WiP Abstract: String stability of commercial adaptive cruise control vehicles

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George Gunter†[1], Yanbing Wang[1], Derek Gloudemans[1], Raphael Stern[1], Daniel Work[1], Maria Laura Delle Monache[2], Rahul Bhadani[3], Matt Bunting[3], Roman Lysecky[3], Jonathan Sprinkle[3], Benjamin Seibold[4], and Benedetto Piccoli[5]

[1]Vanderbilt University, Nashville, Tennessee,USA
[2]Univ. Grenoble Alpes, Inria, CNRS, Grenoble INP, GIPSA-Lab, 38000 Grenoble, France
[3]University of Arizona, Tucson, Arizona, USA
[3]Temple University, Philadelphia, Pennsylvania,USA
[3]Rutgers University, Camden, New Jersey, USA

1 Introduction

Adaptive cruise control (ACC) is the first wave of vehicle automation that will reach the mainstream. It has been shown in [3] that automation of a small fraction of vehicles in traffic (e.g., 5%) can change the emergent properties of the flow, for example by dissipating phantom jams. Substantial theoretical and experimental underpinnings of vehicle automation and platooning were established in the from the USDOT Automated Highway System effort [1]. However, it is not yet clear whether the ACC vehicles that are currently commercially available will dampen or amplify phantom jams.

The relevant measure for phantom traffic jam occurrence is string stability, which tells whether small perturbations from the equilibrium flow are amplified (unstable) or dissipated (stable) as they propagate from one vehicle to another along a string of vehicles. It has been shown that by using vehicle connectivity, ACC controllers can be designed to be string stable. Yet the commercially available ACC vehicles do not use connectivity. There is also significant interest to model the real impacts of ACC vehicles in the traffic flow by the traffic engineering community.

In this work, we conduct a series of car-following experiments with seven different ACC vehicles and use the collected data to model the car-following behavior of each vehicle. Using a linear stability analysis, the string stability of each tested vehicle is analyzed. Additionally, platoon experiments with platoons of up to eight identical vehicles are conducted to validate the stability findings. Previously, only one commercial ACC system has been evaluated for string stability [2]. The visual aspects of the data make this work best suited for a poster presentation.

2 Experimental Data Collection

The goal of the experimental collection is to collect data to characterize the string stability of a broad range of commercially available ACC vehicles and test their performance. Furthermore, each vehicle tested has several different following settings. To test the range of behaviors, the maximum and minimum following setting are tested for each vehicle. Experimental data are collected for a total of seven different vehicles. In each experiment, a lead vehicle drives with a pre-determined speed profile. The following (test) vehicle then drives behind the lead vehicle with ACC engaged. The position and speed of each vehicle are measured with high-accuracy GPS receivers on each vehicle. Additionally, overhead video footage is recorded with a drone.

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†email:gunter1@illinois.edu

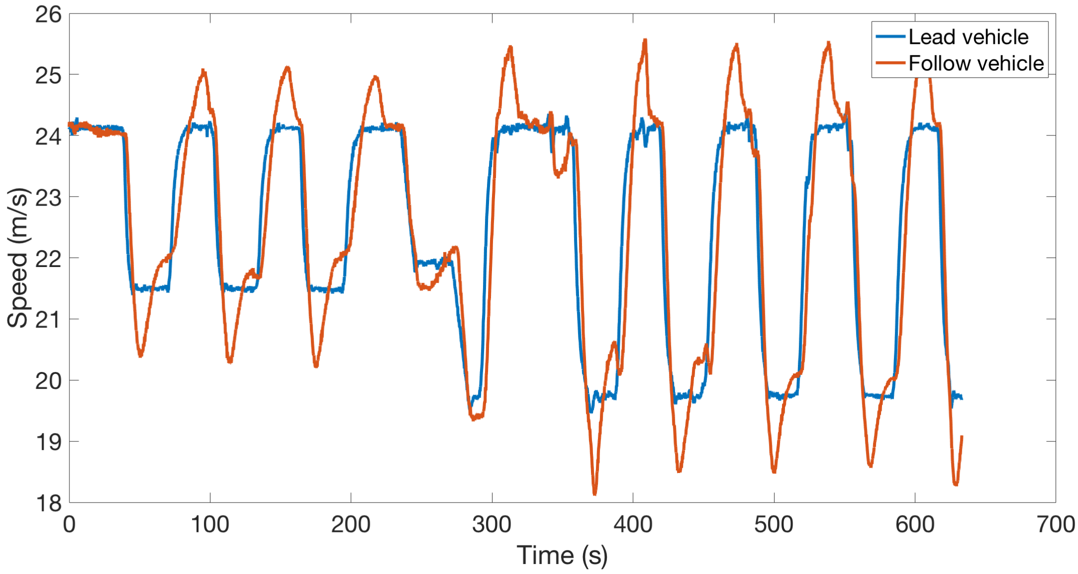

Figure 1: Sample data from car following experiment showing lead vehicle executing pre-determined speed profile and test vehicle following under ACC.

For each vehicle, a series of repeatable experiments is conducted to test the ACC behavior at different speeds, relative speeds, and at different following settings. An example of such an experiment is presented in Figure 1, where the lead vehicle (blue) drives a pre-specified speed profile and the subject vehicle (red) follows with ACC engaged. A total of over 1,200 miles of driving data are collected as part of these experiments.

Additionally, platoon experiments with between four and eight vehicles arranged as seen in Figure 2 are conducted. For these experiments, the lead vehicle drives a pre-determined speed profile and all test vehicles follow with ACC engaged.

3 ACC Model and calibration

A constant time headway model is fit to the experimental data and the string stability of the calibrated model is assessed. The ACC system is modeled as an *optimal-velocity relative-velocity* (OVRV) model with an optimal velocity component that corresponds to a constant effective time-gap term:

$$\dot{v} = f(s, v, \Delta v) = k_1(s - \eta - \tau_e v) + k_2(\Delta v). \tag{1}$$

Here s is the inter-vehicle space gap, v is the speed of the ACC vehicle, Δv is the relative speed with respect to the vehicle immediately in front of the ACC vehicle, η is the jam distance (space-gap when vehicles are stopped), τ_e is the desired effective time-gap, k_1 is the gain parameter on the constant effective time-gap term, and k_2 is the gain parameter on the relative velocity term.

Model (1) is calibrated to find the best-fit model parameters (k_1, k_2, η, τ_e) by solving a constrained optimization problem with the objective to minimize the mean square velocity error between the simulated ACC vehicle speed using the calibrated model parameters, and the ACC speed observed in the experiments.

4 String Stability Results

The string stability of each vehicle tested is analyzed using a linear stability analysis. Specifically, the condition outlined by Wilson and Ward [4] is used to check string stability:

$$\lambda_2 := \frac{f_s}{f_v^3}\left[\frac{f_v^2}{2} - f_{\Delta v} f_v - f_s\right] < 0. \tag{2}$$

Figure 2: Platoon of vehicles in experiment with lead vehicle followed by four test vehicles and a safety chase vehicle. Test vehicle fronts blurred to remove branding.

Here $f_s = \partial f/\partial s \geq 0$ is the partial derivative of f with respect to space gap, $f_{\Delta v} = \partial f/\partial \Delta v \geq 0$ is the partial derivative of f with respect to the relative speed, and $f_v = \partial f/\partial v \leq 0$ is the partial derivative of f with respect to the speed.

Using the string stability criterion (2), the interaction between the lead vehicle and the following vehicle for each vehicle tested is found to be string unstable. Thus, each vehicle tested will amplify some perturbations as they propagate from one vehicle to the next, causing the resulting traffic wave to grow. This is validated in the platoon experiments where small perturbations from the equilibrium flow are amplified as they propagate from one vehicle in the platoon to the next.

5 Further work

Additional efforts will address how to calibrate more nuanced models for the ACC vehicle that can be used to better model ACC vehicle behavior in simulation. Further analysis will also reveal what ranges of disturbance frequencies are amplified, and what ranges of frequencies are dissipated. Another interesting possibility is that a heterogeneous platoon of several different vehicle makes could amplify disturbances, or be susceptible to certain disturbances, as we will explore in further analysis. The string stability analysis that will result from this work will help further the understanding of how changing the dynamics of some vehicles in the traffic flow will change the emergent properties of the flow.

6 Acknowledgements

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