Comparative Study of Anti-windup Techniques on Performance of Adaptive Cruise Control

Ankur Jain and Prangshu Saikia

Abstract Over recent years, a steep rise in the number of auto mobiles has been recorded on the limited capacity roads. As a result, this led to investments in the fields of accident minimisation research in vehicles and the development of newer models of auto mobiles with enhanced safety features. Advanced techniques such as adaptive cruise control (ACC), collision avoidance and collision warning system (CWS) are some of the fruitful outcomes that have proved their effectiveness in the prevention of hazards from time to time. In this paper, we will do a comparative study of two anti-windup strategies (back calculation, conditional integration) in a PID speed controller. These techniques are used to mitigate the undesired phenomenon known as integrator windup whenever the control input leads to events that saturate the actuator limits. A nonlinear vehicular dynamic model is linearised at the desired speed set-point, and the effect of these anti-windup schemes on cruise control of the vehicular model is compared. The proposed procedure can also be extended for different set-point and environment condition for an advanced method such as gain scheduling. These techniques can be incorporated in the existing controller with minute changes in software architecture. We will evaluate these schemes based on steady-state error analysis through simulation.

Keywords Adaptive cruise control (ACC) · Integrator effects · Actuator constraints · Conditional integration · Back-calculation

1 Introduction

Existing cruise control system (CC) for highway speed regulation can be attained by adapting the velocity of preceding vehicles. A vehicle equipped with adaptive cruise control (ACC) is able to adapt to an optimum velocity with respect to the way in which the vehicle in front of it behaves. The system accomplishes this feat by

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producing the optimal power through the application of brakes, thereby modulating the throttle. It has the potential to prevent numerous highway accidents caused by careless drivers. Survey report shows that the ACC system is capable of preventing 40% of accidents according to the scenario. In this context, PID-type controllers are amongst the most commonly used controllers aiding in the regulation of cruise speed in vehicles by driving its component DC motors or engines. Its model-free nature provides the robustness against the unmodelled dynamics of the road inclination and wind gust. However, if these disturbances exceed the bounds of controller dynamics due to large error changes, its output shoots up and goes beyond the actuator operating region. It causes the actuator saturation which results in long settling time and large overshoot control system (CC) [1]. This phenomenon is termed as integrator windup. This effect could lead to numerous casualties as it may lead to violation of safe inter-vehicle distance. This is quite troublesome in the case of ACC as timing is the most crucial factor; even a fraction of a second is detrimental between life and death on the road. In order to prevent this, researchers proposed various anti-windup techniques which are worth mentioning.

We can classify the algorithms proposed by the various researches as error recalculation [2], limited integration [3], back calculation [4] and conditional integration [5]. The brief introduction of these techniques is described as follows. Error recalculation anti-windup technique proposed in 1986. In order to sustain a consistent relation between the real value applied in process and calculated control signal, the technique involves the recalculation of the error. In conditional integration technique, the integral part of the controller is made to frequently switch modes as and according to the situation, it seizes to work when saturation occurs and again starts working when saturation subsides. The improved version of the above technique is incremental algorithm. Due to the ease of its application in digital controllers, it has become an industry favourite. Additionally, this technique is quite advantageous as error signal does not need any integration when control signal violates the saturation limits, and bump-less response can be achieved while switching between manual and auto modes. Peng at. al. also designed an anti-windup scheme for bump-less transfer in [6]. Fertik and Ross (1967) suggested a back calculation strategy [7], which is still common in the industries due to its good performance. They introduced an additional feedback signal to the integrator data,and this input is the error produced by integrating the controller output signal and compounded plant input signal with a constant gain, which is the variable of monitoring time [8]. Several studies have taken it as an objective to fine-tune this gain for optimal response. In Hansson, an approach for back calculation proposes an idea of updating the integral term for only some specific conditions. Anti-windup strategies have also emerged as presented in [1, 9] with a unification of conditional integration and tracking back calculation approaches. More complex algorithms for nonlinear system framework are studied in [10].

The above techniques work on two-step process as firstly the controller parameters are tuned while ignoring the actuator saturation limits, and secondly, an auxiliary scheme is designed to decrease the effects of the actuator constraints. Numerous approaches to counter the problem related to windup are still an active field of research. During designing of the controllers, designers have modelled controllers which explicitly consider the nonlinearities to avoid windup, such as model-based predictive controllers. Some good works on comparative study of anti-windup technique are as follows [2, 9]. In this paper,the effects of anti-windup techniques are observed in situations where the control signal saturates the actuator limits compared to a simple PID controller. Anti-windup is inmplemented and tuned in addition to the designed controller. In this case in ACC, it is used with the PID controller in order to obliterate error that saturates the actuator. Reliability, safety and performance are the basic requirements sought by user of the ACC system. The ACC system can operate in combination of few modes such as velocity control mode, spacing control, stop and go mode and collision avoidance mode. The mode selection can be done using switching algorithm which continuously monitors the events and the surrounding environment. In most of these cases since the primary dependence of the system is on the controller, which is PID in this case, a suitable anti-windup design must be modelled in order to account for the large and sudden high inputs that saturate the actuator limits of the cruise control system. Speed control of the system requires anti-windup measures to control the car velocity, thereby making it a crucial part in collision avoidance.

The rest of the paper organised as follows. We defined problem formulation in Sect. 2. Section 3 describes the methodology used to solve the problem defined. Numerical values of parameters and simulation results are presented in Sect. 4. Section 5 concludes the research study.

2 Problem Formulation

2.1 Modelling of the Plant [11]

We have used the dynamics of the vehicles from [12]. In this paper, we have considered a homogeneous vehicles, i.e. each of the vehicles in the group follows the same dynamics. Suppose, there are j vehicles forming a platoon at a particular time. Mathematically, we can represent for the ith vehicle as (Fig. 1).

$$\dot{x}^i(t) = Ax^i(t) + Bu^i(t) \tag{1}$$

$$y^i(t) = Cx^i(t) \tag{2}$$

where $x^i(t)$, $y^i(t)$ and $u^i(t) \in R^m$ are the state vector, output vector and input vectors, respectively. A, B, C are the appropriate dimensional constant matrices. The detail derivation is described in Sect. 5. Here, the velocity and position of a vehicle, in global coordinates, are the states of the system, and acceleration is the input of the system. We have assumed that onboard sensor (i.e. radar) provides space error which serves as an output of the system. We did not consider the power-train dynamics of

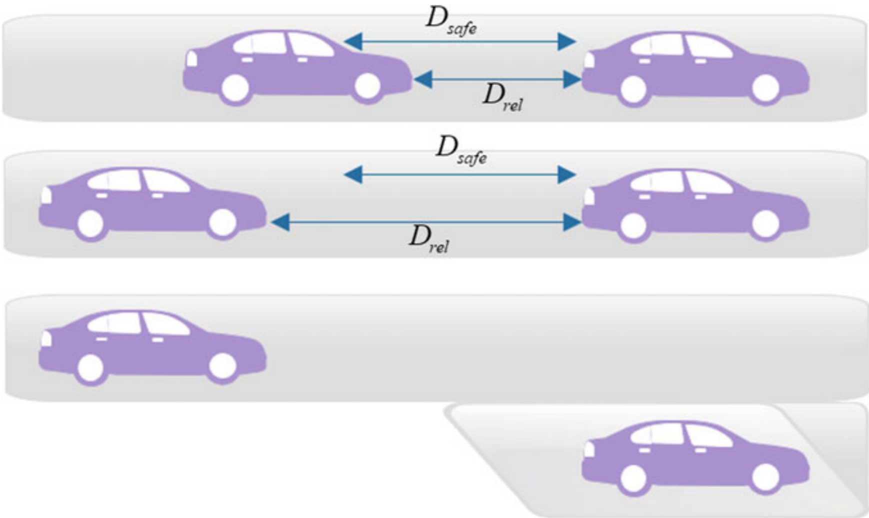

Fig. 1 Real-time scenario of a CACC

a vehicle because our aim is to present an adaptive cruise control feasibility and not the individual vehicle control. So for generalisation, we have assumed that we can control the force which is directly proportional to acceleration. We have approached the problem of regulating a driver's desired velocity while maintaining the required inter-vehicle distance according to the traffic norms. All the vehicles are arranged in a longitudinal manner. We have used predecessor following information topology and velocity-dependent inter-vehicle spacing policy where the safe spacing ($D_{\text{safe},i}$) between ith the vehicle and its predecessor $(i-1)$th is

$$D_{\text{safe},i} = d_i + h_{d,i} * v_i \tag{3}$$

where i is the vehicle index,d_i a constant safe gap, $h_{d,i}$ represents the time to take the ith vehicle to arrive at the same position as its predecessor when $d_i = 0$, and v_i is the vehicle velocity. To preserve the generality, we consider constant safe gap, i.e. $d_i = 0$.

3 Methodology

3.1 Conditional Integration [13]

In this technique, the integrating unit of the PID controller is automatically clamped when the output y reaches the saturation value. It monitors and prevents the increase

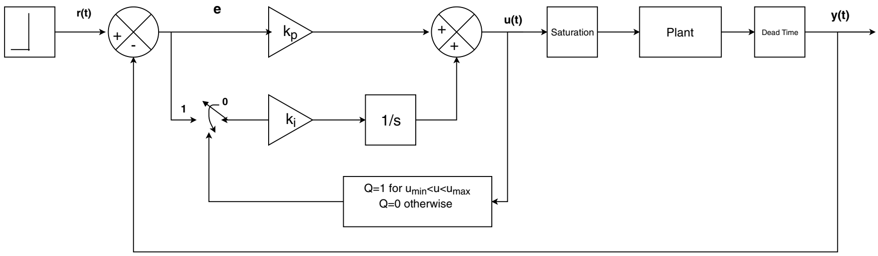

Fig. 2 Conditional integration technique

in the output '*y*' during the conditions of controller saturation. After some time, if the error falls within the limit such that its corresponding output again operates below saturation than the integrator becomes operational again. The PID controller output never infringes the saturation limits in this scheme. The value of stabilisation for integrator output during saturation solely depends on the proportional constant and the input error magnitude. Enhancement in this technique may allow a controller to attain a predetermined value (Fig. 2).

3.2 Back Calculation

This scheme is based on the idea of re-computing the integral to an optimised value to deliver a saturation limit output. It is always better to update the integrator continuously with a constant period instead of immediately resetting this. In this technique, by formulating the error signal (ES) by measuring the difference between the actual actuator output and the controller output, an extra feedback path is formed. With the received ES, a 1/T {t} gain is multiplied which is then transferred to the integrator. In the absence of saturation, this signal is zero. Accordingly, there will be no interference with the normal operation of the actuator when it is unsaturated. However, when saturation occurs, the ES deviates from zero. The typical feedback direction around the system is out of service due to the constant actions of the process data in this situation. Nonetheless, due to the presence of an alternate feedback path around the integral component, the output is required to obtain a value such that the integrator input is zero afterwards (Fig. 3).

4 Results

The performance of these two methods is clearly depicted by the results obtained from the simulations. The results of back calculation are seen to be closely tracking the output during the saturation time, and a minute delay can be observed during the

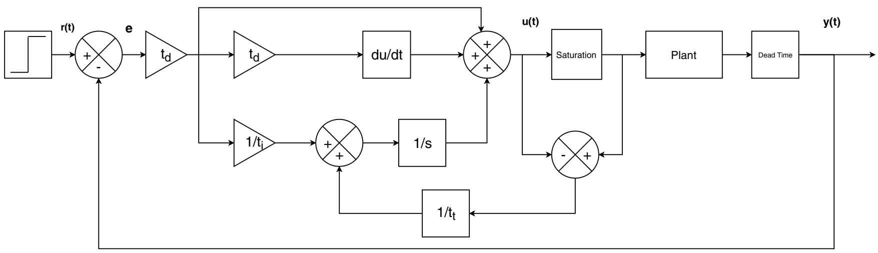

Fig. 3 Back calculation technique

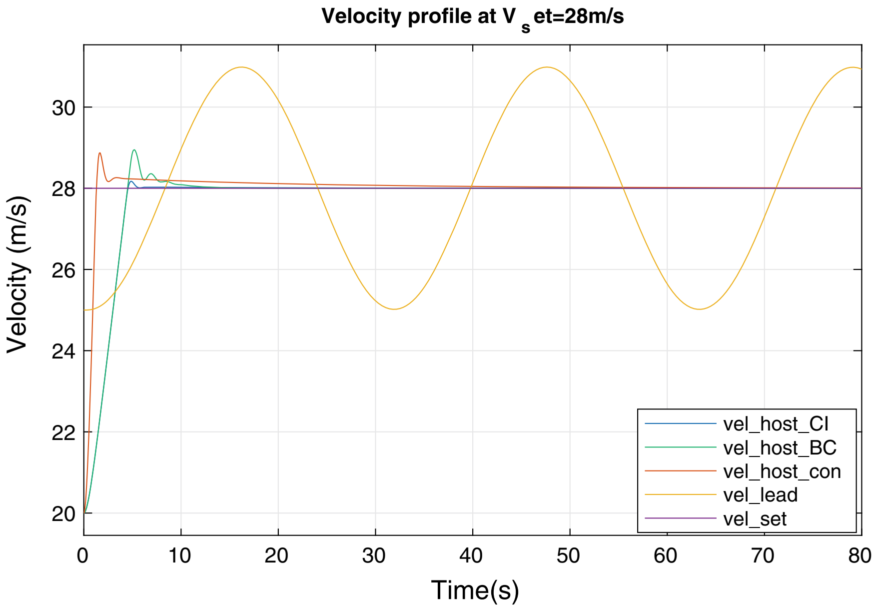

Fig. 4 Velocity profile

step change of the signal, whereas in case of the conditional integration technique, fluctuations are obtained around the step change, and also, the output signal has a minimal error while tracking the reference signal. The model was designed while taking the following parameters for the various schemes proportional gain $\left(K_p\right) = 5$, differential gain $(K_d) = 2.5$, integral gain $(K_i) = 0.5$ and in back calculation tracking constant $(t_t) = 0.3065$.

The obtained results on velocity profile shown in Fig. 4 clearly depict the merits and demerits of various control schemes used. The simple PID controller used for the purpose gives us a response with a rise time of 1.3 s with an overshoot of 3.1% and a settling time of approximately 30 s. The PID controller using back calculation anti-windup technique gives a rise time of 4.5 s and settling time of approximately 13 s with an overshoot of 3.39%. The third scheme, conditional integration gives a

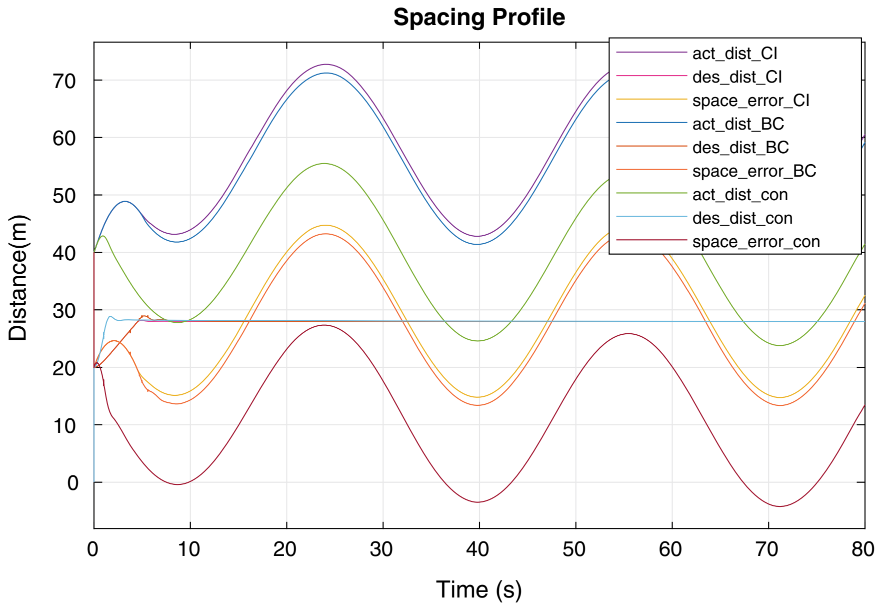

Fig. 5 Spacing profile

rise time of 4.54 s and settling time of approximately 10 s. It gives a lower overshoot 0.64 %. Amongst the controllers, the simple PID has the merit of a fast rise time, but however in other aspects, the conditional integration scheme gives a far superior response compared to other two.

The inference drawn from the spacing profile shown in Fig. 5 gives a clear depiction of the optimal performance of the controllers with anti-windup scheme. In both the conditional integration and back calculation scheme, the actual distance observed is always beyond the desired distance, whereas in the simple PID controller, the actual distance of the vehicle follows the desired distance very closely and even crosses the limits below desired spacing at certain points of time (e.g. between 7.5 and 9.8 s). It was also observed that all of the controllers meet the primary objective as none of these allow any collision at any point of time.

From the acceleration profile shown in Fig. 6, we observe that without any of the schemes, the control input has a sudden spike in the acceleration which reaches beyond actuator saturation limits. The simple PID controller makes the acceleration fluctuate within a range of ± 1 m/s^2 never settling down to zero. The controller with back calculation scheme cuts of the overshoot by limiting it to ± 2 m/s^2, and the response also settles down in 10 s. The conditional integration makes the response even better by reducing the overshoot significantly and attaining the response approximately within 7 s.

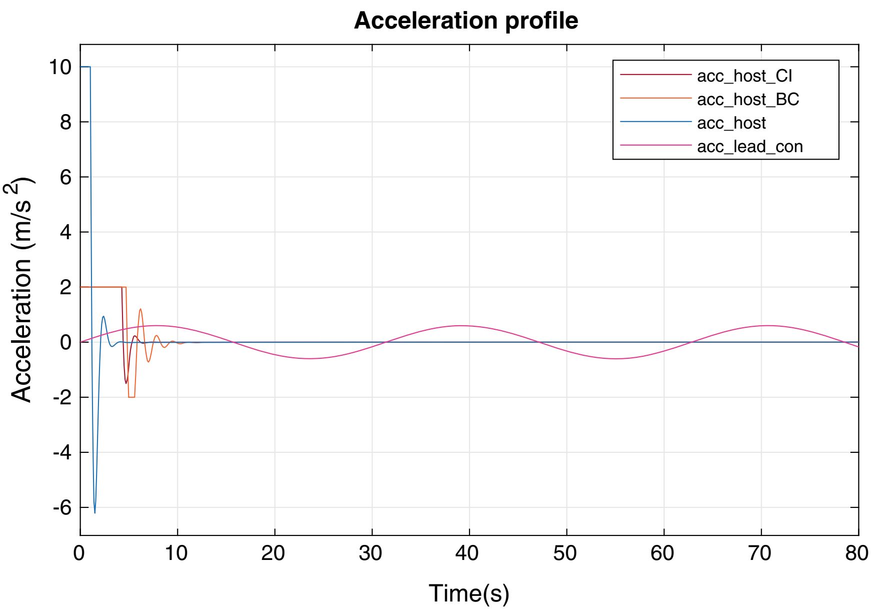

Fig. 6 Acceleration profile

5 Conclusions

Windup hampers the system performance significantly. By adapting anti windup schemes, it is possible to avoid this phenomenon. The degree to which various anti-windup schemes improve the response has been shown in this paper while incorporating it in cruise control of a vehicle. By the comparative study, it was evident that while the conditional integration scheme enhanced the performance of the controller during saturation across various profiles of cruise control but it was actually the controller with back calculation scheme that provides the optimal response in each of these case. Therefore, we may conclude that a PID controller with back calculation is the best amongst the proposed control schemes.

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Appendix

The vehicle model considered in Sect. 2.1 is shown in Fig. 7 described as follows. Let us suppose our vehicle has mass M and moving with a velocity v. We considered resistive forces, and bv is presumed to change linearly with the speed of the vehicle

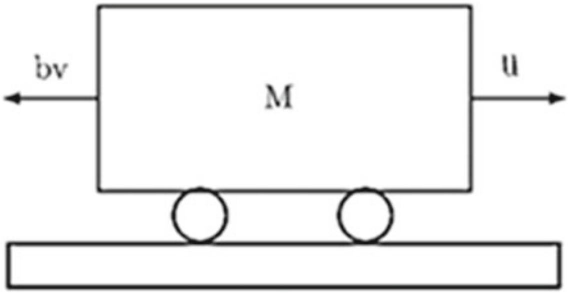

Fig. 7 Point mass model

owing to rolling resistance and wind drag. Such resistive forces function in the direction opposite to the movement of the vehicle.

Force balance equations

Now with these observations, we have a first-order mass-damper system. We come to the following process equation summing up forces in the x-direction by applying Newton's second law:

$$m\dot{v} + bv = cu \tag{4}$$

Since we are interested in controlling the vehicle speed, the formula of measurement is selected as follows.

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

State-space model

First-order systems have only one energy storage mode (in this case, the car's kinetic energy), and thus, only one state parameter, i.e. the velocity, is required. The state-space representation is therefore:

$$\dot{\mathbf{x}} = [\dot{v}] = \left[\frac{-b}{m}\right][v] + \left[\frac{c}{m}\right][u] \tag{6}$$

$$y = [1][v] \tag{7}$$

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