Exploring the optimal feedback delays of a lane-keeping controller

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Abstract

This study presents a hierarchical lane-keeping controller for active steering systems, accounting for two sensory delays. We develop a dynamics model of the vehicle to examine the impact of these delays on system stability and control performance. Our approach includes upper-level feedback control for steering angle and lower-level steering torque control. We derive optimal control gains for various delay scenarios and identify the optimal delay combination for these gains. The findings show that the system achieves the fastest decay rate with the optimal control gains and delay combination, highlighting significant improvements in stability and performance.

Introduction

In the past twenty years, autonomous vehicle (AV) research has seen incredible progress. One area that is crucial for making these vehicles safe and stable is active steering control, as highlighted by [1]. Even though control systems have made essential progress, surprisingly little attention has been given to studying the effects of time delays within them, despite the fact that time delays persist as a critical issue.

Signal congestion has emerged as a significant challenge for modern AV systems. Variations in sensor configurations and estimation methods at the upper controller levels result in differences in feedback delays related to state variables in [2, 3]. These differences can potentially cause unforeseen effects on system behavior. Hence, conducting an in-depth investigation into the effects of two time delays within upper-level controllers is essential for developing robust and safe control for AV.

Vehicle dynamics modelling

- The lateral dynamics of vehicles are commonly studied using the well-known bicycle model, which assumes a constant longitudinal speed V_x (see Fig. 1). This model is widely used due to its simplicity and effectiveness in capturing vehicle behavior. V_y is the lateral speed, ψ is the yaw angle, δ is the steering angle, Ω is yaw rate, ω is the steering rate, X_G and Y_G represent the longitudinal and lateral position, respectively. In case of small tire deformations, the linearized brush tire model (see [4]) provides.

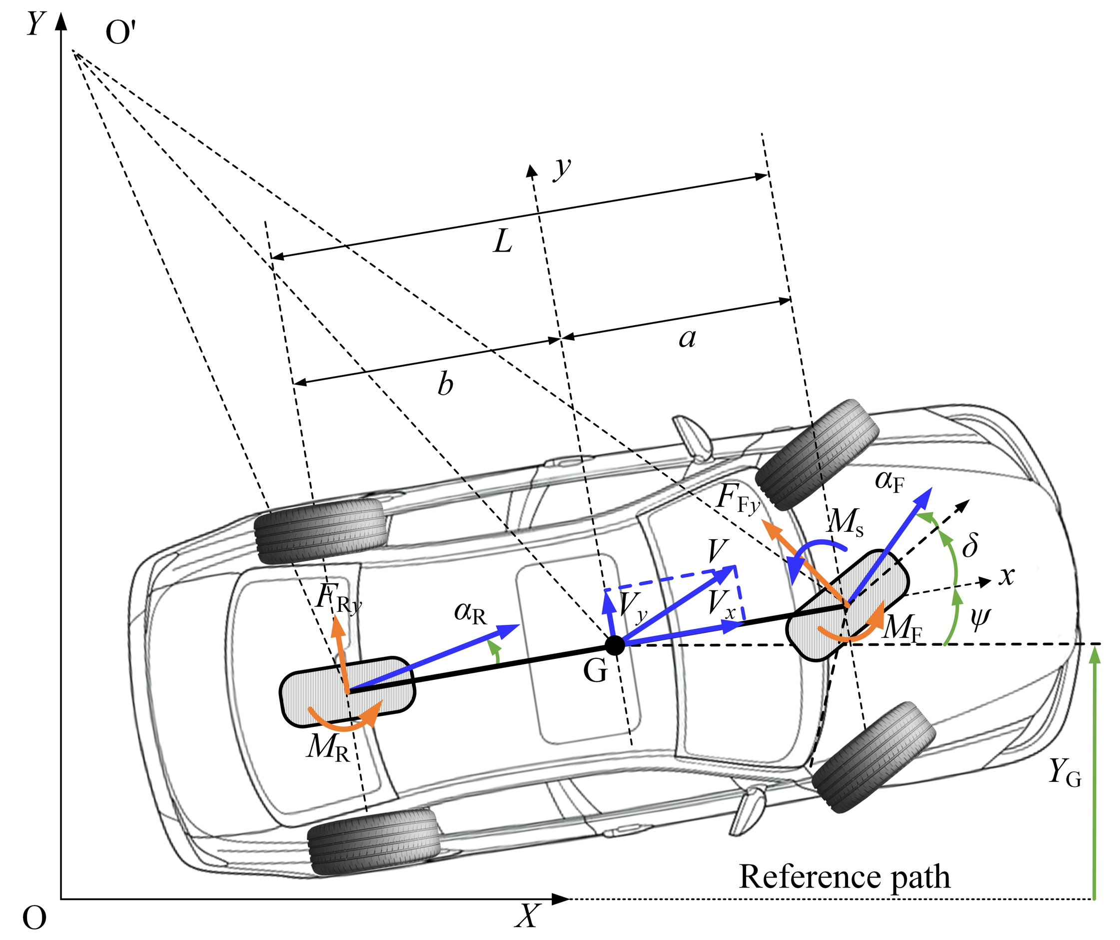

Figure 1: Representation of planar bicycle model and reference path.

- In case of the straight motion of the vehicle, the steady-state solution reads $V_y \equiv 0$, $\Omega \equiv 0$, $\omega \equiv 0$, $\psi \equiv 0$, $\delta \equiv 0$, $X_\mathrm{G} = V_x t$, and $Y_\mathrm{G} \equiv 0$. After linearizing the equations of motion considering the control laws. Thus, the state vectors $\mathbf{x}$ of the linearized closed-loop system can be defined as $\mathbf{x} = \left[Y_\mathrm{G}\ \psi\ \delta\ \dot{Y}_\mathrm{G}\ \Omega\ \omega\right]^\mathrm{T}$.

Hierarchical linear state feedback controller

- In this study, we consider that the desired path of the vehicle is the X-axis. Namely, the lateral error of the vehicle is the position Y_G of the vehicle's center of gravity, while the angle error is equal to the yaw angle ψ. To accomplish the vehicle path-following, a hierarchical steering control strategy is constructed.
- An upper-layer control law for calculating the desired steering angle δ_d is designed to accommodate variations in feedback delays for lateral position error and yaw angle error. The control law is based on a linear state feedback:

$$\delta_\mathrm{d}(t) = -P_y Y_\mathrm{G}(t-\tau_y) - P_\psi \psi(t-\tau_\psi)\,, \tag{1}$$

where P_y and P_ψ are the feedback control gains. The time delays corresponding to the different signals are τ_y and τ_ψ.

- In order to achieve the desired steering angle, the steering torque M_s is generated by a lower-level PD controller:

$$M_\mathrm{s} = -k_\mathrm{p}(\delta - \delta_\mathrm{d}) - k_\mathrm{d}\omega\,, \tag{2}$$

where k_p and k_d are the lower-level feedback gains.

The effects time delays on the linear stability

By means of the semi-discretization method[5], stability charts are constructed in the plane (P_y, P_ψ) of the higher level control gains while all the other parameters of the system are fixed. The control gain setup, for which the system has the most stable configuration (i.e., the largest absolute value of the characteristic multipliers of the semi-discretized system is minimal), can also be determined. This setup varies as the parameters of the system are changed, in the same way as with the variation of the time delays.

This is shown in Fig. 2, where the colorbar refers to the magnitude of the largest multiplier and time delays vary in a wide range. As it can be seen, there is an optimal time delay combination ($\tau_y = 0.27$ s and $\tau_\psi = 0.01$ s), where vibrations have fastest decay rate. In contrary to our physical sense, there are situations when increased delay may improve the stability of the vehicle system. For example, in case of having $\tau_y = 0.27$ s, using the increased delay $\tau_\psi = 0.479$ s results a better performance than in the case when we use $\tau_\psi = 0.114$ s. The numerical simulations are shown in Fig. 3. Panel (a) shows the time series of the lateral position,and panel (b) shows the yaw angle over time.

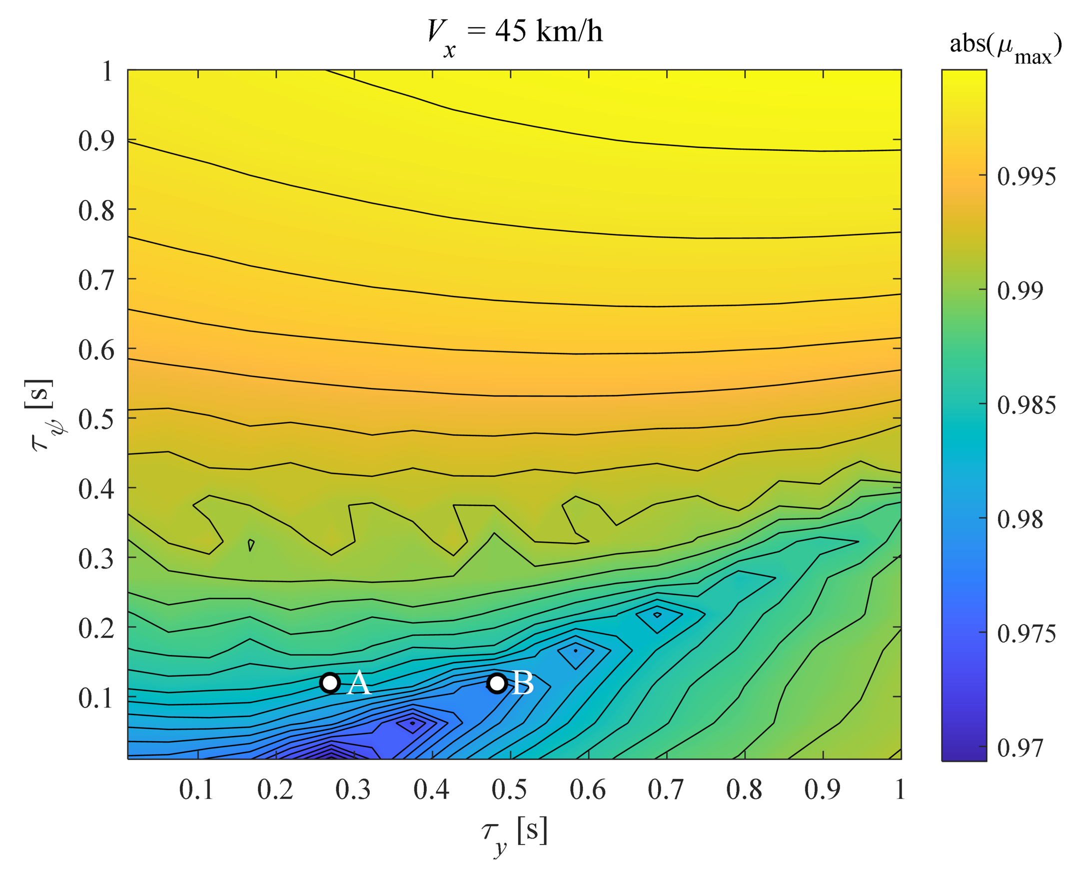

Figure 2: The characteristic multipliers related to the optimal gains for different combinations of time delays, A: $\tau_y = 0.27$ s and $\tau_\psi = 0.114$ s, B: $\tau_y = 0.479$ s and $\tau_\psi = 0.114$ s

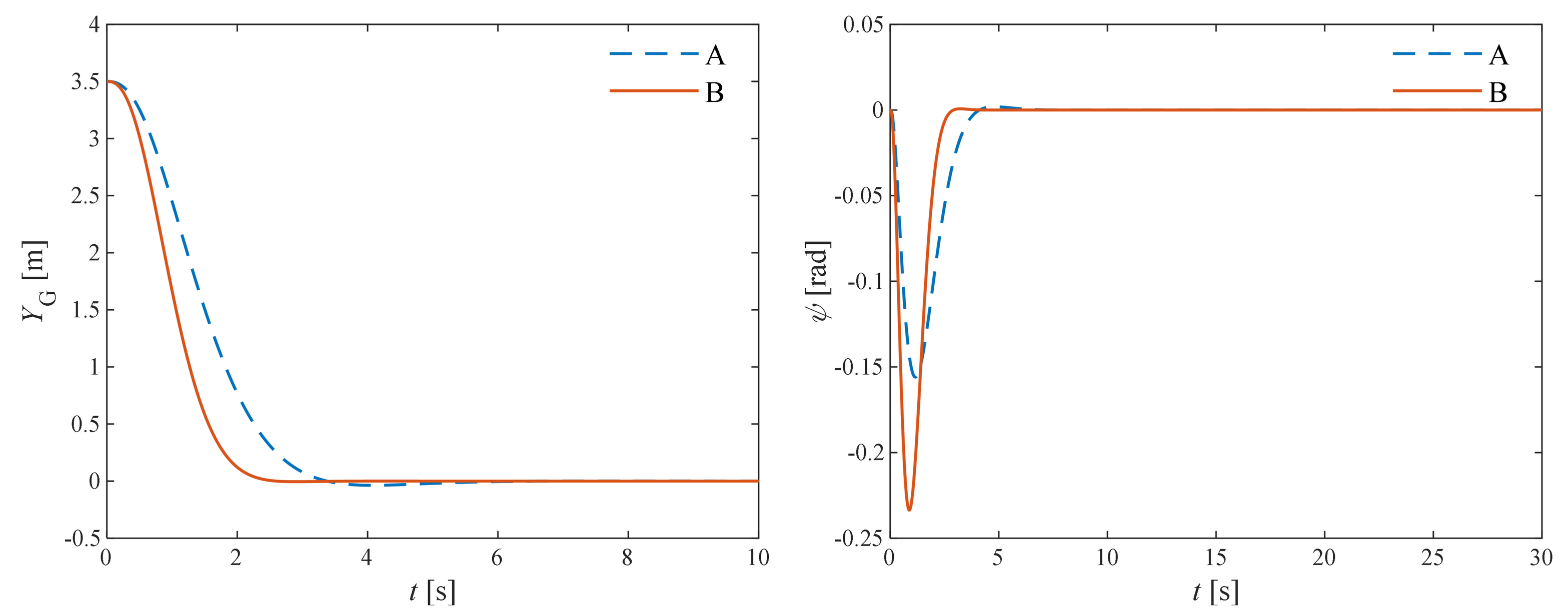

Figure 3: Simulations for different time delay combinations.

Conclusion

In summary, the analysis identifies the control gain setup that yields the most stable configuration, which varies with changes in system parameters, including time delays. Surprisingly, optimal combinations of time delays are found to enhance stability, with specific examples demonstrating improved performance even with increased delays. These findings challenge the conventional wisdom that time delays tend to destabilize dynamical systems: certain scenarios may benefit from larger time delays and these scenarios are also relevant in practical applications like the control of AV.

Acknowledgements

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