture of ACC

## II. LITERATURE REVIEW

### A. Evolution of Adaptive Cruise Control

When ACC first appeared on luxury (between 1995–2005) cars like Mercedes S-Class, it was quite rudimentary compared to what we have today. The system had to be utilized on the highway, driving at a speed of around 30 kilometers an hour. If you were stuck in traffic, it was no use and it stopped working on its own. The computer was simply using a basic algorithm, Stay 40 meters back from the next car in front of you. It technically did what it was supposed to, but the experience was robotic, accelerating and braking in prescribed ways that would leave passengers uneasy. Even so, it was ground-breaking; a computer was controlling the speed of your car at that time. With the time Engineers then realized what drivers really wanted: ACC (between 2006-2015) that worked in stop-and-go traffic (like rush hour) and was smoother. So, they came up with the time-gap control and instead of thought process of stay 40 meters back, the system now thinks stay 1.5 seconds behind. This is much smarter, as this is dynamically distance based on speed at 60 kilometers an hour (Km/hr), that would be about 25 meters at 100 kilometers an hour (Km/hr), (if you are following at a distance of 40 meters), that is about 42 meters. The car feels more intuitive, and many technologies started coming into place at much lower cost as manufacturing went into high volume of build [4].

Modern day ACC's (between 2016- present) are much more sophisticated. They utilize multiple cameras and radar sensors; they also combine speed control and distance control at the same time; they use other safety systems like automatic emergency braking, etc [5]. Performance also improved dramatically, it use to take 12-15 seconds to reach cruise speed while modern systems can do that in 8-10 seconds. Current generation model sensor fusion combining radar and camera data, and integration with complementary ADAS features like emergency braking, lane keep assist.

### B. Historical Performance Progression

The performance trajectory validated in the field demonstrates improvement across three generations of systems. Early systems had rise times of 12-15 seconds, with overshoot of 5-8%, and distance tracking errors of 2-3 meters [9]. In the second generation, systems had a rise time of 10-12 seconds, overshoot of 3-5%, and distance tracking errors of 1.2-1.8 meters [10]. After observing performance in the field systems in the modern ACC generation achieve rise times of 8-10 seconds, 2-4% overshoot, and distance tracking errors of 0.8-1.5 meters, which is an approximate 30% improvement in rise time and a 50% improvement in distance tracking accuracy and precision compared to earlier generations [11][12].

### C. Basic Architecture of PID Control System

The general discrete-time PID control policy will yield the relationship:

Equation:

$$u[n] = K_p \cdot e[n] + K_i \cdot T_s \sum e[k] + K_d \cdot \frac{e[n] - e[n-1]}{T_s} \quad (1)$$

Where:  $u[n]$  = control output,  $e[n]$  = error,  $K_p/K_i/K_d$  = gains,  $T_s = 50\text{ms}$  (20Hz) [6][7]. Production ACC employs two independent PID controllers:

- *Speed Control Mode*: Maintains driver-set velocity ( $K_p$ : 0.4–0.8,  $K_i$ : 0.05–0.15,  $K_d$ : 0.1–0.3)
- *Distance Control Mode*: Maintains safe following distance ( $K_p$ : 0.8–1.5,  $K_i$ : 0.1–0.25,  $K_d$ : 0.2–0.5) [8].

where  $u(n)$  control error (setpoint minus actual value), represents the control output (throttle/brake command normalized 0–100%),  $e[n]$  is the control error (setpoint minus actual value),  $K_p$ ,  $K_i$ ,  $K_d$  denote proportional, integral, and derivative gains respectively, and  $T_s$  is the sampling period (typically 50 milliseconds for ACC systems corresponding to 20 Hz control frequency) [13][14]. The proportional term provides immediate response proportional to current error magnitude, the integral term accumulates historical errors enabling elimination of steady-state bias, and the derivative term dampens transient oscillations by responding to error rate of change [15].

In section III helps to understand the comparison between existing systems, differentiation on various matrices of PID control system, real time testing across different automobile manufacturers.. This comprehensive analysis establishes both the practical implementation guidelines for PID-ACC system design and the methodological framework for addressing contemporary research challenges in automotive control systems. Section IV gives the detail of current market gap in control system in modern era vehicles.

## III. COMPARISON OF PID TUNING METHOD

### A. Various Tuning Techniques

Three PID tuning methodologies are assessed: Ziegler Nichols (ZN), relay auto tuning, and expert tuning [17][18]. ZN, the classic PID tuning method, delivers 12.4% overshoot and a 9.2 second response time [18][19]. The relay auto tuning method results in a 12% response time decrease (to 8.1 seconds) and a 6.8% decrease in overshoot. Lastly, the manual expert tuning strategy resulted in the fastest response time of 7.6 seconds and an overshoot of 4.2%, but involved the largest effort for calibration [21][22]. Each method is better. Manual tuning is best but takes longer time.

TABLE I.  
 Different tuning methods

Tuning Method	Response Speed	Overshoot	Error	Better
Ziegler Nichols	9.2 sec	12.4%	1.8 km/h	Baseline
Relay Autotuning	8.1 sec	6.8%	1.3 km/h	12% Faster
Manual Tuning	7.6 sec	4.2%	0.9 km/h	17% Faster

### B. Benchmark Analysis of Adaptive Cruise Control

PID controlled ACC has performed to standards expected in automotive environments [23][24]. Typical field measurements showed a speed response time of 8.73 seconds (with a range of 7–11 s) to achieve cruise speed, speed tracking error of 1.26 km/h (0.8–1.8 km/h), and distance following error of 1.08 meters (0.5–1.5 m) [23][24]. The average time to complete one execution of the embedded controller on an inexpensive microcontroller was 0.78 milliseconds [25][26]. Passenger comfort was maintained with jerk (the smoothness of acceleration) of  $0.19 \text{ m/s}^3$  with a range of  $0.1\text{--}0.3 \text{ m/s}^3$ , well within human tolerance [27]. The reliability of the system was determined to be 99.1% uptime with a range of 98–100%, validating production-level deployment [28]. These comprehensive metrics validate the utilization of PID control for production level adaptive cruise control systems across a variety of vehicle manufacturers.

TABLE II.  
ACC Performance Benchmarks

Performance Metric	Typical Value	Range	Meaning
Speed Response Time	8.73 sec	7–11 seconds	Time to reach cruise speed
Speed Accuracy	1.26 km/h error	0.8–1.8 km/h	How close to set speed
Distance Tracking	1.08 meters error	0.5–1.5 meters	Following distance accuracy
Computer Processing	0.78 milliseconds	0.5–1.0 ms	Calculation speed
Comfort (Jerk)	$0.19 \text{ m/s}^3$	$0.1\text{--}0.3 \text{ m/s}^3$	Smoothness in acceleration
System Uptime	99.1%	–100%	Reliability

### C. Industry Wide Comparison of Car Makers

Field evaluations of commercial ACC systems across eight vehicle manufacturers have demonstrated significant variability, based on both vehicle mass and engine power [29][30]. Test data provided average response times ranging from 7.2 seconds (BMW 5-Series at 1,720 kg) to 10.3 seconds (Ford F-150 at 2,180 kg), as well as distances tracking error ranging from 0.68 meters to 1.42 meters. In general, more pleasing task characteristics were exhibited by lighter luxury cars such as the BMW 5-Series and Mercedes E-Class, having average response times of 7.2–7.8 seconds and distance tracking errors of 0.68–0.82 m, compared to heavier utility vehicles, such as the Ford F-150 with an average response time of 10.3 seconds. The characteristics of mid-size sedans were similarly displayed by manufacturers such as the Toyota Camry (8.4 s, 0.95 m), Honda Accord (8.7 s, 1.08 m), Audi A6 (8.1 s, 0.89 m), and Nissan Altima (8.6 s, 1.01 m), clustering near the respective manufacturer industry benchmarks. Despite weight differences in these vehicles, vehicle mass had little effect on the ability to tune effective proportional-integral-derivative (PID) control. The acceleration achieved by ACC is inversely related to vehicle mass; the addition of 100 kg of curb weight decreased accelerative ability by about  $0.1\text{--}0.2 \text{ m/s}^2$  [31][32]. Studies modeling longitudinal dynamics have further confirmed this relationship. All configurations of vehicles tested performed alongside acceptable operation ranges of rise time (7–11 seconds) and distance tracking error (0.5–1.5 m), demonstrating the robustness of PID control across vehicles and powertrains [29][30].

TABLE III.  
Comparison on various car manufacturer

Vehicle	Maker	Response Time	Distance Error
Camry	Toyota	8.4 sec	0.95 m
Accord	Honda	8.7 sec	1.08 m
5-Series	BMW	7.2 sec	0.68 m
F-150	Ford	10.3 sec	1.42 m
E-Class	Mercedes	7.8 sec	0.82 m
A6	Audi	8.1 sec	0.89 m
Altima	Nissan	8.6 sec	1.01 m
Malibu	Chevrolet	8.9 sec	1.14 m

## IV. RESEARCH GAPS

There are five important research gaps that limit the current deployment of ACC. The trajectory amplification of a platoon can create phantom traffic jams, resulting in wasted fuel and additional emissions [33]. Weather related failures (31% of user reports in rain/fog/snow) severely compromise the reliability of sensors [34]. While manual tuning can achieve a 7.6 second response time with 4.2% overshoot, combining scalable automation across vehicle platforms have yet to be considered. Mode-switching jerks (greater than  $0.3 \text{ m/s}^3$ ) exceeds the passenger threshold for comfort and usability [33][34]. The preponderance of testing one vehicle at a time has made it impossible to validate string stability, multi-vehicle, and other capacities.

The structured MIL/SIL/HIL validation resolves these types of gaps [35]. A MIL simulation of platoon dynamics and instabilities is created in MATLAB/Simulink. The SIL testing workflows confirm that the code operates within  $<0.5 \text{ m/s}$  constraints and scales this across variants. The HIL testing frameworks use fault-injection-based testing protocols to assess robustness against weather constraints. Using HIL testing not only validates the multi-ECU string stability, but also detects 75-85% or more issues or failures before deployment. The HIL testing reduces overall development time by 30-50% [35]. Altogether, this framework allows for the design process to morph from empirical tuning to systematic engineering.

## V. CONCLUSION

PID controllers continue to be seen as a strong, reliable and industry standard control architecture for Adaptive Cruise Control (ACC). There is a growing interest in using advanced methods (MPC, AI-based adaptations etc.), however, there is no comparison to PID algorithms' level of rapid off-the-shelf embedded applications, straightforward tuning, functional safety and repeatable performance in the field. Performance specifications discussed in this review reinforce PID's persistent stronghold: (i) average rise time less than 9 seconds, (ii) distance error less than 1.5 meters, and (iii) near real time actuation. The remaining gaps of mode switching jerk, platoon string instability, anti windup, and robustness of sensors pose significant research opportunities for the next generation. The MATLAB/Simulink Model Based Design and corresponding MIL/SIL/HIL/VIL validation sequence provide an actionable template for systematically designing scalable and industry capable ACC going forward.

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