String stability of vehicle platoons

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1 Introduction

In recent years, highway capacity has become a limiting factor, regularly causing traffic jams. Obviously, the road capacity can be increased by decreasing the inter-vehicle following distance d_i. As a consequence, however, vehicle automation in longitudinal direction is required in order to still guarantee safety. To this end, Adaptive Cruise Control could be used, which is based on measurement of the inter-vehicle distance and the relative velocity by means of radar. It has however been shown [1] that this will amplify disturbances in upstream direction at short time gaps, causing so-called ghost traffic jams. Application of data exchange by means of wireless communication in addition, is shown to be able to attenuate these disturbances. This is called Cooperative Adaptive Cruise Control (CACC), illustrated in Figure 1 for a one-vehicle look-ahead communication structure.

2 Problem statement

An important control design objective for automated vehicle platoons is, therefore, the ability to attenuate perturbations introduced by an arbitrary vehicle in the platoon along the string in upstream direction. The notion of string stability refers to this requirement. As opposed to system stability, which is concerned with the evolution of system states over time, string stability focuses on the propagation of states over interconnected subsystems. Surprisingly, a uniform definition of string stability does not exist. It is the objective of this research to formalize the notion of string stability, forming a solid basis for CACC control design.

3 String Stability approach

Lyapunov-like approaches for string stability exist [2], but also performance-oriented interpretations are used [1]. An example of string unstable behavior is illustrated in the left part of Figure 2, showing the response of the velocity $v_i(t)$ of six vehicles to a ramp of the lead vehicle velocity $v_1(t)$. In order to arrive at a rigorous definition, it is proposed to formulate string stability in terms of input-output stability, i.e., requiring a bounded norm of the output $y_i(t)$ of vehicle i, with $i \to \infty$, taking the input $u_1(t)$ of the lead vehicle as external input, where $y_i(t)$ and $u_1(t)$ are for instance the velocity of vehicle i and the desired velocity of the lead vehicle, respectively. If the system is linear, the complementary sensitivity $P_i(s)$ can be calculated such that $Y_i(s) = P_i(s)U_1(s)$. Assuming functional controllability, the *string stability complementary sensitivity* $\Gamma_i(s)$ can be defined for all i:

$$\Gamma_i(s) \equiv P_i(s)P_{i-1}^{-1}(s) \tag{1}$$

such that $Y_i(s) = \Gamma_i(s)Y_{i-1}(s)$. As an example, the right part of Figure 2 depicts $|\Gamma_i(j\omega)|$, with $\Gamma_i(j\omega)$ being a scalar transfer function independent of i, in this particular case. Consequently, input-output stability leads to conditions on the norm of $\Gamma_i(j\omega)$, or its impulse response $\gamma_i(t)$, which can be readily used for controller synthesis.

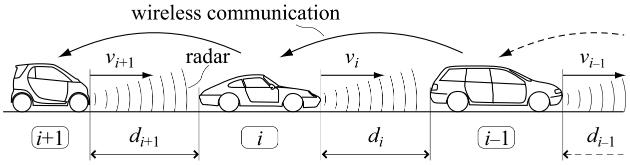

Figure 1: Schematic representation of a vehicle platoon.

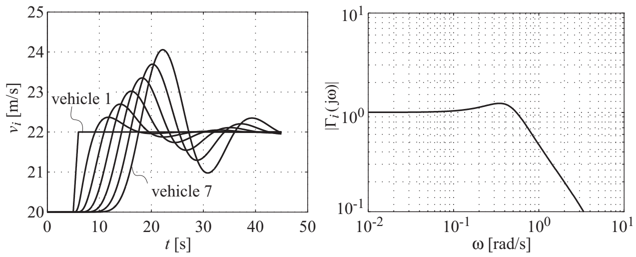

Figure 2: Time-domain response (left) and frequency-domain response (right) of a string-unstable vehicle platoon.

Future research focuses on control design for various communication structures, also taking into account the use of observers to accurately estimate the state of other vehicles.

References

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