Coordinated String Stability Control for Vehicle Platoons with Faster Settling

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Abstract. Coordinated adaptive cruise control (CACC) is a type of adaptive cruise control (ACC) that enables the driver to set the vehicle speed and the distance between current and preceding vehicles as well as helps to gather the data from vehicles around it and form a platoon. The main objectives for the paper are to implement coordinated cruise control, to minimize steady state spacing error while maintaining the string stability and to get earlier settling of string stability under external disturbances. Design, simulation, and testing of CACC under various conditions have been performed. Both feedback and feed forward controls have been employed for implementing the system model with controllers. It is assumed that all vehicles are having wireless access to share the speed and distance related information. It is observed that settling time for the string stability has been improved. The model has been simulated under disturbances and results are compared with existing ACC control. The simulation results validate proposed model in terms of settling of string stability.

1. Introduction
Significant developments in Cruise Control technology have been achieved during the last decade. Cruise Control is a system developed to control the speed of the vehicle automatically. It controls the throttle of the car using servomechanism. The speed is maintained at a set value by the driver. The system that allows setting the values of distance and speed is known as Adaptive Cruise Control (ACC). Depending on whether the preceding vehicle is travelling slowly or is not within the safe distance, the ACC system may switch from speed control to spacing control [1]. The driver sets a value from the various levels of distance provided by the manufacturer. ACC uses both braking and throttle system as an actuator, as compared to the classical CC which only uses throttle system for actuation purposes. The advantage of ACC over cruise control is that it reduces the braking of the vehicle as it slows down autonomously based on the distance of car or obstacle in front of the vehicle. ACC can be operated in two modes – Cruise mode and Follow mode. When the vehicle is in Cruise mode, the vehicle maintains set value of speed. On the other hand, in Follow mode, the vehicle maintains the distance between the preceding vehicles at a set value. When the vehicle cruising at a set speed detects another vehicle, it slows down to match the speed of the preceding vehicle. It will continue to cruise on driver set speed once the vehicle has moved away from the lane.
2. Related Work

ACC typically consists of two parts – a vehicle dependent part and vehicle independent part [3]. The vehicle dependent part ensures tracking of acceleration/deceleration via actuation of braking and throttle system. On the other hand, desired acceleration/deceleration is determined by the vehicle independent part. ACC system consists of two types of communication in terms of the feedback to the driver. This feedback is relating to the proper functioning of the system. One, the driver senses that the system is active when the car is in acceleration/deceleration autonomously. Second, the driver is warned with a beep to take over the control when the vehicle reaches its lower speed threshold [4]. Inter-vehicle distance and relative velocity determine the level of safety in driving. ACC helps to increase the level of safety and at the same time provide comfort to the driver even in high traffic situations. The comfort level for a driver is directly related to the jerks experienced in the vehicle [5]. The main disadvantage of ACC is that because of the lack of need to maintain a constant pressure on the pedal, it can often lead to accidents. But, this can be avoided in future systems with the use of dead man’s control. In recent times, a comprehensive review of the ACC system has been issued, see [6] for specifics.

One of the primary objectives of modern automotive engineering is to improve fuel efficiency in vehicles. This objective can be fulfilled with the use of a model predictive approach for the control of CACC system [7]. The challenging issues in real life situations are identified by the communication, driver characteristics and controls which are three most important aspects of CACC system [8]. Oscillations which are introduced in traffic because of accelerating and braking may be amplified in upstream direction because ACC systems often may not exhibit string stability [9]. CACC help to rectify this problem of ACC with the use of various control strategies and platoon forming techniques [10]. In a similar context, Naus et al. [11] have worked on a model of CACC where its feasibility in real life traffic situations its primary goal is. In order to achieve it, communication with only the preceding vehicle was used. In this paper, a model with simultaneous communication with multiple vehicles for CACC is used for simulation and analysis. Follower vehicles in a platoon may decide to leave the platoon if the leader vehicle is travelling at a relatively lower speed. When a platoon is active in CACC system, one vehicle changing the lane will hinder the overall behaviour of the system. Accurate modelling of asymmetric driver behaviour and vehicle characteristics can be used to improve the stability of the platoon as a whole [8]. While some efforts have been taken to demonstrate the supremacy of CACC over ACC, this paper endeavours to fill the gap with use of Simulink modelling and analysis.

3. Methodology to Implement ACC and CACC

3.1 ACC Model

Adaptive cruise control model has been implemented for the car model with its own parameters as shown in the Table I [14]. Further, by solving the longitudinal force balance equation for the given parameters like mass, height, width and length etc., transfer function for the real car model has been found as follows.

\[ \text{Frontal Area (A)} = W \times H \] 

\[ \text{Frontal Area(A)} = 1.695 \times 1.495 = 2.534 \text{ m}^2 \] 

In order to calculate the transfer function, longitudinal forces acting on car’s body are considered. The longitudinal forces will include the aerodynamic resistance (drag force) \( F_D \) and frictional force \( F_F \). The calculations of various forces have been done as follows [13],

Total force,

\[ F = F_D + F_F \] 

Where
\[ F_D = 0.5\rho C_D A v^2 \]
\[ F_F = (mg - F_{LF} - F_{LR})\mu \]
\[ F_{LF} = 0.5\rho C_{LF} A v^2 \]
\[ F_{LR} = 0.5\rho C_{LR} A v^2 \]
\[ F_F = mg - 0.5\rho A v^2 (C_{LF} + C_{LR}) \]

Substituting in (3),
\[ F = 0.5\rho C_D A v^2 + mg - 0.5\rho A v^2 (C_{LF} + C_{LR}) \]
\[ F = mg + 0.5\rho A v^2 (C_D - C_{LF} - C_{LR}) \] (4)

By applying the Laplace transforms with initial velocity and forces are zero
\[ F(s) = \frac{mg}{s} + 0.5\rho A (C_D - C_{LF} - C_{LR}) \frac{1}{s^2} \]
\[ F(s) = \frac{1}{s^2} (mg s + 0.5\rho A (C_D - C_{LF} - C_{LR})) \]

Then, substituting the corresponding values,
\[ F(s) = \frac{1}{s^2} (10280.2s - 0.0373) \]
\[ TF(s) = \frac{V(s)}{F(s)} = \frac{1}{s^2}(10280.2s - 0.0373) = \frac{s}{(10280.2s - 0.0373)} \] (5)

Where,
\( P = \) Atmospheric air density \(-1.225\text{kg/m}^3\)
\( C_D = \) Drag Factor (0.358 for sedan)
\( v = \) Velocity of vehicle
\( \mu = \)Coefficient of friction (0.85 for asphalt and dry concrete)
\( C_{LF} = \) Front Lift Factor \(-0.136\) for sedan
\( C_{LR} = \) Rear Lift Factor \(-0.246\) for sedan
\( g = \) Acceleration due to gravity \(9.81\text{ m/s}^2\)
| Car                    | Mass M (in kg) | Height H (in m) | Width W (in m) | Length L (in m) |
|------------------------|----------------|-----------------|----------------|-----------------|
| Honda City- Petrol MT   | 1049           | 1.495           | 1.695          | 4.440           |

The obtained transfer function is used to develop a model of the vehicle. The model is shown in Fig.1. It is basic first order transfer function model. The input is force acting on the car’s body and output is the velocity of the car.

![LTI System]

**Figure 1.** Transfer function of proposed car model

Then, the adaptive control model for one vehicle has been implemented as shown in the Fig.2. The ACC model gets the all relevant information from the preceding vehicles and takes the decision accordingly. In the model, distance is given as an input to the vehicle model that is system. The error between the input distance and the output distance is termed as the distance error (Output 1). The distance (Output 3) obtained from the output of the LTI system is differentiated to obtain speed (Output 2). For the following vehicle, input distance is fed as the output distance from the preceding vehicle. In this manner six cars are modelled in similar way to form a platoon with an ACC system.

This model ensures the desired gap between the current vehicle and preceding vehicle. Hence, this model corrects the distance error when the disturbance arrives to maintain the desired gap and thereby to maintain the string stability in the vehicle platoon. Connection of vehicles in one platoon of car model is shown in the Fig3. Based on the distance measured by the distance sensor, the vehicle takes decision. The disturbance on one vehicle will disturb all other vehicles in the platoon. This disturbance is flown across all vehicles. All vehicles take some time to settle down to its previous state of string stability. This settling time is taken as parameter to measure the performance of the different models. In order to reduce the settling time, newer model has been proposed with assumption of all vehicles equipment with wireless module to share speed and distance related information among themselves in the platoon. One such a model is called coordinated adaptive control system.

![ACC model of vehicle]

**Figure 2.** ACC model of vehicle
3.2 CACC Model

The control model of a CACC system basically consists of two parts—feedforward control and feedback control. The feedback control consists of the loop of data gathered from it and fed to control block. On the other hand, the feedforward control consists of data from preceding vehicles and fed to the control block. Fig.4 shows the block diagram with both feedback and feedforward control [12]. In that type of control, distance of the preceding vehicle is taken as process variable for the closed control, and speed-related information of all possible preceding vehicles are taken as set point value in the feedforward control as shown in Fig.4. CACC control for the leader vehicle is same as that of the ACC control as shown in Fig.5. Average value of the speed of preceding vehicles is calculated as desired speed by subsequent vehicles in the CACC model as shown in Fig.6. These speeds are communicated among the platoon via wireless communication. The leader vehicle is fed with the distance it travelled. This type of control in CACC model leads to outperform well in settling time under the disturbances. Interconnection of vehicles in one platoon of CACC model is shown in the Fig.7.
The model of a CACC system with vehicle platoon is a bit complex as it involves communication about the speed from all the preceding vehicles to the followers.

3.3 Hardware Implementation

This paper tries to implement the CACC system using three electrical vehicles travelling in a straight direction. The main objective of this implementation is to demonstrate the working of a CACC system using vehicle platooning. In order to implement the CACC system designed in the model, we need sensors like ultrasonic sensor, RPM sensor or encoder for the motor, ZigBee for wireless communication. The microcontroller is programmed in such a way that once the leader vehicle starts to move, the follower vehicle senses the change in distance using the ultrasonic sensor. This change in distance is compensated by the movement of the follower vehicle. The follower vehicle also matches the speed of the leader vehicle which is transmitted via wireless communication using ZigBee communication device. In order to vary speeds in the vehicle, switches are used in order to have varying speeds for the vehicle. Various information like, speed, actual speed, distance, will be displayed for the user to check using LCD display. The prototype model of platoon is shown in Fig.9.
4. Result and discussion
Using the models for ACC and CACC, various parameters like settling time and steady state error are compared between both systems to validate our proposed model. The parameter used for comparisons are settling time of distance error, velocity and distance travelled as shown in the Table II. The variation in actual distance and the desired distance constitutes the distance error between the two consecutive vehicles. When disturbance arrives at first vehicle, there is change in actual distance of first and second vehicle and thereby the error in distance gap in first and second vehicle. All subsequent vehicles are trying to nullify these distance errors and finally settle down after some time period. It is shown in Fig.9 and Fig.10 for both ACC and CACC models. The settling for the restoring back error as zero is minimal for CACC model compared with ACC model as shown in the Fig.11.

| Car Position | Distance Error | Velocity | Distance travelled |
|--------------|----------------|----------|--------------------|
|              | ACC | CACC | ACC | CACC | ACC | CACC | ACC | CACC |
| 1            | 13.09 | 13.27 | 14.79 | 14.82 | 10.85 | 6.44 |
| 2            | 15.95 | 15.98 | 17.57 | 17.51 | 13.37 | 6.79 |
| 3            | 18.27 | 17.64 | 20.00 | 19.51 | 15.52 | 8.13 |
| 4            | 20.36 | 18.81 | 22.19 | 20.76 | 17.44 | 8.81 |
| 5            | 22.33 | 19.67 | 24.21 | 21.70 | 19.27 | 9.59 |
| 6            | 24.21 | 20.34 | 26.14 | 22.40 | 21.02 | 10.08 |
Velocity change is the disturbance caused by any one of the vehicles in the platoon. It is important for successive vehicles to cope up with current vehicle’s velocity to maintain the platoon for having string stability. The velocity change of one vehicle affects the successive vehicles in the platoon as shown in Fig. 12 and Fig. 13 for the systems ACC and CACC. It is observed that the CACC system quickly traces the velocity change of preceding vehicle as shown in the Fig. 14.
Distance travelled is distance travelled by the vehicles during the settling time period. It is measured in all vehicles as time required for covering one meter distance. Settling times to cover that distance for all vehicles are shown in Fig.15 and Fig.16 for both ACC and CACC systems. Comparison of distance travelled settling time is shown in Fig.17. In addition to the settling time, steady state error is also examined. Steady state for the ACC is not reached the final level of zero for the ACC control system as shown in the Fig.12. Steady state reaches almost zero for our proposed as shown in the Fig.13. Hence, the state error is reduced greatly for the proposed model as shown in the Fig.14.

5. Conclusion
In this paper, the advanced model control has been modelled and implemented in coordinated environment. Simulation results validated our proposed model in terms of the settling time, faster response and reduced inter-gap distance error. When disturbance was introduced in the system, string stability of vehicle platoon got affected. The obtained results are compared with conventional ACC system. Proposed model ensures the string stability in the vehicle platoon to enjoy the features of platoon. It recovers from the string instability under disturbance. In future, by considering different vehicle sizes, noises from state model and measurements, the newer control model will be implemented for string stability in vehicle platoon.
Figure 18. Comparison of distance travelled settling time for ACC and CACC system

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