

Impact of Different Desired Velocity Profiles and Controller Gains on Convoy Driveability of Cooperative Adaptive Cruise Control Operated Platoons

Santhosh Tamilarasan and Levent Guvenc
 The Ohio State University

ABSTRACT

As the development of autonomous vehicles rapidly advances, the use of conveying/platooning becomes a more widely explored technology option for saving fuel and increasing the efficiency of traffic. In cooperative adaptive cruise control (CACC), the vehicles in a convoy follow each other under adaptive cruise control (ACC) that is augmented by the sharing of preceding vehicle acceleration through the vehicle to vehicle communication in a feedforward control path. In general, the desired velocity optimization for vehicles in the convoy is based on fuel economy optimization, rather than driveability. This paper is a preliminary study on the impact of the desired velocity profile on the driveability characteristics of a convoy of vehicles and the controller gain impact on the driveability. A simple low-level longitudinal model of the vehicle has been used along with a PD type cruise controller and a generic spacing policy for ACC/CACC. The acceleration of the previous vehicle is available to the next vehicle as input, and the simulations are performed as Cooperative Adaptive Cruise Control of a convoy of vehicles. Individual vehicle acceleration profiles have been analyzed for driveability for two different velocity profiles that are followed in a stretch of 720 m between stop signs. The controller gains have been re-tuned based on the parameter space robust control PID approach for driveability and compared with the original gains. The US06 SFTP drive cycle has also been used for the comparison of the two different controller gain sets.

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INTRODUCTION

The development of autonomous vehicle technology is advancing every day, and its implementation in Personalized Rapid Transport (PRT) and Bus Rapid Transport (BRT) seem beneficial. There are several discussions happening in city planning departments on the idea of dedicated lanes for buses that operate autonomously. In this scenario, it is important to understand the driveability of a convoy of vehicles in the automated lane as passenger comfort is also an important issue. Driveability refers to the response of the vehicle to the driver input and the smoothness of motion. The intention is that passengers do not feel discomfort when traveling in the vehicle. Being an autonomous vehicle, the human driving is replaced by providing a lead vehicle velocity profile, which is calculated based on a velocity optimization algorithm. The optimization algorithm tries to find the optimized velocity profile based on maximum fuel economy. The optimization is usually not done for optimal driveability, and therefore it is important to study the impact of different velocity profiles on driveability considering that driverless cars are not necessarily passengerless.

Driveability is evaluated by experienced test drivers who observe the vehicle's dynamic response by providing various inputs such as throttle pedal tip-in/tip out, gear shifting and engine idling etc. During these tests, various behaviors such as jerk, vehicle shuffle, hunting, and oscillations are evaluated. The references to driveability measures by Wei *et al* [1] and Yard [2] provide a good insight about

measuring different driveability evaluation metrics. There are also commercially available software packages like AVL Drive [3,4,5] that can be used to evaluate the acceleration profile of a vehicle using neural network algorithms, analyze the data from different vehicles and the ratings provided by different experienced drivers. This paper analyzes information from the acceleration signal and computes various parameters as mentioned by Wei *et al* [1], to arrive at the driveability measures. Signals below 10 Hz are not perceivable by humans as is mentioned by Schoeggel *et al* [5].

The convoy model used in this paper uses Cooperative Adaptive Cruise Control (CACC). In CACC, the vehicles receive information about the acceleration of the preceding vehicle and utilize this information to maintain the time headway between each vehicle. So, the acceleration behavior of the lead vehicle will affect the rest of the vehicles in the convoy. The paper sections are organized as follows. The next section on model development explains the equations used in vehicle dynamics modeling and longitudinal convoy modeling. The section on driveability presents different measures that are used for analyzing the vehicle acceleration signal and their calculation. The section on the desired velocity profile of the autonomous vehicles explains the reasoning behind choosing these different velocity profiles. The section on simulation results discusses the outcome of the convoy model simulated for different velocity profiles. Driveability metrics are presented to evaluate performance. The paper ends with conclusions and recommendations for future work.

MODEL DEVELOPMENT

The models used here have been developed based on the CACC structure described in Gerrit *et al* [6]. A string of homogenous vehicles is being considered for the simulation as shown in **Figure 1**, given that the scenario is a dedicated bus lane, wherein one bus follows the other. The same analysis can be extended to a mixed traffic model also. Acceleration of each vehicle is represented as a_i , the standstill distance between two vehicles is given as r_p , and the length of each vehicle is given as L_i .

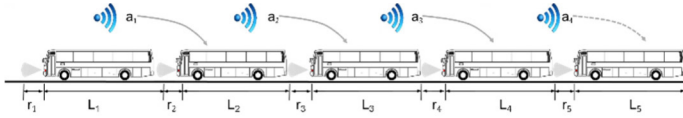


Figure 1. Architecture of the Five Vehicle Convoy

The main control objective of the Cooperative Adaptive Cruise Control model is to follow the preceding vehicle with desired time headway with the information of the acceleration of the preceding vehicle available as input. The vehicle model is a low-level closed-loop longitudinal vehicle dynamics, which can be represented for the i^{th} vehicle as

$$G_i(s) = \frac{1}{s^2(\tau_i s + 1)} e^{-\phi_i s} \text{ for } i \geq 1 \quad (1)$$

The input $u_i(t)$ for the model $G_i(s)$ is desired acceleration. $1/\tau_i$ is the low-level closed loop bandwidth and ϕ_i is the delay in the actuator response and the internal communication delay that are lumped together in **equation (1)**. In **Figure 2**, the acceleration signal from the previous vehicle $\ddot{x}_{i-1}$ is fed via a feedforward filter F_i . A standard PD type controller is used for tracking the desired acceleration, whose gain is given as $K_i(s)$. The PD controller is expressed as

$$K_i(s) = k_{p,i} + s k_{D,i} \text{ for } i \geq 1 \quad (2)$$

where $k_{D,i}$ and $k_{p,i}$ are the gains of the derivative and proportional controller for the i^{th} vehicle.

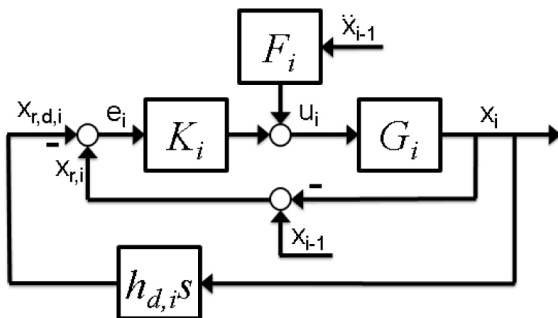


Figure 2. CACC Control block diagram

The spacing policy is used to calculate the desired relative position and consists of the constant distance and a velocity dependent part, and is given as,

$$x_{r,i}(t) = x_{r0,i} + h_{d,i} \dot{x}_i(t) \quad (3)$$

where $x_{r0,i} = L_i + r_p$ are the constant distance and the desired time headway is given as, $h_{d,i}$ in seconds. The vehicle model parameters used are given in **Table 1**.

Table 1. Parameters used in the Model

Parameters	L (m)	R (m)	ϕ_i (s)	τ (s)
Values	10	10	0.1	0.5

DRIVEABILITY MEASURES

Driveability is the perception of the driver about the quality of the drive and how smooth it is. In engineering terms, this can be broken down into some key measures, such as jerk, response time, initial bump, kick, vibration dose value (VDV) and stumble, as shown by Wei *et al* [1], Yard [2] and Jauch *et al* [9]. These measures are calculated by analysis of the acceleration signal to capture its characteristics at its different profile segments.

Initial Response time

Initial response time is defined as the time it takes for the vehicle acceleration to reach 0.5 m/s^2 . For a convoy, this initial response time means how quickly all the vehicles in the convoy start to move and reach the 0.5 m/s^2 acceleration value. The shorter the response time, the faster is the convoy response. It should be noted that each vehicle will have its own response time (depending on the powertrain configurations), and in this paper, since we are considering only homogenous vehicles, the response time of the individual vehicles is the same and the total convoy response time is governed by the lead vehicle velocity profile.

Initial Bump

This is gradient of the acceleration rise, meaning the angle between the time axis and the initial acceleration profile slope. A higher initial slope means that the vehicle can accelerate quickly and this has a direct relationship to the response time. If the vehicle initial bump is higher, then the convoy will also accelerate faster and therefore the response time will be shorter.

Kick

The kick is defined as the maximum drop in the acceleration after the vehicle attains its maximum acceleration. The higher the kick value, the more the driver feels the sharp jerk and resulting discomfort. A too steep acceleration rise will also lead to a higher drop in the acceleration and therefore the kick will be higher.

Stumble

Stumble is defined as the drop in the acceleration when the torque is requested from the vehicle. This will also capture the behavior when the acceleration shuffles between positive and negative values and

the driver will feel that the vehicle might stall and might experience severe oscillations. The more the stumble, the worse is the driveability.

Jerk

Jerk is calculated as the derivative of the acceleration, and the faster the acceleration changes, the more is the jerk. As mentioned in Wei *et al* [3], a value of 2 m/s³ is an acceptable jerk. Note that jerk is sometimes calculated differently for driveability evaluation purposes.

Vibration Dose Value (VDV)

It has been shown in Wei *et al* [1], that the VDV value gives a holistic indication of the vibration experienced by the human driver, who is in contact with the vibrating surface. This was mainly used as a measure in the industry to see the vibration experienced by the workers working with vibrating surfaces or machines. The acceleration signal is filtered between 1 Hz to 32 Hz using a time window between t_0 and final time t_f as given by Horste [8]. The VDV calculation is made according to

$$VDV = \left[\int_{t_0}^{t_f} \tilde{a}^4(t) dt \right]^{1/4} \quad (4)$$

where $\tilde{a}$ is the filtered acceleration value.

DESIRED VELOCITY PROFILE FOR AUTONOMOUS VEHICLE

In this paper, we have tried two different desired velocity profiles to analyze the driveability of each vehicle in the convoy. The total distance is 720 m between two stop signs as shown in Figure 3 and is covered in different durations of time depending on the speed profile. The maximum speed limit for the stretch considered is 35 mph which corresponds to 15.4 m/s.

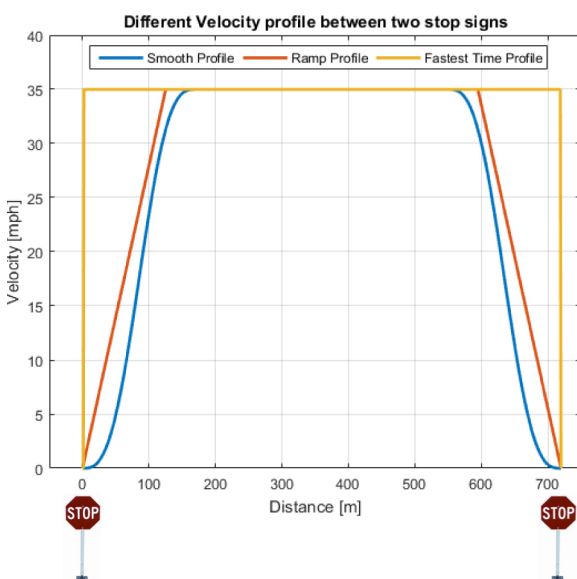


Figure 3. The two different desired velocity profiles between two stop signs

The ramp velocity profile increases the velocity to have a maximum acceleration of 3m/s². The second profile is the smooth velocity profile obtained by using cubic polynomials to achieve a smooth rise in the velocity. The step profile where the vehicle velocity reaches the speed limit instantly is given as a reference in this figure. This is not a practical scenario. We have used it to show the difference in the ramp velocity profile & smooth velocity in contrast to the theoretical fastest vehicle speed profile (shortest time). The durations of the velocity profiles have been tabulated in Table 2.

Table 2. Time taken for each velocity profile to cover 720m

Velocity profiles	Time taken (s)
Step profile	46.1582
Ramp profile	55.7001
Smooth profile	60.2573

Along with the theoretical profiles above, the simulation was also performed on the US06 drive cycle, which is the supplemental federal test procedure developed to represent the aggressive, high acceleration driving behavior of the driver.

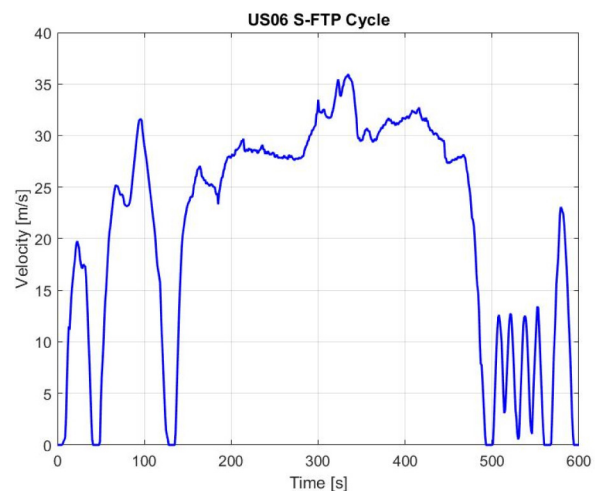


Figure 4. The US06 supplemental federal drive cycle contains high accelerations

As we see from Figure 4, the US06 drive cycle has very high acceleration peaks due to the steep rises and falls in velocity early in the cycle which thereby makes it a good candidate to use in the evaluation of CACC convoy driveability

CACC CONTROLLER PARAMETERS

Based on the literature review, the CACC controller gains were taken as $k_{D,i} = 2$ and $k_{P,i} = 4$ for the model, and we denote this as the original controller in this paper. The performance of the CACC controller depends heavily on the headway time gap and, therefore, the selection of the suitable headway time gap is important. According to Gerrit *et al* [6], the headway time gap of 0.6s has been achieved for best performance. In this paper, we have analyzed the model for 0.3s and 0.6s to find out the suitable headway time gap for driveability performance.