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Control design for robust platoons with communication delays

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Summary. This work investigates platooning systems employing Adaptive Cruise Control (ACC) and Cooperative Adaptive Cruise Control (CACC) strategies, with the main focus being on controller parameter design for string stability under communication delays. ACC relies on onboard sensors, while CACC augments this capability with vehicle-to-vehicle (V2V) communication and both systems are used to synchronize vehicle speeds and maintain precise inter-vehicular spacing in platoons. Our goal is to find conditions on the controller's proportional and derivative gains to balance individual vehicle stability and string stability. The latter is crucial to ensure that spacing errors do not amplify as vehicles traverse the platoon, a fundamental requirement for safe and efficient platooning. We provide a method for characterizing controller gains for string and individual stability based on the well-known D -decomposition in the time-delay systems literature. Numerical simulations validate the theoretical results.

Introduction and Problem formulation

ACC and CACC are designed to regulate vehicle speed and inter-spacing in response to traffic conditions [1, 2, 3]. While ACC operates based on information from onboard sensors, CACC additionally incorporates vehicle-to-vehicle (V2V) communication, enabling real-time data exchange among the platoon's members. Both strategies offer the potential to enhance road safety and traffic flow by reducing human error, mitigating congestion, and optimizing fuel consumption. The success of ACC and CACC in platooning scenarios crucially depends on the correct tuning of control parameters. Specifically, both controllers are of Proportional-Derivative (PD) type and the choice of the proportional and derivative gains (k_p and k_d) is essential for the performance of the closed-loop system. These parameters dictate the response of the control system to deviations in vehicle spacing, directly impacting individual vehicle stability and, more critically, string stability [4]. String stability is an essential criterion for safe and efficient platooning since it ensures that inter-spacing errors do not amplify when a perturbation occurs.

We consider a platoon of N identical (homogeneous) vehicles. The purpose of each vehicle $i \in \mathbb{N}^+$ ($i = 0$ is the leader) is to follow the preceding vehicle $i - 1$ while maintaining a desired distance $d_{r,i}$ from it. We define the spacing error $e_i(t)$ as

$$e_i(t) = q_{i-1}(t) - q_i(t) - hv_i(t) - r_i - L \quad (1)$$

where $q_{i-1}(t)$ and $q_i(t)$ are the positions of vehicles $i - 1$ and i at time t , L is the length of any vehicle, r_i is the minimum safe distance between consecutive vehicles, h is the desired constant time gap and $v_i(t)$ is the velocity of vehicle i at time t . We assume that each vehicle of the platoon is strictly identical with an inertia τ . Thus, the dynamics of the i -th vehicle is described by :

$$\begin{cases} \dot{v}_i(t) = a_i(t) \\ \dot{a}_i(t) = -\frac{1}{\tau}a_i(t) + \frac{1}{\tau}u_i(t) \\ \dot{u}_i(t) = -\frac{1}{h}u_i(t) + \frac{1}{h}\chi_i(t) \end{cases} \quad (2)$$

where $v_i(t)$ and $a_i(t)$ are respectively the speed and acceleration of the vehicle i at time t while $u_i(t)$ represents the desired acceleration at time t and $\chi_i(t)$ the control input at time t . The relative error dynamics is:

$$\dot{e}_i(t) = v_{i-1}(t) - v_i(t) - ha_i(t) \quad (3)$$

For ACC, the control input comes from a PD controller where $k_p > 0$ and $k_d > 0$ are the controller gains. For CACC, we add the desired acceleration $u_{i-1}(t)$ of the previous vehicle which is received with a communication delay $\Delta > 0$;

$$\chi_{i,ACC}(t) = k_p e_i(t) + k_d \dot{e}_i(t), \quad \chi_{i,CACC}(t) = k_p e_i(t) + k_d \dot{e}_i(t) + u_{i-1}(t - \Delta) \quad (4)$$

Main results

Let us use $E_i(s)$ to denote the error variable in the Laplace domain. For an ACC control strategy, the transfer function of outputs E_i and E_{i-1} between the vehicle i and its predecessor $i - 1$ in the Laplace domain can be found from the plant dynamics (2) and the control input (5):

$$\frac{E_i(s)}{E_{i-1}(s)} = \frac{sk_d + k_p}{s^4 h \tau + s^3(\tau + h) + s^2(1 + h k_d) + s(k_d + h k_p) + k_p} \quad (5)$$

with s being the Laplace variable. To ensure the closed loop stability of the individual system, we use the Routh criterion which gives us a first condition on k_p and k_d as seen in [5], i.e., $k_d > \tau k_p$.

To study the string stability of the ACC system, we employ a rigorous mathematical analysis rooted in the properties of the transfer function. The H_∞ norm of the transfer function (5) must be less than or equal to 1 for string stability.

Sufficient conditions to satisfy this criterion (using some calculations with $s = j\omega$ and the property that $\sin \omega \leq \omega$) can be expressed as an inequality involving a polynomial of degree 6, where negative solutions are sought.

$$\left\| \frac{E_i(s)}{E_{i-1}(s)} \right\|_{H_\infty} \leq 1 \Leftrightarrow \max_{\omega \in \mathbb{R}} (\omega^6 f_6 + \omega^4 f_4 + \omega^2 f_2 + f_0) \leq 0 \Leftrightarrow f(W) \leq 0 \quad (6)$$

Here, f_6, f_4, f_2 , and f_0 are coefficients that depend on k_p and k_d . We redefine the angular frequency as $\omega^2 = W \in \mathbb{R}^+$ and formulate the function $f(W) = f_6 W^3 + f_4 W^2 + f_2 W + f_0$. The conditions for string stability are then derived through an analysis of the discriminant Δ^* and the maximum W_m of f :

$$f_0 < 0, \quad \Delta^* > 0, \quad W_m > 0, \quad f(W_m) = 0. \quad (7)$$

The conditions $f_0 < 0$ and $\Delta^* > 0$ yield constraints on k_p . Additionally, the condition $W_m > 0$ imposes further constraints on both k_p and k_d . The resulting expressions for k_{pmin} and k_{pmax} are given by:

$$k_{pmin} = \begin{cases} \max \left(\frac{2}{h^2}, \frac{-h^4 \tau^2 k_d^2 - 2h^2 \tau^3 k_d + 4h^4 \tau k_d - \tau^4 - h^4 + \tau^2 h^2}{6h^4 \tau^2} \right) & \text{if } k_d \geq \frac{\tau^2 + h^2}{2h^2 \tau} \\ \max \left(\frac{2}{h^2}, \frac{h^2 k_d^2 + 1 - 2\tau k_d}{2h^2} \right) & \text{else} \end{cases} \quad (8)$$

$$k_{pmax} = \frac{k_d}{\tau} \quad (9)$$

These limits on k_p provide necessary but not sufficient conditions to solve the problem (7). To satisfy the last condition $f(W_m) = 0$, we look for the roots of f in this range to determine the areas of string stability. MATLAB or similar tools can be employed to solve $f(W_m(k_p, k_d)) \leq 0$ under the condition $k_{pmin} < k_p < k_{pmax}$, yielding values of k_d corresponding to string-stable regions.

Associated with the condition of individual stability, we find all the values of the controller's gains which make it possible to have a stable platoon with an ACC control strategy.

The same method can be extended to find the solutions of the controller for a CACC control strategy.

Simulation and Conclusion

To obtain results that can be easily interpreted, we plot the solutions of problem (7) in the k_p/k_d space. For instance, consider two CACC controls with an inertia $\tau = 0.1$, a time-gap $h = 0.6s$, and a delay that is varied between 0.1s and 0.01s in order to study its impact on the solution. The areas of individual and string stability are illustrated in green on Figure 1. As the delay decreases, the string stability limit tends towards the individual stability limit. A simulation of the platoon using MATLAB was used to validate its behaviour and therefore its stability according to the k_p and k_d parameters used.

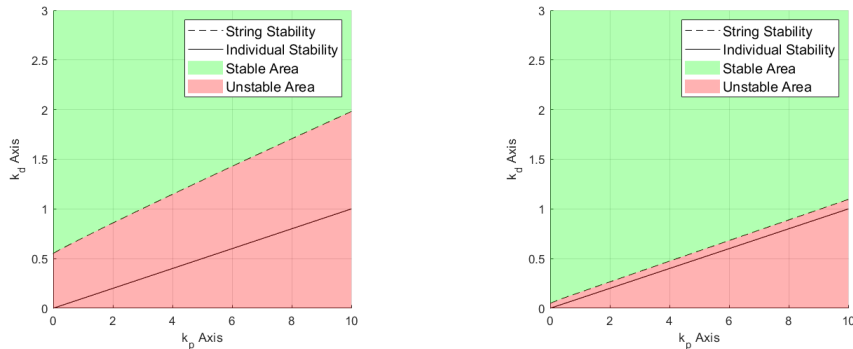


Figure 1: CACC stable region in k_p/k_d space for $\tau = 0.1$, $h = 0.6$. Left: $\Delta = 0.1$. Right: $\Delta = 0.01$

In conclusion, the study provides a new perspective on the design of ACC and CACC controllers that ensures their stability under communication delays. The representation in 2D space makes it easy to visualise the solutions.

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