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# Infrastructure assisted adaptive driving to stabilise heterogeneous vehicle strings

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A B S T R A C T

Literature has shown potentials of Connected/Cooperative Automated Vehicles (CAVs) in improving highway operations, especially on roadway capacity and flow stability. However, benefits were also shown to be negligible at low market penetration rates. This work develops a novel adaptive driving strategy for CAVs to stabilise heterogeneous vehicle strings by controlling one CAV under vehicle-to-infrastructure (V2I) communications. Assumed is a roadside system with V2I communications, which receives control parameters of the CAV in the string and estimates parameters *imperfectly* of non-connected automated vehicles. It determines the adaptive control parameters (e.g. desired time gap and feedback gains) of the CAV if a downstream disturbance is identified and sends them to the CAV. The CAV changes its behaviour based on the adaptive parameters *commanded* by the roadside system to suppress the disturbance.

The proposed adaptive driving strategy is based on string stability analysis of heterogeneous vehicle strings. To this end, linearised vehicle dynamics model and control law are used in the controller parametrisation and Laplace transform of the speed and gap error dynamics in time domain to frequency domain enables the determination of sufficient string stability criteria of heterogeneous strings. The analytical string stability conditions give new insights into automated vehicular string stability properties in relation to the system properties of time delays and controller design parameters of feedback gains and desired time gap. It further allows the quantification of a *stability margin*, which is subsequently used to adapt the feedback control gains and desired time gap of the CAV to suppress the amplification of gap and speed errors through the string.

Analytical results are verified via systematic simulation of both homogeneous and heterogeneous strings. Simulation demonstrates the predictive power of the analytical string stability conditions. The performance of the adaptive driving strategy under V2I cooperation is tested in simulation. Results show that even the estimation of control parameters of non-connected automated vehicles are imperfect and there is mismatch between the model used in analytical derivation and that in simulation, the proposed adaptive driving strategy suppresses disturbances in a wide range of situations.

## 1. Introduction

Automated vehicles have attracted considerable attention from the public since they may completely change the way we operate our vehicles today and consequently may have great implications for the tra c operations. It is therefore important to design such systems in a scrutinized manner to ensure benefits to the tra c systems. Automated vehicles can be classified as non-connected/

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autonomous and connected/cooperative vehicle systems. Non-connected automated vehicles (NAVs) rely solely on on-board sensors (VanderWerf et al., 2001; Kesting et al., 2008; Xiao and Gao, 2011; Mullakkal-Babu et al., 2016), while connected automated vehicles (CAVs) exchange (e.g. output, state or control) information with each other via Vehicle-to-Vehicle (V2V) communication or with road infrastructure via Vehicle-to-Infrastructure (V2I) communication to improve situation awareness and/ or to manoeuvre together under a common goal (Varaiya and Shladover, 1991; Van Arem et al., 2006; Wang et al., 2014b; Ge and Orosz, 2014; Wang et al., 2015; Milanés and Shladover, 2014).

Adaptive Cruise Control (ACC) is one of the earliest NAV systems, which is designed to enhance driving comfort (VanderWerf et al., 2001). The most widely used ACC systems is based on linear state feedback control, where the controlled acceleration is proportional to the deviation of the gap from a desired value under the constant time gap (CTG) policy and the speed error, i.e. the relative speed with respect to the preceding vehicle (VanderWerf et al., 2001; Ploeg et al., 2014; Mullakkal-Babu et al., 2016).

One of the problems with autonomous ACC is the string instability, i.e. tracking errors in one vehicle can be amplified when propagating in a platoon. The major influencing factors for vehicular string stability properties are the system properties, notably time delays of the vehicle dynamic system, and control (design) parameters, e.g. the desired gap and feedback gains. Two types of system delays can be distinguished, being sensor delay and actuator lag (Xiao and Gao, 2011; Wang et al., 2016c). Sensor delay is caused by the process of sensing and filtering, due to the discrete sampling of on-board measurements, the radar or lidar filtering, and the bandwidth of low pass filters used for other sensors such as wheel speed sensors (Xiao and Gao, 2011; Wang et al., 2017). The actuator lag lies in the lower level of the vehicle control system when executing the desired acceleration command from the upper level ACC controller, due to the time delay in the generation of traction/brake wheel torques in the power-train or brake actuator (Xiao and Gao, 2011).

Much work on control design and stability analysis of NAV/CAV platoons did not explicitly address both time delays (Wang et al., 2014a; Ge and Orosz, 2014; Jia and Ngoduy, 2016; Zhang and Orosz, 2016; Zhou et al., 2017; Talebpour and Mahmassani, 2016). Omitting the combination of sensor delay and actuator lag in the control loop may result in over-optimistic evaluations of the controller performance and the corresponding impacts on traffic flow (Wang et al., 2016c). Few studies addressed both sensor delay and actuator lag, but are restricted to the linear feedback control law with the CTG policy (Xiao and Gao, 2011). String stability conditions of autonomous vehicle platoons employing general nonlinear gap policies with both sensor delay and actuator lag remain largely unresolved.

With V2V communication, cooperative ACC (CACC) systems that use information of platoon leader, multiple predecessor or the acceleration of the direct predecessor in addition to on-board measurements lead to enhanced string stability performance. As a result, CACC can maintain much shorter time gaps compared to ACC systems and has potential to increase roadway capacity (Van Arem et al., 2006; Shladover et al., 2012; Milanés and Shladover, 2014; Jia and Ngoduy, 2016). The fact that CACC leads to enhanced string stability properties with information from multiple predecessors is that the additional term in the control law works as a feedforward term and compensates system delays effectively (Treiber et al., 2006). However, CACC systems require CAVs following each other in a platoon. At low market penetrations rates, the probability of CACC vehicles forming a platoon in an ad-hoc way is very low and the potentials of the CACC system are thus confined. To circumvent the problem, a few approaches have been proposed, including variant of CACC systems that seek consensus control decisions using multiple vehicles ahead in a heterogeneous fashion (Ge and Orosz, 2014; Ngoduy, 2015; Monteil et al., 2014) or optimize platoon performance looking at not only the vehicles in front but also (human-driven) followers (Wang et al., 2014b, 2016b). However, this still requires substantial penetration rates of equipped vehicles to enable the connectivity. Otherwise, the variant CACC system based on V2V communication will only generate traffic benefits at low probabilities.

Parallel to V2V based systems, another paradigm in cooperative traffic systems aims to connect traffic control with vehicle control with V2I/I2V communication, using CAVs as distributed sensors (Hegyi et al., 2013) and actuators (Wang et al., 2016a). The combination of the aforementioned problem and the V2I/I2V based traffic control paradigm leads to the main objective of this contribution: to design an adaptive driving strategy for CAVs in mixed vehicular strings to attenuate disturbances at low market penetration rates under *vehicle-infrastructure cooperation*. We assume that a roadside system with V2I communications receives control parameters of CAVs in a string and estimates car-following parameters (imperfectly) of non-connected human-driven/automated vehicles. Given this assumption, the key is to determine the control parameters of the CAV to suppress a downstream disturbance and send them to the CAV via communication. The CAV changes its behaviour based on the adaptive parameters *commanded* by the road infrastructure. The CAV restores its default parameters once the disturbance is attenuated.

The adaptive driving strategy is based on string stability analysis of vehicle strings around equilibria. We derive sufficient conditions for string stability of a general heterogeneous platoon with mixed vehicle classes and different parameter settings. To this end, linearised vehicle system dynamics model and the acceleration control law is used in control parametrisation and Laplace transform of the speed and gap error dynamics in time domain to frequency domain enables the determination of sufficient string stability criteria of a heterogeneous vehicle string. The sufficient conditions give new insights into the relationship between the string stability properties, the system properties of time delays and controller design parameters of feedback gains and desired time gap. The sufficient conditions further allow the quantification of a stability margin, which is subsequently used to parametrise the feedback control gains and desired time gap of the CAV to suppress the amplification of gap and speed errors in a platoon.

The proposed approach is applied to examine the influence of control design parameters and system delays on the resulting string stability of ACC vehicles and to find the adaptive parameter range of adaptive driving to stabilise a vehicle string passing a disturbance that is unstable otherwise. We verify the analytical results with simulation of vehicle strings subject to exogenous disturbance, parameter estimation error and modelling uncertainties, assuming the infrastructure has *imperfect* knowledge on behaviours of non-connected vehicles in the platoon.