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Optimal Design of an Adaptive Cruise Control System for Driving Comfort and Fuel Economy

M. Z. Che Mustafar[*1,2], S. A. Abu Bakar[1], Z. Zainuddin[2], M. S. F. Mansor[2], N. H. F. Ismail[2] and M. R. Rani[2]

[1]School of Mechanical Eng., Faculty of Engineering, Universiti Teknologi Malaysia, 81310 Skudai, Johor, Malaysia
[2]Perusahaan Otomobil Nasional Sdn. Bhd., 40400 Shah Alam, Selangor, Malaysia

[*]*Corresponding author: m.zulfadzli@graduate.utm.my*

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Abstract – *Adaptive Cruise Control (ACC) is introduced to allow the subject vehicle to follow a target vehicle at a pre-selected time gap, up to a driver-selected velocity by controlling the engine and/or service brakes as defined in SAE J2399. A typical ACC ensures passenger comfort by minimizing the subject vehicle's rate of acceleration and deceleration when following a target vehicle. However, if the ACC rate of velocity change is too slow, the subject vehicle might not be able to follow the target vehicle at the set time-gap. On the other hand, if the ACC responds too quickly to the changes in the target vehicle velocity, it might cause passenger discomfort and reduce energy efficiency due to the high rate of acceleration and deceleration. Thus, a research gap in ACC is identified, and this paper seeks to investigate an optimal ACC for driving comfort and fuel economy. This paper models the performance of a passenger vehicle with ACC using feedback control in Matlab Simulink. Three types of ACC control systems are simulated and compared; proportional-integral (PI) control, fuzzy logic control (FLC), and Linear-Quadratic Regulator (LQR). The performance of the control systems is simulated using set test scenarios, and an optimal ACC design is selected based on minimum acceleration, deceleration, and jerk performance, as defined in ISO 15622, following performance and minimum fuel consumption. Results show that the LQR controller has the best performance in meeting the ISO 15622, the lowest target vehicle the following root mean square error (RMSE), and the second-lowest New European Drive Cycle (NEDC) urban cycle fuel consumption.*

Keywords: Adaptive Cruise Control (ACC), proportional-integral control, fuzzy logic control, linear quadratic regulator

1.0 INTRODUCTION

Advanced Driver Assistance System (ADAS) and active safety features are the main areas of research in the automotive industry in recent years. One of the earliest driver-assist features introduced in vehicles is the Conventional Cruise Control (CCC) system, which is a vehicle control system that is able to control the velocity of a subject vehicle as selected by the driver without consideration of in-path forward vehicle as defined in SAE J2399 (SAE International, 2014). This limitation forces the driver to constantly manually intervene when there is an object in front of the vehicle. With the recent development of object detection sensors such as radar, stereo camera, and lidar technologies, various vehicle technologies with different autonomy levels as defined in SAE J3016 (SAE International, 2016), such as Adaptive Cruise Control (ACC) are developed. ACC is introduced as an enhancement to CCC that allows the ACC-equipped vehicle to follow a forward vehicle at a pre-selected time gap, up to a driver-selected velocity by controlling the engine and/or service brakes as defined in SAE J2399 (SAE International, 2014).

According to ISO 15622 (ISO, 2018), during ACC active state, the system shall be in either ACC velocity control mode or ACC following control mode. ACC speed control mode is when the subject vehicle is cruising at set velocity, and ACC following control mode is when the subject vehicle is following the leading vehicle at a pre-selected time gap. During the ACC active state, the subject vehicle velocity is controlled by the ACC controller's vehicle torque management. The ACC controller produces positive torque via engine torque request to the Engine Management System (EMS) and produces negative torque via brake pressure request to the Brake Control Unit (BCU).

Shakouri et al. (2012) chose to gain a scheduling-PI controller to meet the requirement of the ACC system. In this concept, the PI controller parameters change in accordance with the condition in which the system operates by applying a gain scheduling technique. The criteria for switching between each operating points are based on the current speed of the vehicle. These operating points are introduced by the normalized variation of the throttle opening position varying from 0 to 1 with an interval of 0.1 and tested using three different scenarios: velocity tracking mode, distance tracking mode, and switching mode.

Pananurak et al. (2009) used FLC for ACC, or intelligent vehicle control, whilst (Panse et al., 2015, Pananurak et al., 2009) adopted FLC for controlling ACC parameters using two inputs and two output variables fuzzy structure. The inputs are error between current and desired vehicle speed and rate of change in error with respect to time. The outputs are vehicle throttle and brake and tested using for speed and error response. The performance comparison was made using a mean square error (MSE).

Changwoo et al. (2015) used LQR as the control algorithm using two inputs and one output. The two inputs are different between the desired and actual relative distance and the relative velocity between the subject and the target vehicle. The output on the LQR controller is the target acceleration of the subject vehicle. The effectiveness of the algorithm is simulated based on fuel consumption evaluated on the FTP-75 driving cycle.

Other researches include the works of Shakouri et al. (2012), which used balance based adaptive control technique, Kanjee et al. (2013) used a vision-based algorithm to determine the gap in implementing features, Ganji et al. (2014) used sliding mode control for ACC, Lee et al. (2013) implement Cooperative Adaptive Cruise Control (CACC) for the autonomous vehicle application and Chen et al. (2019) studied an automobile intelligent cruise system based on fuzzy control adopting hierarchical structure.

In summary, various research has been conducted to develop the ACC algorithm and methods in which to validate the effectiveness of the algorithms. However, there is little research on the evaluation of ACC algorithms optimized for comfort and fuel economy. Thus, this paper shall seek to investigate three types of ACC controllers; Proportional-Integral (PI) controller, Fuzzy Logic Controller (FLC), and Linear-Quadratic Regulator (LQR) controller and seek to suggest an optimal ACC algorithm to meet minimum acceleration, deceleration, jerk performance (as defined in ISO 15622), following performance and minimum fuel consumption as evaluated on the New European Drive Cycle (NEDC) urban cycle using Matlab Simulink.

2.0 CONTROL ALGORITHM

Figure 1 depicts the ACC system block diagram used in the modeling and vehicle simulation. The ACC controller consists of two modules; ACC speed control and ACC following control. This paper focusses on the ACC following algorithm development in the ACC following module. The ACC speed algorithm uses a PI control based on priori information.

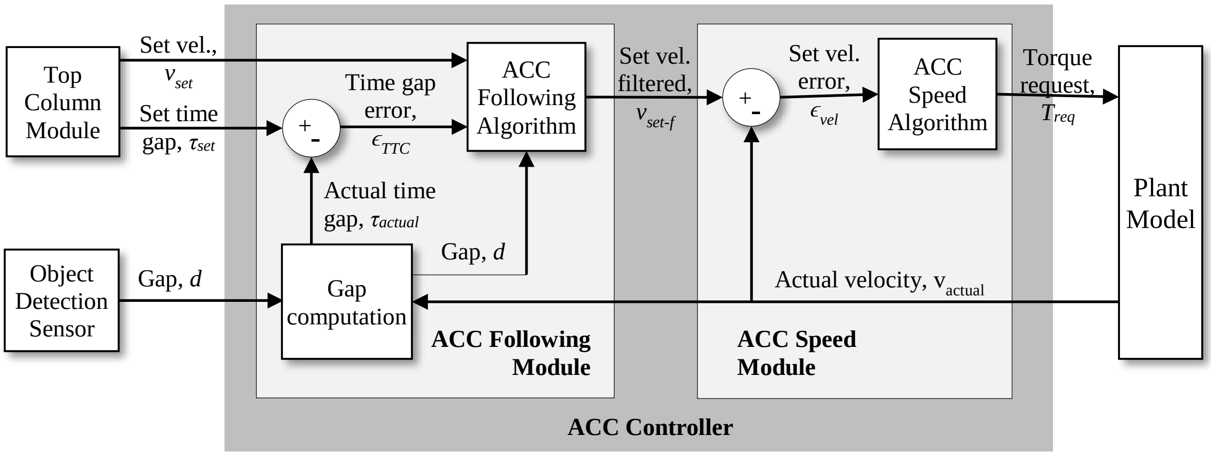

Figure 1: ACC system block diagram

2.1 Plant Model

The plant model consists of a passenger vehicle, i.e., subject vehicle containing models on vehicle dynamics, engine torque curve, engine brake specific fuel consumption (BSFC) curve, gearshift schedule, accelerator pedal map, and brake model.

The drag force against vehicle velocity is measured using the coast down method. The drag force F_d acting on the vehicle is modeled using the equation obtained from the 2nd order polynomial curve fitting method from the coast down data, as shown in (1).

$$F_d = 0.0558v^2 - 0.5061v + 218.16 \quad (1)$$

The input torque request, T_{req} to the plant model from ACC controller is split; positive torque request to the engine and negative torque request to the brake. The tractive force F_{tract} acting on the vehicle is computed from engine torque, transmission gear ratio, and tire radius. The braking force F_{brake} acting on the vehicle is computed from the brake pad coefficient of friction, brake pressure, brake pad radius, brake actuator bore diameter, number of disc pads, hydraulic lag, and tyre radius.

The subject vehicle actual velocity is computed from drag, tractive and brake forces acting on the subject vehicle with mass, $m = 1{,}775kg$ as shown in (2).

$$v_{act} = \int \frac{F_{tract} - F_d - F_{brake}}{m} \quad (2)$$

2.2 ACC Controller

The object detection sensor feedbacks gap, d between subject and lead vehicle. This information is utilized to compute the time-to-collision (TTC) or time gap, which is the time duration before the subject vehicle reaches the target vehicle. The time gap input from the driver is taken from the top column module. In real world application, time gap setting options will usually have three values; where at least one value will be in the range of 1.5 to 2.2 seconds and a minimum value of 0.8 seconds as defined in ISO15622. This paper sets the TTC or time gap, τ equals to 2 seconds. Set vehicle velocity is also taken from the top column module to determine the cruising velocity target of the subject vehicle.

2.2 ACC Following Proportional-Integral (PI) Control

A PI controller is used to produce filtered reference vehicle velocity, v_{set-f} as summarized in (3) to control the subject vehicle to meet the desired time gap setting. The output is computed from the products of proportional gain, k_p and integral gain, k_i with the error, ε_{TTC} and integral of the error respectively which is the difference between actual and desired time gaps.

$$v_{set-f} = k_p \varepsilon_{TTC} + k_i \int \varepsilon_{TTC} \quad (3)$$

2.3 ACC Following Fuzzy Logic (FL) Control

A fuzzy logic controller is also modelled and evaluated to produce filtered reference vehicle velocity to control the subject vehicle to meet the desired time gap setting. The fuzzy structure is designed based on two inputs and one output variable. The first input is the error between actual and desired time gaps, ε_{TTC} and the second input is the gap. Based on these two inputs, the output on the reduction of set velocity is computed. Two membership functions (MF) are produced for the TTC error fuzzy interference system (FIS); high TTC error and low TTC error. Two MFs are also produced for gap FIS; near and far. For output computation, two MFs are produced for deceleration FIS; partial and full deceleration. Four fuzzy rules are formulated in Table 1 and the surface viewer for the fuzzy logic controller is shown in Figure 2.

Table 1: ACC following fuzzy logic rules

Rule	Description
1	If TTC error is low and gap is near then deceleration is full braking
2	If TTC error is low and gap is far then deceleration is partial braking
3	If TTC error is high and gap is near then deceleration is full braking
4	If TTC error is high and gap is far then deceleration is full braking

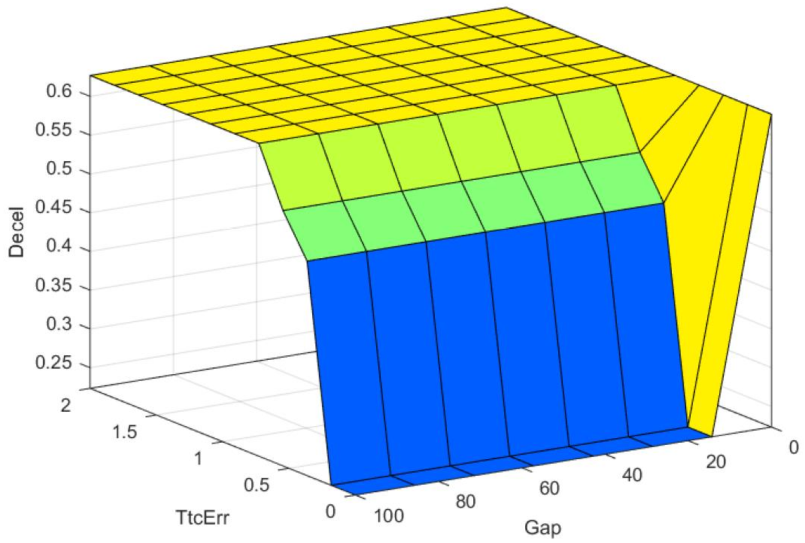

Figure 2: ACC following fuzzy logic control surface viewer

2.4 ACC Following Linear Quadratic Regulator (LQR) Control

A third controller is also modelled and evaluated to produce the desired subject vehicle acceleration, a_{set} which is then computed to produce filtered reference vehicle velocity for the ACC speed control. This subject vehicle target acceleration is the system input, u . The goal of this algorithm is to optimize comfort and fuel economy whilst maintaining safety. If the subject vehicle reacts quickly i.e. a high degree of acceleration or deceleration, it can minimize potential frontal collision with the lead vehicle and increase safety. However, harsh braking and acceleration will reduce comfort and fuel economy.

To solve this problem the LQR controller is modelled based on one system output; the error between actual and desired gaps, ε_d which is computed from the subject vehicle velocity and time gap setting. The state equation of the system can be written as shown in (4) and (5) where x is the state matrix.

$$\dot{x} = Ax + Bu = [0]x + [1]u \quad (4)$$

$$x^T = [x_1] = [d_{set} - d_{actual}] \quad (5)$$

The goal of the LQR controller is to minimize the cost function of the state equation as shown in (6) with weighting matrices Q and R in (7) below.

$$J = \int_0^\infty \left(x^T Qx + u^T Ru \right) dt \tag{6}$$

$$Q = [p_1], R = [r] \tag{7}$$

A feedback control $u = -Kx$ is formulated to minimize the cost function where K is the gain matrix given by equation (8) and P is found by using Lyapunov's second method and solving the continuous-time algebraic Riccati equation in (9).

$$K = R^{-1} B^T P \tag{8}$$

$$A^T P + PA - PBR^{-1} B^T P + Q = 0 \tag{9}$$

The finalized feedback control for the desired subject vehicle acceleration with LQR gain k_1 is shown in (10).

$$a_{set} = -Kx = -k_1 \left(d_{set} - d_{target} \right) \tag{8}$$

3.0 RESULTS AND DISCUSSION

The ACC system was simulated using the PI, fuzzy logic and LQR controllers described in section 2. The validation scenario of the system was based on how well the subject vehicle follows the lead vehicle when driven using the NEDC urban cycle.

Table 2 below summarizes the performance of each control system in meeting the minimum acceleration, deceleration, and jerk performance as defined in ISO 15622. From the result, all the controllers are able to meet the desired target specifications with the LQR controller having the best performance result.

Table 2: ACC PI, fuzzy logic and LQR controllers comparison in meeting subject vehicle acceleration, deceleration and jerk performance based on ISO 15622

Parameter	Target	PI	FL	LQR
Acceleration [ms^{-2}]	≤ 2.0	1.69	1.85	0.99
Deceleration (average over 2s) [ms^{-2}]	≤ 3.5	1.05	1.24	0.99
Negative jerk (average over 1 s) [ms^{-3}]	≤ 2.5	0.164	0.287	0.143

Table 3 below summarizes the performance of each control system in following the lead vehicle using the root mean square error (RMSE) method. Figure 3 shows the vehicle velocity NEDC urban profiles for all three control systems and lead vehicle reference. From the result, the LQR controller has the best following performance result.

Table 3: ACC PI, fuzzy logic, and LQR controllers lead vehicle following performance comparison based on RMSE evaluation

Parameter	PI	FL	LQR
RMSE	0.803	0.819	0.248

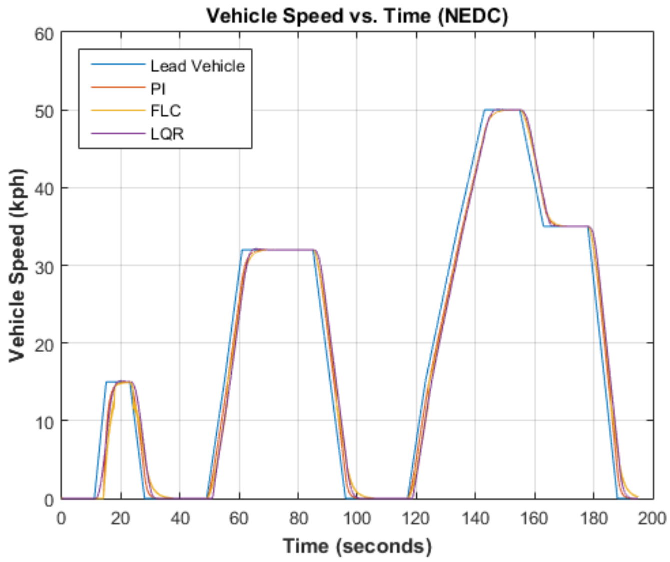

Figure 3: ACC PI, fuzzy logic, and LQR controllers subject vehicle and lead vehicle NEDC velocity profiles

Table 4 summarizes the fuel consumption performance for each control system when the subject vehicle follows a lead vehicle travelling with an NEDC urban cycle velocity-time profile. FL controller has the highest fuel consumption due to higher acceleration and deceleration events over the cycle in keeping the time-gap with the lead vehicle. PI and FL have lower fuel consumption due to a smoother response in following the lead vehicle. Figure 4 below shows a sample of the BSFC engine operating points for the LQR controller which is distributed in the regions below 60Nm and 4,000rpm. From the result, the PI and LQR controllers have the best fuel consumption result.

Table 4: ACC PI, fuzzy logic and LQR controllers NEDC urban cycle fuel consumption comparison

Parameter	PI	FL	LQR
Fuel consumption (L/100km)	10.3	10.9	10.4

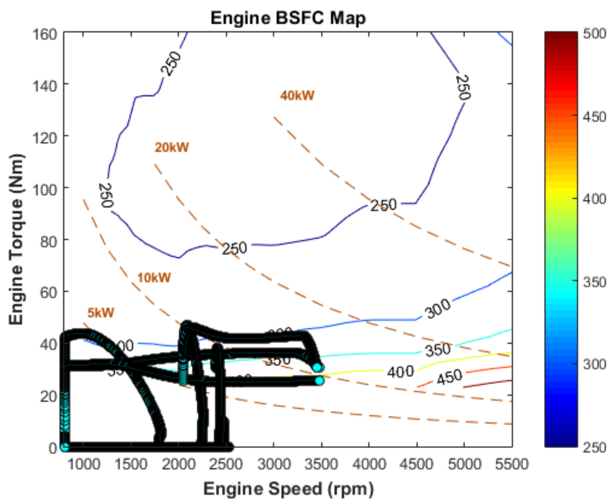

Figure 4: LQR controller BSFC engine operating points

4.0 CONCLUSION

Advance Driver Assistance System (ADAS) technologies such as the Adaptive Cruise Control (ACC) adoption in passenger vehicles is growing in recent years. Therefore, establishing an optimal ACC system for comfort and fuel economy is critical. In this paper, the ACC LQR controller is the best compared to PI and FLC controllers when evaluated in meeting the minimum acceleration of $2ms^{-2}$, minimum deceleration of $3.5ms^{-2}$ (average over 2s), and minimum negative jerk of $2.5ms^{-3}$ (average over 1s) as defined in ISO 15622. Apart from that, LQR is also the best in ACC lead vehicle following performance when evaluated using the Urban New European Drive Cycle (NEDC) urban cycle with a root mean square error (RMSE) of 0.248. For NEDC urban cycle fuel consumption, PI is the best controller with a fuel consumption performance of 10.3L/100km followed by LQR with 10.4L/100km. However, other controllers e.g. Sliding Mode Control (SMC) and neural network shall be used in the future for evaluation. Controller hardware shall also be developed to be evaluated in an actual subject vehicle to ensure the correlation between model-based simulation and actual vehicle performances.

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