Parameter Space-Based Fractional-Order PD Controller Design and Analysis for Cooperative Adaptive Cruise Control Systems

Dorukhan Astekin[1,*], Mümin Tolga Emirler[1], Erkin Dinçmen[1]

[1]Yildiz Technical University, Faculty of Electrical and Electronics Engineering, Department of Control and Automation Engineering, İstanbul, Türkiye

Introduction

Cooperative adaptive cruise control systems are highly affected by model uncertainties and communication delays, which make controller tuning more challenging and may degrade tracking and platoon performance. To address these issues, this study proposes a parameter-space-based fractional-order PD controller for CACC systems. In the proposed approach, both the controller gains and the fractional order are considered as design parameters, allowing the stable regions to be determined analytically. The effectiveness of the proposed method is evaluated in terms of tracking and string stability performance and compared with a conventional integer-order PD controller.

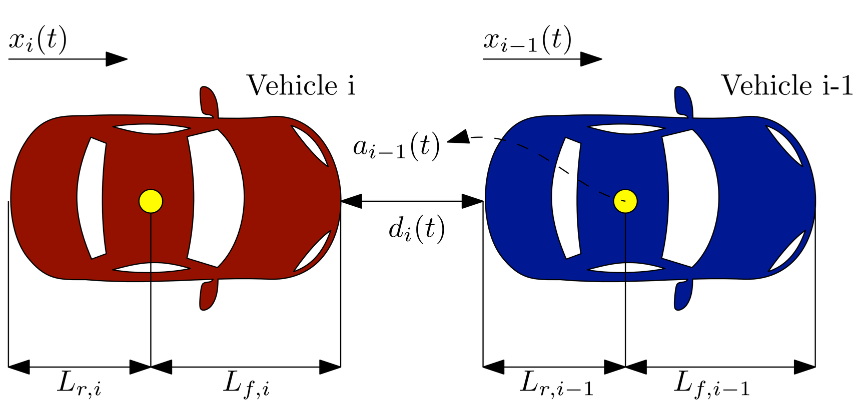

Figure 1: CACC equipped consecutive vehicles in the convoy.

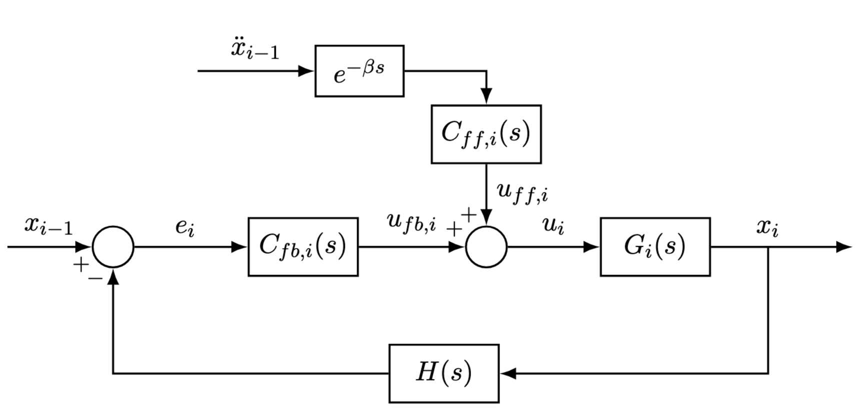

Figure 2: CACC system structure for a single vehicle.

Controller Synthesis

A fractional-order PD controller is considered for the feedback channel of the vehicle-following system. The controller is defined as

$$C_{fb,i}(s) = k_p + k_d s^{\mu} \tag{1}$$

The vehicle dynamics are represented by a delayed transfer function

$$G_i(s) = \frac{N(s)}{D(s)} e^{-\theta_i s} \tag{2}$$

while the spacing policy is described by the constant time-headway model

$$H(s) = t_{hd,i}s + 1 \tag{3}$$

Frequency-domain analysis is applied by substituting $s = j\omega$ into the characteristic equation. The resulting real and imaginary parts yield the complex-root, real-root, and infinite-root boundaries, which define the admissible stability region in the (k_p, k_d) plane.
Plus, the feedforward controller is designed as

$$C_{ff,i}(s) = \frac{\tau_i s + 1}{t_{hd,i}s + 1} \tag{4}$$

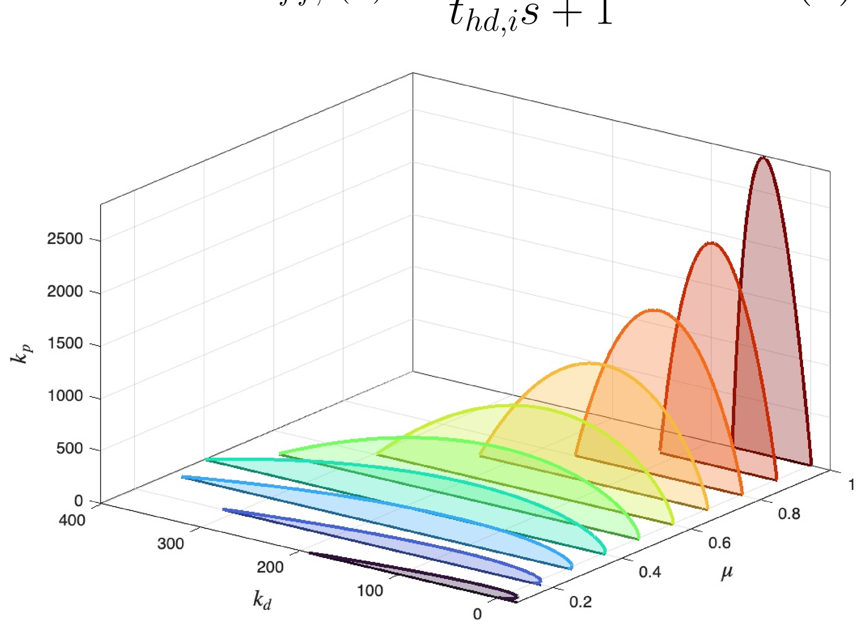

Figure 3: 3D representation of the stability regions in the (k_p, k_d, μ) parameter space.

Vehicle Modeling

For controller design, the ideal longitudinal dynamics of the i^{th} vehicle are first described by

$$\ddot{x}_i(t) = u_i(t) \tag{5}$$

By incorporating actuator and powertrain dynamics, the vehicle model is written as

$$G_i(s) = \frac{X_i(s)}{U_i(s)} = \frac{1}{s^2(\tau_i s + 1)} \tag{6}$$

To obtain a more realistic representation, the input delay is explicitly included as

$$G_i(s) = \frac{e^{-\theta_i s}}{s^2(\tau_i s + 1)} \tag{7}$$

where τ_i denotes the powertrain time constant and θ_i denotes the input delay of the i^{th} vehicle.

Spacing Policy

A constant time-headway spacing policy is adopted. Accordingly, the desired spacing is defined as

$$d_{r,i}(t) = \dot{x}_i(t)\, t_{hd,i} \tag{8}$$

Considering the vehicle lengths, the actual inter-vehicle spacing is expressed as

$$d_i(t) = x_{i-1}(t) - x_i(t) - L_{r,i-1} - L_{f,i} \tag{9}$$

Hence, the spacing error becomes

$$e_i(t) = x_{i-1}(t) - x_i(t) - L_{r,i-1} - L_{f,i} - \dot{x}_i(t)\, t_{hd,i} \tag{10}$$

The control action includes feedback and feedforward terms. The feedback part regulates the spacing error, while the feedforward part uses the preceding vehicle acceleration.

Abstract

Cooperative adaptive cruise control (CACC), an extension of adaptive cruise control (ACC), is an important intelligent transportation solution for future mobility. It leverages vehicle-to-vehicle information to improve longitudinal tracking, traffic throughput, energy consumption, and string stability. However, controller tuning remains sensitive to model uncertainties and communication delay. This paper presents an analytical parameter-space-based fractional-order PD (FOPD) controller tuning framework for the CACC problem. For the constant-time headway spacing policy, the fractional-order controller parameters are explored over the (k_p, k_d, μ) parameter space, accounting for plant uncertainties. To enable a tractable stability assessment for the commensurate fractional-order characteristic equation, a variable transformation is used to obtain an equivalent polynomial form, and stability is then verified using the Hurwitz criterion. The resulting parameter-space maps provide a transparent graphical approach to controller gain and fractional-order selection. Moreover, the CACC design is implemented by a feedforward controller that uses preceding vehicle acceleration information within the predecessor-vehicle-following communication topology. The proposed method is tested in a vehicle platoon simulation environment with respect to string stability and the time-domain responses of position, velocity, acceleration, and headway time. The fractional-order CACC is compared with integer-order controllers. Simulation studies under representative CACC maneuvers demonstrate that the proposed parameter-space approach enables systematic FOPD tuning and achieves improved performance requirements compared to integer-order PD control.

Metric	ACC-IO	ACC-FO	CACC-IO	CACC-FO
$\|SS(s)\|_\infty$	$1 + 0.289 \times 10^{-15}$	1.0000	$1 + 0.155 \times 10^{-14}$	1.0000
String stability level (dB)	0.0000	-0.000001	0.0000	-0.000002
Settling average	0.06670	0.06640	0.00735	0.00726
Peak average	0.06670	0.06646	0.00736	0.00727

Table 1: Comparison of performance metrics for different ACC and CACC structures.

String Stability

String stability ensures that spacing disturbances do not grow along the platoon. The string stability condition is employed and verified in the frequency domain as

$$\|SS_i(s)\|_\infty \le 1 \Leftrightarrow \left|\frac{X_i(j\omega)}{X_{i-1}(j\omega)}\right| \le 1, \forall\omega \tag{11}$$

For the considered CACC structure, the string stability transfer function is written as

$$SS_{\text{CACC},i}(s) = \frac{\left(C_{fb,i}(s) + s^2 e^{-\beta s} C_{ff,i}(s)\right) G_i(s)}{1 + C_{fb,i}(s) G_i(s) H_i(s)} \tag{12}$$

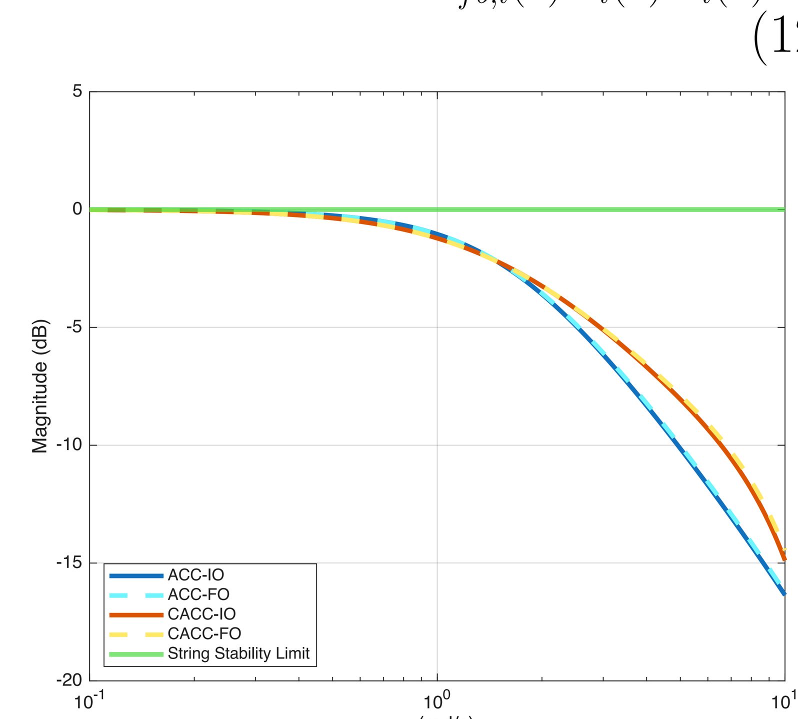

Figure 4: String stability comparison of different ACC and CACC structures.

Simulation Results

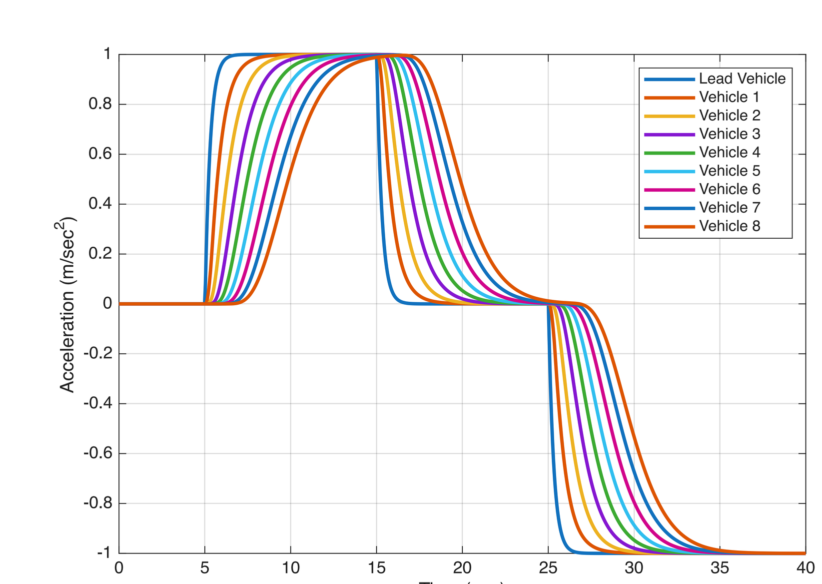

Figure 5: Acceleration profiles of the vehicles for the FO controller with $\mu = 0.97$.

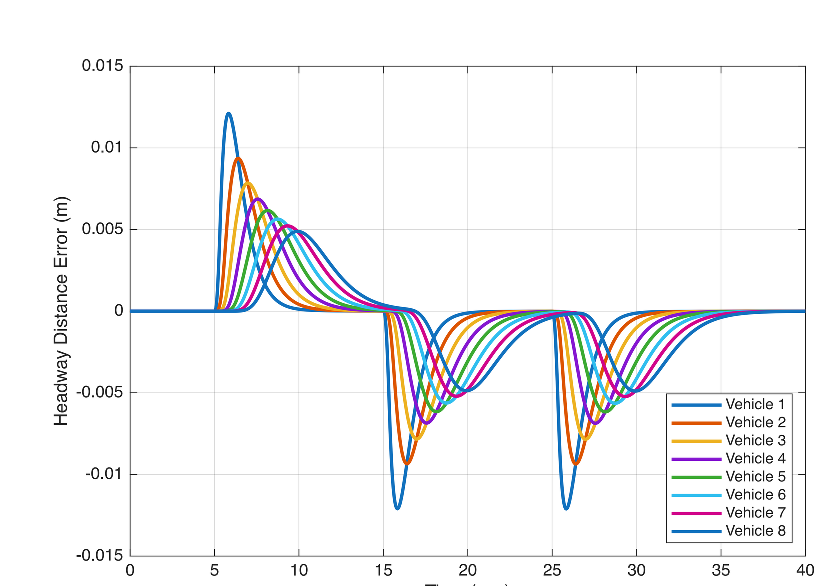

Figure 6: Headway distance errors of the follower vehicles with $\mu = 0.97$.

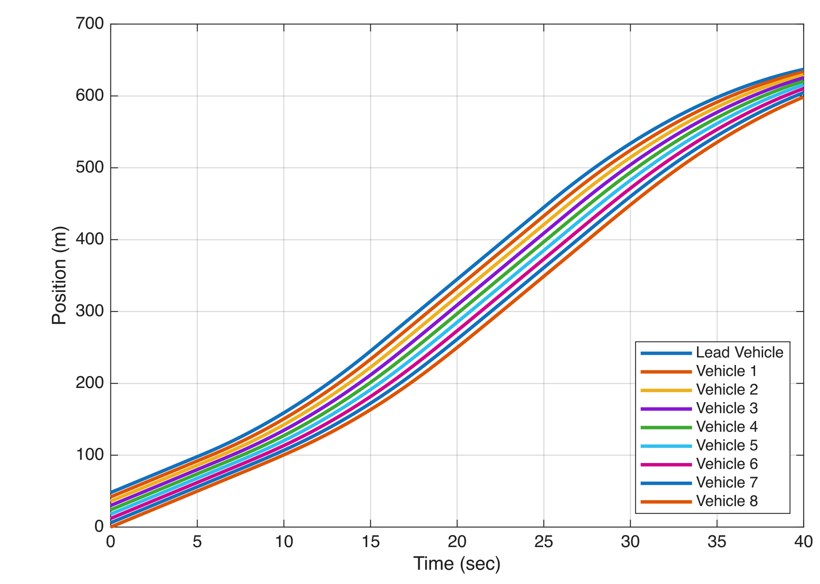

Figure 7: Position trajectories of the vehicles for the FO controller with $\mu = 0.97$.

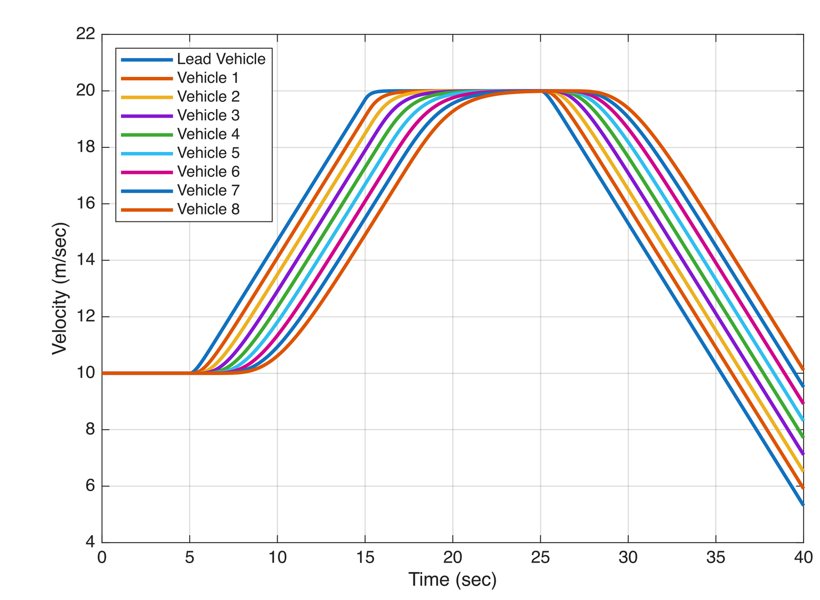

Figure 8: Velocity profiles of the vehicles for the FO controller with $\mu = 0.97$.

Conclusion

This study presented a parameter-space-based FOPD controller design framework for CACC systems under delayed vehicle dynamics. By considering both the controller gains and the fractional order as design variables, the proposed approach provides a systematic and practical way to identify stable controller settings. The results show that the fractional-order CACC structure preserves string stability and achieves slightly improved settling and peak response characteristics compared with the corresponding integer-order designs. Overall, the method offers an effective analytical tool for robust and transparent controller tuning in vehicle platooning applications.

References

[1] M.T. Emirler, L. Güvenç, and B.A. Güvenç. Design and evaluation of robust cooperative adaptive cruise control systems in parameter space. *International Journal of Automotive Technology*, 19(2):359–367, 2018.

[2] C. Flores and V. Milanés. Fractional-order-based ACC/CACC algorithm for improving string stability. *Transportation Research Part C: Emerging Technologies*, 95:381–393, 2018.

[3] F. Ma, J. Wang, Y. Yang, L. Wu, S. Zhu, S.Y. Gelbal, B.A. Guvenc, and L. Guvenc. Stability design for the homogeneous platoon with communication time delay: F. ma et al. *Automotive Innovation*, 3(2):101–110, 2020.

Contact Information

Email: dorukhan.astekin@std.yildiz.edu.tr*