Evaluation of MRAC based Adaptive Cruise Control for Semi-Autonomous Vehicle using Virtual Simulation Platform

Vimal Rau Aparow and Henry Siew Sheng Hoong

Department of Electrical and Electronics Engineering, Faculty of Science and Engineering, University of Nottingham Malaysia, Jalan Broga, 43500, Semenyih, Selangor, Malaysia.

Vimal.Rau@nottingham.edu.my

Abstract. Autonomous vehicle is the topic where the automotive industry in the world is emphasizing. It has been a hot topic for the automotive manufacturer in the world in emphasizing Smart City for a safer city in the effort of reducing road accidents due to the mitigation of driver’s error and flaw in computerised auto-pilots. Semi-autonomous vehicles equipped of technologies such as Lane-Keep Assist (LKA), Adaptive Cruise Control (ACC) and Autonomous Emergency Braking (AEB) are among the technological discussion topics in self-driving vehicle. This paper illustrates the technique to accomplish the design of an Adaptive Cruise Controller for passenger vehicle in longitudinal direction. The response of the vehicle model is verified using virtual simulation tool, IPG CarMaker. A design methodology of advance PID controller using Model Reference Adaptive Control (MRAC) based PID technique is designed in this study to compare its performance against a conventional PID controller based on different road surface and various vehicle set speed.

1. Introduction
Adaptive Cruise Control (ACC) is a driver assistance system targeting to increase efficiency, comfort and safety on the road. It consists of distance control technology which is a supplement to the traditional cruise control system [1]. With the ideology was first used in the Chrysler 1958 Imperial, the conventional cruise control is a system that automatically regulates the speed of a road vehicle when the desired velocity is set by the driver [2]. Adaptive Cruise Control enhances the feature of a conventional cruise control system helping in maintaining a velocity set by the driver by having two radar modules which maintain a safe distance with the preceding vehicle and calculates the adjustment of velocity required so that the current referenced vehicle follows the speed of the preceding vehicle when it is detected [3]. This control methodology is accomplished by having a minimum two modes of control, velocity control and distance control. These modes will be useful to control vehicle speed as well as the relative distance with frontal vehicle to avoid any rear-end accidents.
Most of the automotive researchers explore Adaptive Cruise Control strategy using simulation based testing and then direct implementation in actual vehicles for on-road testing [4]. Some other researchers focused their testing procedures using hardware-in-the-loop testing which is focusing on the actuator or ECU hardware controls. These kind of testing does not involve with actual driving scenarios which involves with dynamic obstacles such as targeted vehicle, motorbikes, cyclist or pedestrians. This kind of testing is insufficient and inadequate to optimize the performance of...
autonomous vehicles on highway roads. In order to overcome these drawbacks, an adequate co-simulation is required to evaluate the performance of MRAC PID controller for ACC strategy before deploying the developed control algorithm for semi-autonomous vehicle on highway driving road. This approach will help to further optimize the performance of MRAC to adapt with actual highway driving road network to minimize the road accidents.

This paper is organized as follows: Section one provides an overview of the study. Section 2 discussed about the vehicle model and then section 3 discussed about co-simulation using IPG CarMaker. Next section discussed about the control structure using PID and MRAC PID controller. Fifth section explained about the results using PID and MRAC PID. Section 6 concludes the outcome of this study.

2. Vehicle longitudinal model
The vehicle longitudinal model of a passenger vehicle consists of a single sprung mass representing the vehicle body. This sprung mass is connected to four unsprung masses representing the wheels at the corners, thus representing as a Nine Degree of Freedom (9-DOF) system as shown in Figure 1[5,6]. Tire vertical behaviour is represented as a linear spring without damping, whereas the lateral and longitudinal behaviours are represented with Pacejka Magic tire model. In order to validate the non-linear vehicle longitudinal model, the model has been tested using various driving profiles. The detailed derivation and the verification results can be referred from Aparow et al., [6].

3. Co-simulation with IPG CarMaker
In this study, simulation tool called IPG CarMaker is used for the co-simulation process with Matlab Simulink as shown in Figure 1. This is mainly because a highway driving scenario is used in IPG CarMaker using the Scenario Editor.

![Figure 1. Simulation architecture using Matlab Simulink and CarMaker](image)

This is mainly to evaluate the performance of the semi-autonomous vehicle performance using Adaptive Cruise Control (ACC) system. Therefore, a sedan vehicle, BMW 5 series was used in this simulation tool as the semi-autonomous vehicle by integrating with radar, camera and lane sensors which are mainly required for highway driving scenario. Figures 2 show the driving scenarios that occurred during the simulation testing using IPG CarMaker. During the driving conditions, a few traffic vehicles such as passenger vehicle and trucks are included to observe the vehicle speed changes during driving. The controller from IPG CarMaker is replaced with MRAC PID controller to evaluate different driving speed profile using dry and wet surfaces. The detail configuration of CarMaker for virtual testing can be referred to Aparow et al., [7].

4. Adaptive cruise control using PID controller
In order to further verify the results and performance of the developed PID controller, various set-point is tested, ranging from 70km/h to 120km/h which is the range of speed where a conventional passenger vehicle commonly travelling on the highway. Table 1 shows the performance spectrum of the PID controller designed in terms of rising-time, settling-time, maximum overshoot and steady-state error on dry surfaces. Based on the results in Table 1, it shows that as the desired velocity of the vehicle increases, the rising-time and settling-time of the step responses increase; nevertheless, the gap between rising-time and settling-time started to reduce as speed increases. This is because as speed
increases, the maximum overshoots of the responses reduce, and hence when there is a lesser overshoot, the controller settles faster.

![Figure 2(a) and 2(b). Highway driving scenario in IPG CarMaker using BMW 5 Series](image)

Table 2 shows the performance of the PID controller designed acting on the vehicle velocity on wet surfaces. By comparing the results in Table 1 and 2, it can be observed that under wet condition, the controller is not having a linear trend as the desired velocity increases, resulting in a non-linear increase in rising and settling time. Nevertheless, the maximum overshoot is lower than compare with the vehicle travelling on dry surfaces, but returning a fluctuated steady-state error trend as velocity increases. This is because the PID controller is trying to deal with the wheel spin on wet surfaces while at the same time trying to regulate the desired velocity. It shows that the controller is able to settle to the desired velocity set by the user quickly, with rewarding a low percentage of maximum overshoot, either in dry or wet condition. In order to further enhance the performance of the PID on various surface condition, Model Reference Adaptive Control (MRAC) PID is explored in this study.

**Table 1.** PID controller response designed for ACC on dry surfaces

| Desired Vehicle Velocity, V (km/h) | Rising-Time, t_r (s) | Settling-Time, t_s (s) | Maximum Overshoot (%) | Steady-state Values (km/h) | Steady-state Error (%) |
|------------------------------------|----------------------|------------------------|-----------------------|---------------------------|------------------------|
| 70                                 | 3.360                | 3.660                  | 5.241                 | 70.030                    | 0.043                  |
| 80                                 | 3.941                | 4.231                  | 4.379                 | 80.035                    | 0.044                  |
| 90                                 | 4.549                | 4.840                  | 3.749                 | 90.035                    | 0.039                  |
| 100                                | 5.187                | 5.470                  | 3.248                 | 100.050                   | 0.050                  |
| 110                                | 5.862                | 6.150                  | 2.725                 | 110.100                   | 0.091                  |
| 120                                | 6.571                | 6.850                  | 2.415                 | 120.100                   | 0.083                  |

**Table 2.** PID controller response designed for ACC on wet surfaces

| Desired Vehicle Velocity, V (km/h) | Rising-Time, t_r (s) | Settling-Time, t_s (s) | Maximum Overshoot (%) | Steady-state Values (km/h) | Steady-state Error (%) |
|------------------------------------|----------------------|------------------------|-----------------------|---------------------------|------------------------|
| 70                                 | 4.766                | 5.080                  | 3.692                 | 70.025                    | 0.036                  |
| 80                                 | 5.644                | 5.972                  | 3.024                 | 80.040                    | 0.050                  |
| 90                                 | 6.674                | 6.940                  | 2.581                 | 90.065                    | 0.072                  |
| 100                                | 7.673                | 7.990                  | 2.098                 | 100.100                   | 0.100                  |
| 110                                | 8.831                | 9.069                  | 1.726                 | 110.100                   | 0.091                  |
| 120                                | 10.120               | 10.370                 | 1.499                 | 120.100                   | 0.083                  |

5. Adaptive cruise control using model reference adaptive control based PID controller

MRAC PID controller consists of two loops, inner loop composed of a feedback loop from the feedforward controller and the plant and external loop which is an adjustment mechanism loop as shown in Figure 8. The external loop adjusts the controller parameters which is K_p, K_i and K_d in such a way that the error is the difference between the process output, y_p and the reference model output, y_m, being reduced to zero. An adaptive mechanism is needed to tune the PID parameters to make overall system behaves as the reference model. Therefore, a model reference adaptive control (MRAC) using MIT
rule is used as an adaptive mechanism for PID controller. The adaptive PID controller parameters are adjusted to give desired closed-loop performance for ACC model. According to Figure 3, the MRAC PID controller consists of four parts, a plant model, a PID controller, a reference model and an adjustment mechanism. The plant consists of the known structure of a vehicle model [8]. The reference model is present to give an ideal response of the adaptive control system to the reference input. An adaptive controller is typically dictated by a number of adjustment parameters, consisting of different sets of control parameter values in deciding the achievability of the control tasks. In terms of adjustable parameters, the control law is usually linear. There is only one control parameter, $\theta$ in MRAC PID design, where the $\theta$ value is dependent on adaptation gain. The adjustment mechanism tunes the parameters in the control law where adaptation law is applied to manipulate the gain in the controller so that the plant will respond in accordance to the reference model. It is designed to acquire the stability of the control system and reducing tracking error to zero. Also, from Figure 9, $y_m(t)$ is the output of the reference model and $y_p(t)$ is the output of the actual plant, and the difference between them is denoted by $e(t)$ which is the tracking error where

$$e(t) = y_p(t) - y_m(t)$$ (1)

MIT Rule denotes that a cost function is defined as

$$J(\theta) = \frac{1}{2} e^2(\theta)$$ (2)

![Figure 3. Adaptive PID using MIT Rule](image_url)

where $e(\theta)$ is the error as a function of $\theta$ between the outputs of the plant and the reference model and $\theta$ is the adjustable parameter mentioned earlier where it is adjusted to minimize the cost function to zero, and with that reason, the rate of change of $\theta$ is proportional to the negative gradient of $J$ [8], giving

$$\frac{d\theta}{dt} = -\gamma \frac{\partial J}{\partial \theta} = -\gamma e \frac{\partial e}{\partial \theta}$$ (3)

where the partial derivative term $\frac{\partial e}{\partial \theta}$ is known as the sensitivity derivative of the system, indicating the changing of error with respect to $\theta$. The parameter $\gamma$ is denoted as the adaptation gain. Based on Figure 3, it shows that the final approximation of the vehicle model using second-order open-loop transfer gives a closer result to the actual vehicle model. The second-order open-loop transfer function approximated vehicle model has a delay in terms of rise time and settling time, but this is the best approximated that has been tested for the vehicle model. Based on the estimated transfer function, the control structure with the updating mechanism for MRAC PID controller design can then be developed. Based on Figure 4, the closed-loop transfer function of the second-order system with a conventional PID design gives
and from Equation (4), a reference model transfer function is obtained as follow:

\[
\frac{y_r(s)}{u_c(s)} = \frac{b(K_ds^2 + K_p s + K_i)}{s^3 + (a_1 + bK_d)s^2 + (a_2 + bK_p)s + bK_i}
\]

where \(b_{m_1} = bK_d, b_{m_2} = bK_p, b_{m_3} = bK_i, a_{m_1} = a_1 + bK_d, a_{m_2} = a_2 + bK_p, a_{m_3} = bK_i\).

As the actual vehicle model is the main interest of this study, the performance of MRAC PID controller is further evaluated using the actual vehicle model in IPG CarMaker. By comparing between Table 3 with Table 1, it shows that the improvement in terms of rising-time, settling-time, maximum overshoot and steady-state error is acceptable when MRAC PID is utilised in controlling the vehicle velocity than compared with conventional PID. As the speed increases over 120 km/h, the MRAC PID controller illustrates a much stable reading and less fluctuation. Therefore, MRAC PID controller has an advantage if a more precise controlling algorithm in ACC design is required. To further justify that MRAC PID controller has adaptive capability is wet condition, its performance on wet surface is evaluated. By comparing Table 4 with Table 2, the performance improvement is gradually increased when MRAC PID is utilised in regulating the vehicle velocity than compared with conventional PID. Also, by varying the adjustment parameters, \(y_r, y_i, y_d\), the performance of the MRAC PID is evaluated with using vehicle speed range from 70 km/h to 120 km/h on dry surface to see if there is any improvement. Based on the response from Figure 5, it can be observed that MRAC PID although has advantages in correcting very small steady-state value, the effect is significant and able to provide improvement performance in terms of rising-time, settling-time, maximum overshoot and steady-state error over the conventional PID in regulating the vehicle velocity either in dry or wet surfaces. The adaptation mechanism helps the controller to adapt with different driving road profile of the vehicle which helps to improve up to 21% during sudden change of speed profile.

### Table 3. MRAC PID controller in regulating the vehicle velocity on dry surface.

| Desired Vehicle Velocity, \(V(km/h)\) | Rising-Time, \(t_r(s)\) | Settling-Time, \(t_s(s)\) | Maximum Overshoot (%) | Steady-state Values \(U_{steady}(km/h)\) | Steady-state Error (%) |
|--------------------------------------|--------------------------|--------------------------|------------------------|--------------------------------------|------------------------|
| 70                                   | 3.360                    | 3.660                    | 5.241                  | 70.030                              | 0.043                  |
| 80                                   | 3.941                    | 4.230                    | 4.379                  | 80.035                              | 0.044                  |
| 90                                   | 4.572                    | 4.840                    | 3.732                  | 90.040                              | 0.044                  |
| 100                                  | 5.187                    | 5.470                    | 3.248                  | 100.050                             | 0.050                  |
| 110                                  | 5.859                    | 6.150                    | 2.772                  | 110.050                             | 0.045                  |
| 120                                  | 6.571                    | 6.850                    | 2.415                  | 120.100                             | 0.083                  |

### Table 4. MRAC PID controller in regulating the vehicle velocity on wet surface.

| Desired Vehicle Velocity, \(V(km/h)\) | Rising-Time, \(t_r(s)\) | Settling-Time, \(t_s(s)\) | Maximum Overshoot (%) | Steady-state Values \(U_{steady}(km/h)\) | Steady-state Error (%) |
|--------------------------------------|--------------------------|--------------------------|------------------------|--------------------------------------|------------------------|
| 70                                   | 4.747                    | 5.081                    | 3.692                  | 70.025                              | 0.036                  |
| 80                                   | 5.644                    | 5.971                    | 3.204                  | 80.040                              | 0.050                  |
| 90                                   | 6.615                    | 6.942                    | 2.570                  | 90.065                              | 0.072                  |
| 100                                  | 7.673                    | 7.990                    | 2.098                  | 100.100                             | 0.100                  |
| 110                                  | 8.832                    | 9.070                    | 1.726                  | 110.100                             | 0.091                  |
| 120                                  | 10.120                   | 10.370                   | 1.499                  | 120.100                             | 0.083                  |
6. Conclusion
From the results above, it can be concluded that using MRAC PID control able to improve the vehicle speed profile while driving on the highway scenario. It can be observed that the MRAC PID able to adapt with different road surfaces without effecting the longitudinal speed which was tested from 70km/h to 120 km/h. Besides, MRAC PID has been implemented and tested using virtual testing simulation, IPG CarMaker and the controller can be used in different road profile and vehicle speed.

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