String stability of a vehicular platoon with disturbances, using macroscopic information

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I. Abstract

Traffic control is one of the most studied issues in the last decades because of its impact on daily life and economics [1]. An increase in traffic efficiency has several positive effects, such as the reduction of dangerous emissions and of travel times due to less frequent and minor traffic congestion due to car accidents or traffic jams [2]. Different approaches have been proposed in the literature, as for example traffic management through intelligent infrastructures and the displacement of autonomous vehicles, either in fully autonomous platoon formations or with a certain level of penetration rate among normal vehicles (see [3] and [4]). Although autonomous vehicles are not a new idea, only recent developments in the transportation industry and in communication technologies allow considering their use in real traffic situations. In fact, nowadays Vehicle-to-Infrastructure (V2I) and Vehicle-to-Vehicle (V2V) communication technologies are a reality in the smart transportation domain [5], and enhance the employment of advanced control systems empowering the classical Adaptive Cruise Control (ACC) technology. Then, it is important to define dedicated control policies that guarantee the stability of the traffic flow by correctly exploiting the available shared data. Interconnected autonomous vehicles can indeed reduce stop-and-go waves propagation and traffic oscillations if they satisfy properties such as String Stability and Disturbance String Stability, which are based on the idea that the oscillations coming from a vehicle should not amplify backwards in the string [6], [7].

The present abstract is based on the framework developed in [8]. A platoon of autonomous vehicles is considered and a controller that uses macroscopic information is proposed. Each vehicle is considered to correctly measure the distance and the speed of its predecessor, using for example radar and LIDAR. The vehicles are supposed to share local and global information, either through V2V or V2I technology or both. The macroscopic information we use is embedded in a few variables, such as for example distance or speed difference mean and variance, and replaces the need for sharing some microscopic variables among the whole platoon, e.g. the head vehicle acceleration or its desired speed (see [7] and [9]). Consequently, no direct communication among the first vehicle and the others is required. Moreover, complexity reduction of both the considered interconnected framework and the system modeling is obtained, without any reduction of the level of available information.

The introduction of macroscopic information in a microscopic framework leads to a mesoscopic dynamical model based on a bottom-up approach. Mesoscopic models are already known in the literature, but usually they incorporate microscopic information in macroscopic models of the traffic flow in a top-down approach [10]. Indeed, this family of dynamical models is mainly used for the analysis of the traffic flow, e.g. for describing the influence of microscopic controllers on the whole traffic flow [11], [12]. On the contrary, here the macroscopic information is actively used for the control of autonomous vehicles, and a theoretical proof of the platoon Disturbance String Stability is given. Disturbance String Stability is a concept introduced in [9] that extends the classic definitions of String Stability and Asymptotic String Stability to the case where disturbances are present. This allows taking into account disturbances due to, for example, reference speed variation, external inputs, and unmodeled dynamics.

The dynamics of the vehicle $i \in \mathcal{I}_N = \{0, 1, 2, ..., N\}$ in the platoon together with the macroscopic information described by an appropriate dynamical system is represented by an extended state vector $\hat{\chi}_i$. Let $\hat{\chi}_{e,i}$ be the corresponding equilibrium point. Disturbance String Stability can be defined as follows [9]:

Definition 1. *(Disturbance String Stability) The equilibrium $\hat{\chi}_{e,i}$, $i \in \mathcal{I}_N^0$, in closed loop is said to be Disturbance String Stable if there exist functions β_d of class $\mathcal{KL}$ and σ_d of class $\mathcal{K}_\infty$ and constants $\delta > 0$, $\delta_d > 0$, such that, for any initial condition $\hat{\chi}_i(0)$ and disturbance $\bar{d}_i$ satisfying*

$$\max_{i \in \mathcal{I}_N^0} |\hat{\chi}_i(0) - \hat{\chi}_{e,i}| < \delta, \ \max_{i \in \mathcal{I}_N^0} |\bar{d}_i(\cdot)|_\infty^{[0,t]} < \delta_d \tag{1}$$

the solution $\hat{\chi}_i(t)$ exists for all $t \geq 0$ and satisfies

$$\max_{i \in \mathcal{I}_N^0} |\hat{\chi}_i(t) - \hat{\chi}_{e,i}| \leq \beta_d \left(\max_{i \in \mathcal{I}_N^0} |\hat{\chi}_i(0) - \hat{\chi}_{e,i}|, t \right) + \sigma_d \left(\max_{i \in \mathcal{I}_N^0} |\bar{d}_i(\cdot)|_\infty^{[0,t]} \right). \tag{2}$$

In the present work we design a mesoscopic controller that exploits macroscopic information to ensure Disturbance String Stability. A variable time spacing policy based on the

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shared macroscopic variables is defined, and the stability of the platoon subject to external disturbances is shown. Although our focus is the control of autonomous vehicles in platoon formation, the stability results are proven for a general class of cascaded interconnected systems and, as a consequence, can be applied to any system in this class.

Simulations show the efficacy of the proposed approach and the capability of each vehicle in the platoon to avoid the amplification of the oscillations deriving from both speed reference variation and external disturbances acting on each vehicle. Indeed, thanks to the macroscopic information, each vehicle has a global view on all its predecessors. Consequently, it is able to identify if the platoon is in a transient or steady-state situation, and to anticipate its reaction with respect to it. This leads to a filtering of the oscillations propagating from the head vehicles. We consider a platoon of $N + 1 = 31$ vehicles with perturbed initial conditions, and several sinusoidal disturbances acting on each vehicle. Moreover, each vehicle actuates its input with a delay that is not directly taken into account in the modeling. This actuator delay can be seen as an additional unknown disturbance. The simulation results, reported in Figures 1 and 2 corresponding respectively to the distance trajectories and the speed difference trajectories, show that the proposed controller is able to guarantee Disturbance String Stability for the platoon. It can be seen that the perturbations due to the initial conditions ($t \in [0, 15]$ s), to the speed reference variation ($t \in [15, 30]$ s) and to the external disturbance acting on each vehicle ($t \in [30, 60]$ s) do not amplify through the string of vehicles.

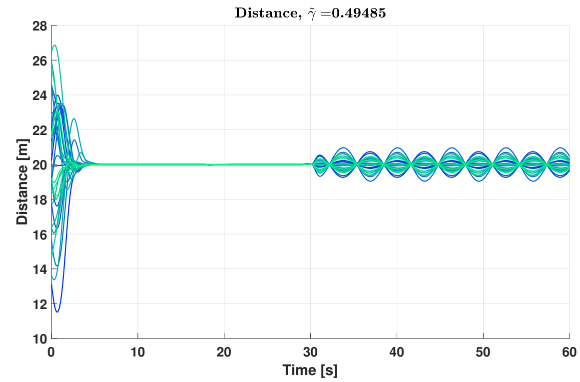

Fig. 1. Inter-vehicular distances ($-\Delta p_i$): each line represents the distances between vehicles $(i-1, i)$, $i = 1, ..., N$. The color scale from the blue tint to the light green one represents the vehicles of the platoon, from the head vehicles to the tail ones respectively.

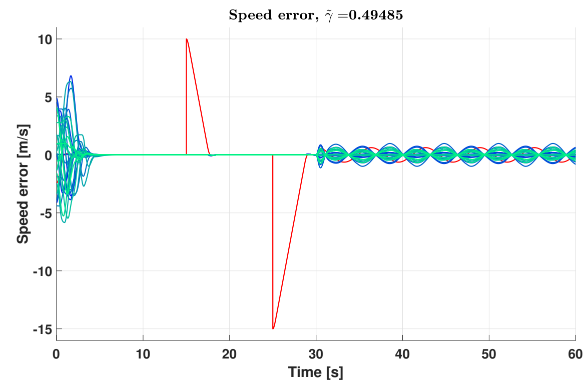

Fig. 2. Inter-vehicular speed differences ($-\Delta v_i$): each line represents the speed errors between vehicles $(i-1, i)$, $i = 1, ..., N$. The color scale from the blue tint to the light green one represents the vehicles of the platoon, from the head vehicles to the tail ones respectively. The red line is associated to the speed difference between vehicle $i = 0$ and $\bar{v}$.

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