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Designing a PID Controller for a Cruise Control System using Genetic Algorithm

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ABSTRACT

Car cruise control systems have become a common feature of modern vehicles for the driver's comfort during long journeys. The main problem of this system is maintaining the speed set by the driver, or in other words, the car's speed must match the predetermined value. In this article, a Proportional-Integral-Derivative (PID) controller using Genetic Algorithm (GA) is designed for this system. Three objective functions Integral Square Error (ISE), Integral Absolute Error (IAE) and Integral Time Absolute Error (ITAE) were investigated for this controller and the function with the best response was selected as the final controller. The results obtained for the selected controller are compared with the results of the PID controller adjusted by the Ziegler-Nichols method and a fuzzy controller. The results show that the controller designed with the GA based on the ITAE objective function had the best performance compared to other controllers.

1. Introduction

Various parts of a vehicle, including the suspension system, speed control system, etc., have been investigated for stability, comfort and safety [1]. One of the most important parts is the use of cruise control system in vehicles. Cruise control has been introduced as one of the key features in most modern vehicles. This technology helps to increase passenger safety by reducing driver engagement on highways and less-trafficked areas. Additionally, cruise control can contribute to optimizing fuel consumption and reducing traffic congestion [2,3]. As technology advances and the cost of related equipment decreases, more and more vehicles will be equipped with this technology to enhance their functionality [4-7]. In a cruise control system, the vehicle's speed is adjusted to match a reference speed selected by the driver. This feature can enhance safety even if the driver is not fully attentive [8]. The fundamental challenge with this system is maintaining the speed set point by the

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driver. in other words, ensuring the vehicle's speed aligned with the pre-determined value. The primary disturbances affecting this system are; first, the speed variations induced by road gradients, and second, the wind resistance opposing the vehicle's speed. The cruise control system calculates this difference in speed caused by these disturbances and generates a control signal sent to the throttle actuators of the vehicle. This allows the system to maintain the optimal fuel injection to the engine and provide the desired optimal speed [9,10]. For designing a controller of a cruise control system, various methods can be employed based on the specific requirements. One approach involves using the Lyapunov control function method, where the Lyapunov function is expressed in terms of the system's energy, similar to Newtonian mechanics. This leads to decentralized feedback laws designed for each vehicle in a network of vehicles on circular roads without lanes [11]. Another option is the implementation of Proportional Integral (PI) controllers in a vehicle speed control system, with the goal of minimizing overshoot, settling time, and steady-state error [12]. Despite the availability of several proposed controllers, the PID controller remains the most popular choice due to its simple implementation. However, the main challenge in implementing PID controllers is tuning of the PID parameters. In the past, many researchers have explored various artificial intelligence techniques for tuning PID controllers in different nonlinear systems. Acharya and Das also utilized several evolutionary algorithms based on swarm intelligence to optimize the PID controllers applied to the human respiratory system [13]. Moreover, a Model Predictive Control (MPC) framework can be utilized for simultaneous optimization of fuel consumption and tracking performance in adaptive cruise control scenarios, considering the trade-off between tracking error, fuel consumption, and safety constraints [14]. Cao et al. developed an end-to-end ACC controller based on timing neural network, which was trained with big driving data in a machine learning framework [15]. Plessen et al. introduced an integrated control strategy for autonomous vehicles, utilizing the MPC method for longitudinal control. They additionally reconstructed the vehicle model as a nonlinear dynamic bicycle model [16].

As urban traffic congestion increases and the possibility of driving at a constant speed diminishes, conventional cruise control systems in passenger vehicles are becoming less prevalent. Instead, more advanced systems that not only control speed but also manage the distance to preceding vehicles are being recognized as Adaptive Cruise Control (ACC) systems. ACC systems are an evolution of Conventional Cruise Control systems (CCC) that regulate the vehicle's speed and provide a predefined distance to the preceding vehicle through automatic control of the throttle and/or brakes. A key component of an ACC system is the onboard sensor module (such as radar, lidar, or camera) that measures the relative distance and speed between two consecutive vehicles [17]. Due to sensor issues and high costs, only a few experimental vehicles have been built. Daimler-Benz began working on longitudinal control in 1980. The initial experiments with a linear PID controller were not successful as the controller struggled to handle sensor noise data, resulting in highly aggressive driving behavior. The next stage involved a non-linear soft controller that operated on a regular cruise control and an automatic braking system. This approach proved successful, and used to conduct approximately 50,000 kilometers of driving tests [18]. ACC systems typically operate at speeds above 30 km/h and employ a dual-loop control structure. The system consists of an inner loop controller, also known as the low-level controller or servo loop, and an outer loop controller, referred to as the upper-level controller [19]. The control parameters computed by the outer loop in order to be sent to servo loop is either the reference torque [20]. Choi et al proposed the model free control approach for designing the low-level controller to obtain the desired torque, so as to reduce the impact of existing nonlinearity in the brake and engine model on the control process [21].

In this study, a PID controller is designed using GA for a cruise control system. The gains obtained for this PID are optimized based on ITAE, IAE and ISE objective functions. The function that shows the best performance in optimization is selected as the main function for this controller. In the following, the performance of the controller designed with the GA under the selective objective function is compared with a fuzzy controller and a PID tuned with Ziegler-Nichols method.

2. System Specifications

The vehicle velocity of a cruise control system is regulated in accordance with the reference value of the velocity set by the driver. The error signal generated between the desired reference velocity and actual output velocity is applied to the throttle, The basic problem of cruise control system is to maintain the velocity set by the driver. The velocity of the vehicle should match the preset value; therefore, the cruise control system calculates the velocity difference due to the existing disturbances and delivers a control signal to the actuators of the throttle. This action controls the fuel injection to the engine and thus provides the optimal speed. The transfer function of a cruise control system is derived from the longitudinal dynamics of the vehicle based on Newton's second law and can be defined as follows [8]:

$$F_d = M\frac{dV}{dt} + F_a \tag{1}$$

$$F_a = C_a(V - V_w)$$

$$F_d = \frac{C_1 e^{-\tau s}}{Ts + 1} \tag{2}$$

Where F_d is the force generated by throttle and generally can be represented as a first order lag system. F_a, C_a, V and V_w are the aerodynamic force, the aerodynamic coefficient, the vehicle velocity and the wind speed, respectively. τ is delay time representing actuator and system delay and T is the time constant. In the following, by assuming the initial conditions to be zero and neglecting wind speed, the output relations are found to be [22]:

$$\dot{V} = \frac{1}{M}(F_d - C_a V^2) \tag{3}$$

$$\dot{F_d} = \frac{1}{T}(C_1 u(t - T) - F_d) \tag{4}$$

$$y = V \tag{5}$$

By linearizing above equations and using power series expansion, final transfer function is obtained as equation (6):

$$G_p(s) = \frac{\frac{C_1}{MT}}{\left(s+\frac{2C_aV}{M}\right)\left(s+\frac{1}{T}\right)\left(s+\frac{1}{\tau}\right)} \quad \textbf{(6)}$$

Considering the $C_1=743$, $T=1s$, $\tau=0.2s$, $C_a=1.19N/(m/s)^2$ and $M=1500kg$, the final transfer function becomes:

$$G_p(s) = \frac{2.4767}{(s+0.0476)(s+1)(s+5)} \quad \textbf{(7)}$$

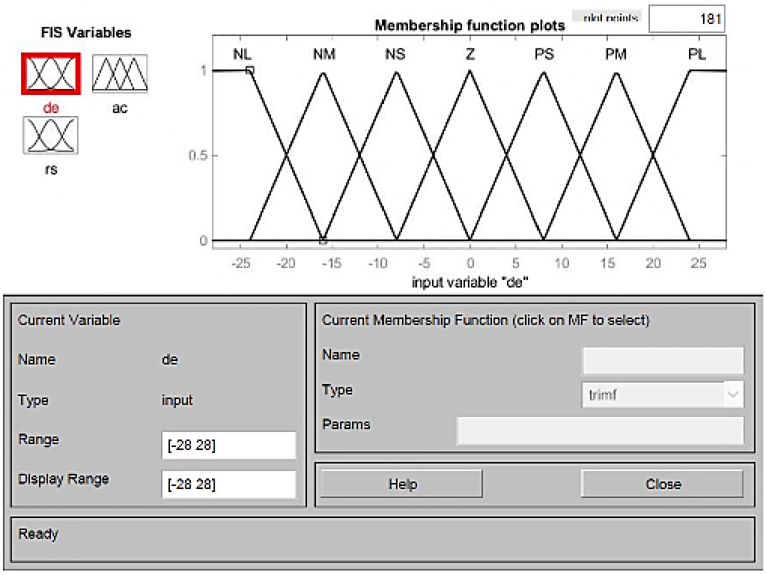
3. Controllers

In this research, three different types of controllers will be applied on this cruise control system. These controllers are Fuzzy controller, PID controller tuned based on Ziegler- Nicholes method and PID controller tuned by GA through three different objective functions. The results of all controllers will be compared to achieve the best controller for this system.

3.1 Fuzzy Controller

The fuzzy controller designed for this system is a Mamdani fuzzy type that consists of two inputs and one output. The relative speed and the displacement error are considered as the first and second inputs, respectively. and the acceleration of the car is considered as the output.

The membership functions used for all three variables are the triangular shaped types that have the range from Negative Large (NL) to Positive Large (PL) for inputs. Output number of membership functions are nine and starts from Negative Very Large (NVL) to Positive Very Large (PVL) which were given as follows:



Current Variable
Name de
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Range [-28 28]
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Current Membership Function (click on MF to select)
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Figure. 1. Schematic of distance error membership function

The first membership function which is shown in ***Figure 1*** is the distance error percentage to the reference distance, it is one of the inputs and has a range between -28 to 28.

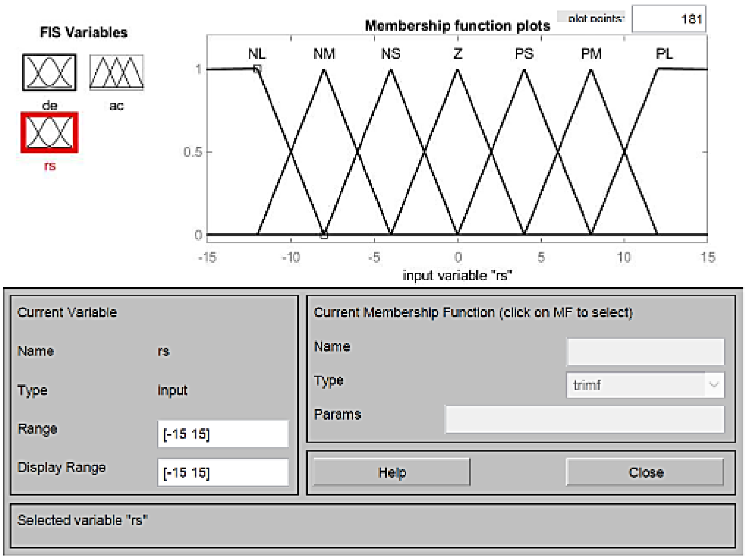

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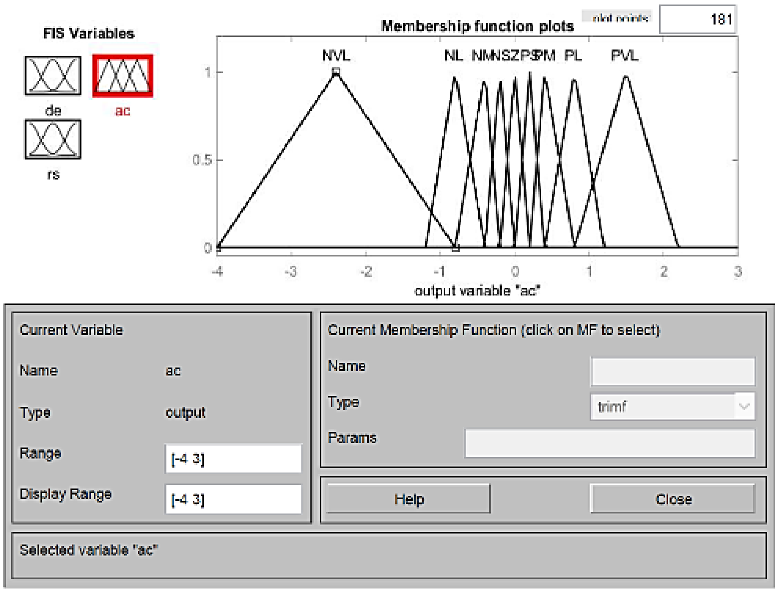
Figure. 2. Schematic of relative speed membership function

As shown in ***Figure 2***, the relative speed between the two vehicles has a triangular shaped and its range is between -15m/s to 15m/s.



Current Variable

Name ac

Type output

Range [-4 3]

Display Range [-4 3]

Current Membership Function (click on MF to select)

Name

Type trimf

Params

Selected variable "ac"

Figure. 3. Schematic of acceleration or deceleration membership function

The actuator has a limited range of automatic acceleration and deceleration, ranging from 2.5 m/s² to 1.5 m/s². If a maximum deceleration of -2.5 m/s² is insufficient for a specific driving situation, the driver is alerted by a buzzer to apply stronger braking force. To achieve exceptionally smooth control, we have implemented nine membership functions for the output variable. This consideration must be taken into account when defining the output membership functions and selecting the defuzzification method. For instance, if we employ the centroid method for defuzzification, the centroids for the leftmost (NVL) and rightmost (PVL) membership functions should be at -2.5 m/s² and 1.5 m/s², respectively. This ensures that all output values fall within the desired range.

The output of controller is the gas\brake pedal to accelerate or decelerate the speed and it does not have equidistant triangular shaped membership function. The range of this function is between -4 to 3m/s^2 which is shown in ***Figure 3***. Fuzzy logic uses rules that controller decisions are made according to these rules. The number of rules for the fuzzy controller designed for the cruise control system are 49 which are shown in the ***Table 1***.

Table 1. The rules of fuzzy controller

rs \ de	NL	NM	NS	Z	PS	PM	PL
NL	NVL	NVL	NVL	NL	NM	NS	NS
NM	NVL	NL	NM	NS	Z	Z	Z
NS	NL	NM	NS	Z	Z	Z	Z
Z	NM	NS	Z	Z	Z	PS	PS
PS	NS	Z	Z	Z	Z	PM	PL
PM	NS	Z	Z	PS	PM	PL	PVL
PL	NS	Z	Z	PS	PL	PVL	PVL

The Simulink part of MATLAB software has been used to design this controller. ***Figure 4*** shows the block- diagram of designed controller for this system. Since the step response of the system for the fuzzy controller has steady-state error, coefficients 3 and 100 are used to remove the steady-state error.

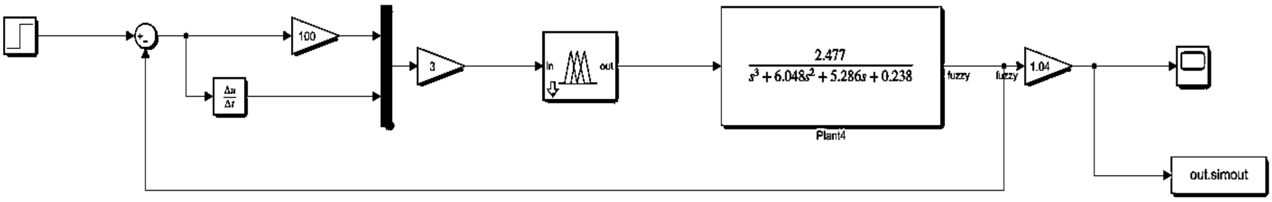


Figure. 4. block- diagram of system with fuzzy controller

3.2 PID Controller tuned by Ziegler-Nicholes

In this section, a PID controller will be designed for a cruise control system based on Ziegler-Nicholes classical method. The technique is based on adjusting a closed loop until steady oscillations occur. In this method, all three PID controller gains are set to zero and the step response of the system is obtained. Then, the K_p gain is set until the system reaches the limit of unstable dynamics. The value that causes the system to reach this instability limit is called K_u and the period of each unstable oscillation is called T_u. The tuning formula of Ziegler-Nichols rule for getting the parameters are written in the following equations [23] and the calculated parameters are given in ***Table 2***.

$$\begin{aligned} &K_p = 0.6K_u \\ &T_d = \frac{T_u}{8}\ , \qquad T_i = \frac{T_u}{2} \\ &K_i = \frac{K_p}{T_i} \qquad K_d = T_d K_p \end{aligned} \tag{8}$$

Table 2. Gains of PID controller tuned by Z-N

K_d	K_i	K_p	T_d	T_i	T_u	K_u
2.64	5.58	7.68	0.3438	1.3750	2.75	12.8

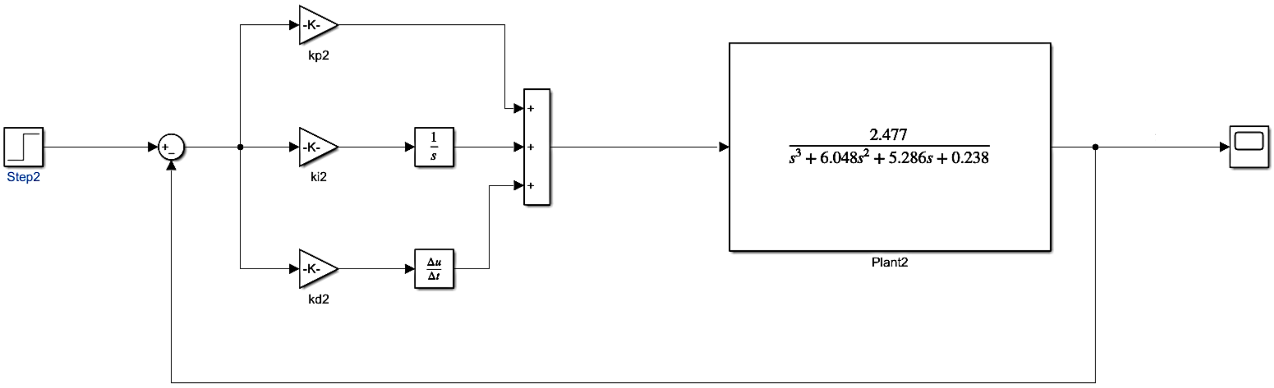


Figure. 5. block- diagram of system with PID controller tuned by Ziegler-Nichols

3.3 PID Controller tuned by GA

The last controller designed for this system is a PID controller which coefficients are estimated using GA. The GA tries to achieve optimal solution through the idea of survival of the fittest chromosomes. At first step of the classical GA, the initial population is created based on genetic encoding and then selection operator tries to select some members of initial population for crossover and mutation operation. In this study, the GA toolbox of MATLAB software is used for optimization process. The controller is considered as a performance indicator based on the reduction of the output response error with respect to the reference signal. If the values of the parameters K_p, K_i and K_d are selected so that the performance index is the smallest, the performance of the control system is considered optimal. By defining error, e, as the difference between the input and feedback signals, three objective functions that are considered to minimize the error are IAE, ITAE and ISE, respectively.

$$IAE = \int_0^t |e(t)|dt \tag{9}$$

$$ITAE = \int_0^t t|e(t)|dt \tag{10}$$

$$ISE = \int_0^t e(t)^2 dt \tag{11}$$

All three gains of the PID controller were obtained using the GA. This process was conducted twice over different intervals, as detailed below:

$$3 \leq K_p \leq 4\,, \quad 0.1 \leq K_i \leq 0.25\,, \quad 3 \leq K_d \leq 4 \tag{12}$$

$$0 \leq K_p \leq 10\,, \quad 0 \leq K_i \leq 10, \quad 0 \leq K_d \leq 10 \tag{13}$$

Additionally, the settings considered for GA parameters are shown in the ***Table 3***:

Table 3. Parameters of GA

Population Type	Double Vector
Population Size	40
Creation Function	Uniform
Scaling Function	Rank
Selection Function	Stochastic Uniform
Elite Count	2
Crossover Fraction	0.8
Crossover Function	Scattered
Mutation Function	Uniform
Mutation Probability	0.125

In the following, the control gains obtained by the GA for all three objective functions are presented in the ***Table 4***.

Table 4. PID Gains obtained by GA through different objective functions

Gains / Function	Range [0-10]			Range [3-4]		
	K_p	K_i	K_d	K_p	K_i	K_d
IAE	0.992	0.019	0.458	3.992	0.246	3.001
ITAE	2.05	0.04	0.964	3.288	0.231	3
ISE	0.990	0.03	0.465	3.303	0.25	3

4. Results

Consequently, the gains obtained by the objective functions are applied in the PID controller. Subsequently, the step response is obtained for all three functions in the selected intervals and compared with each other. The ***Figures 6-8*** show the step response for ITAE, IAE and ISE objective functions in both intervals.

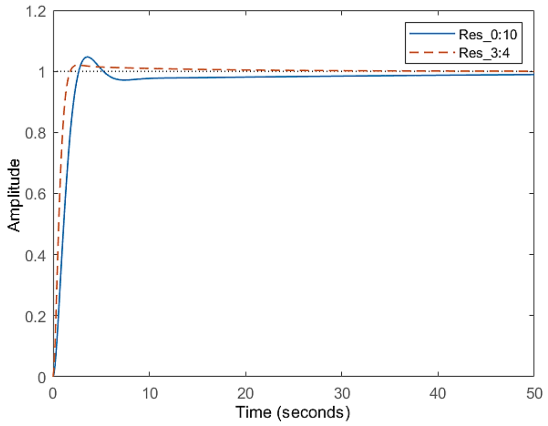


Figure. 6. Step response for PID controller optimized by ITAE

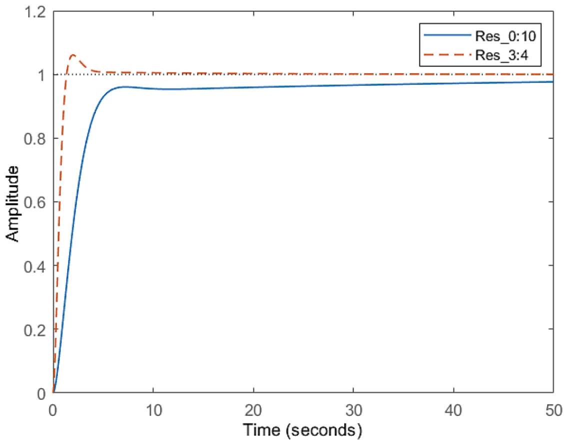


Figure. 7. Step response for PID controller optimized by IAE

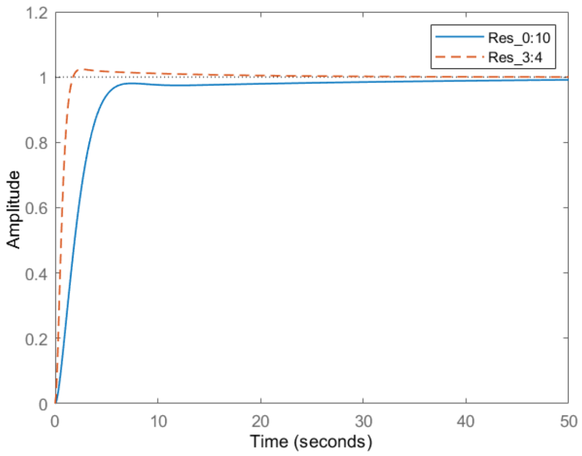


Figure. 8. Step response for PID controller optimized by ISE

The numerical results of different control parameters for each objective function have been obtained and compared with each other which can be seen in ***Table 5***.

Table 5. Numerical results for step response of objective functions

Functions / Parameters	Range [0-10]			Range [3-4]		
	ITAE	IAE	ISE	ITAE	IAE	ISE
Rise Time	1.7712	3.8861	3.7097	1.0305	0.8895	1.0240
Settling Time	16.8953	58.5706	21.0105	2.8652	3.3887	3.7480
Overshoot	4.7160	0	0	2.0521	6.1206	2.3968
Undershoot	0	0	0	0	0	0
Peak	1.0472	0.9966	0.9965	1.0205	1.0612	1.0240
Peak Time	3.5814	155.6383	79.75	2.6008	1.9804	2.6029

By analyzing the results in ***Table 5***, it is evident that controllers with gains ranging from 3 to 4 perform better than those with gains from 0 to 10. Furthermore, a detailed analysis of the 3 to 4 interval reveals that the ITAE objective function achieves lower settling time and overshoot compared to other functions. ***Figure 9*** qualitatively illustrates the superior performance of this objective function.

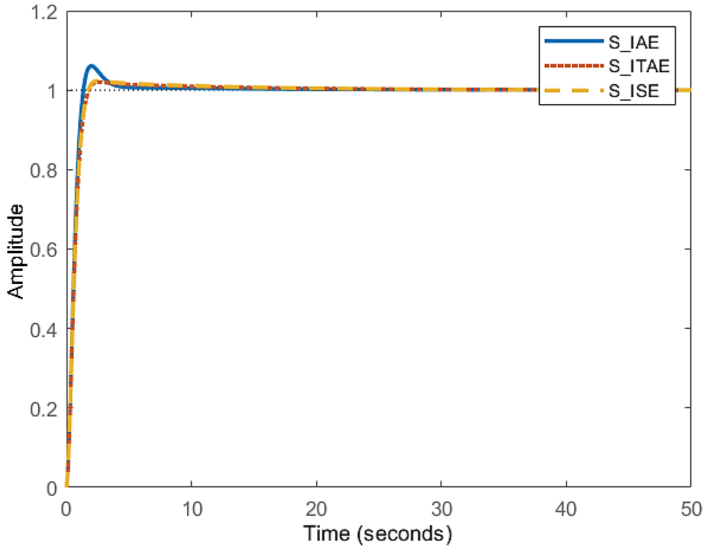


Figure. 9. Step response of PID controllers with different objective functions

According to ***Figure 9*** and ***Table 5***, the controller with the gains adjusted by ITAE objective function is selected as the main PID controller designed with GA.

After selecting the PID controller designed with the GA based on the ITAE objective function as the main controller, this section investigates its performance in comparison to the Fuzzy controller and the PID controller tuned using the Ziegler-Nichols method.

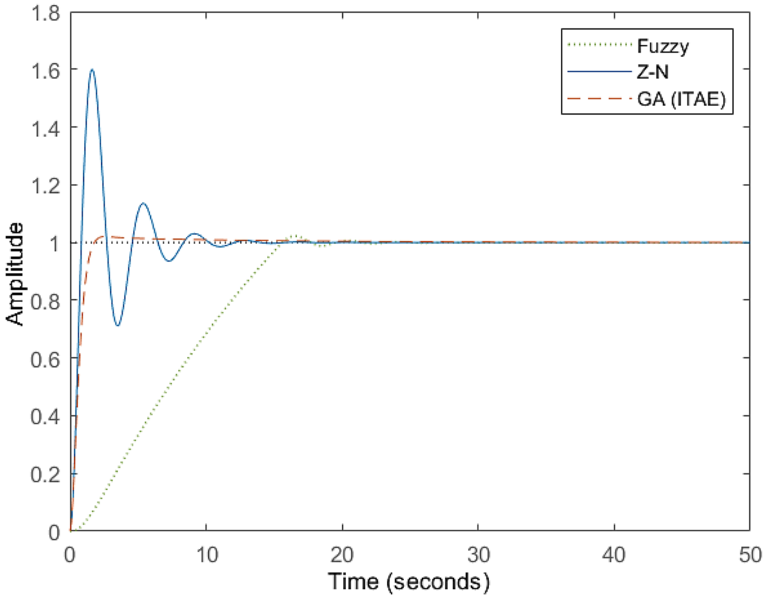


Figure. 10. Step response of system through different controllers

Table 6. Numerical results for step response of objective functions

Function	**Fuzzy**	**Ziegler-Nicholes**	**GA**
Rise Time	11.479	0.5669	0.9394
Settling Time	21.908	9.6617	1.4559
Overshoot	2.577	60.0380	1.1456
Undershoot	1.755	0	0
Peak	1.022	1.6004	1.0115
Peak Time	16.593	1.6126	2.1166

According to ***Table 6***, by analyzing the rise time, settling time, overshoot and undershoot as the most important parameters in transient response, the fuzzy controller exhibits the biggest rise time and settling time among the controllers and also includes an undershoot, which does not appear in other controllers. The GA controller displays better performance in comparison to the Ziegler-Nichols controller by 84% in settling time and 98% in overshoot. Moreover, an analysis of the other parameters indicates that the GA controller demonstrates the best overall performance. Therefore, the results indicate that the PID controller, designed using GA based on the ITAE objective function, surpasses the other controllers in terms of settling time and overshoot.

5. Conclusion

Cruise control systems are an essential feature in modern automobiles, enhancing driving comfort and safety. By automatically regulating a vehicle's speed, these systems allow drivers to maintain a steady pace without continuous manual input on the accelerator pedal. This functionality is particularly beneficial during long-distance highway driving, reducing driver fatigue and contributing to fuel efficiency. In this study, three PID controllers designed by GA through ITAE, IAE and ISE object functions. The results show that the ITAE one has better performance than two others. Additionally, the results of this controller compared with two other controllers designed by fuzzy logic and a PID tuned by Ziegler-Nicholes. According to results the PID controller designed by GA has less settling time and overshoot.

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