# Phantom Traffic Jams from Adaptive Cruise Controlled Vehicles


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## Background and Motivation

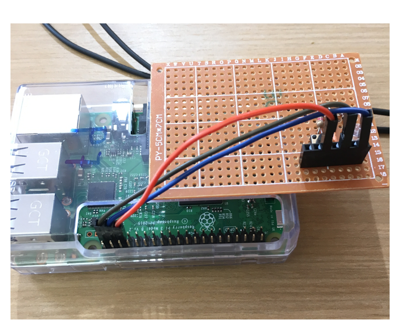
- Traffic jams arise due to human driving behavior alone because traffic is unstable
- Adaptive cruise control (ACC) is becoming a standard feature on commercially-available cars and are the first step toward an autonomous future
- Unclear how ACC vehicles contribute to or detract from traffic stability

Objective: Measure the response of ACC controlled vehicles to disturbances in a traffic stream.

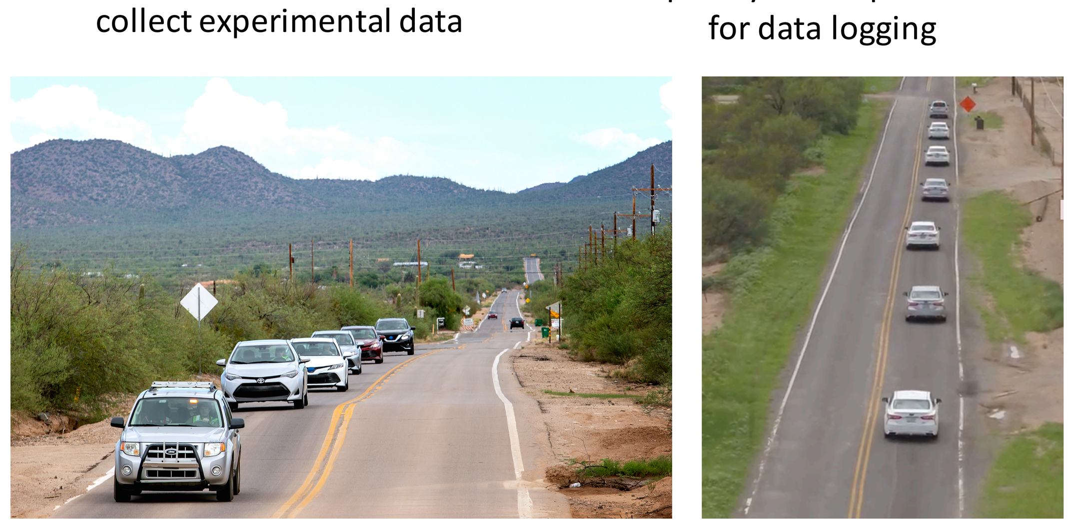
## Experimental Setup

- Test 7 common, commercially-available ACC vehicles
- Lead vehicle drives a specific speed profile
- Observe response of following vehicle
- Test platoons of up to 8 ACC vehicles to verify unstable driving behavior
- Use uBlox GPS sensor to track each vehicle throughout the experiment

uBlox evaluation kit used to collect experimental data



Raspberry Pi computer used for data logging

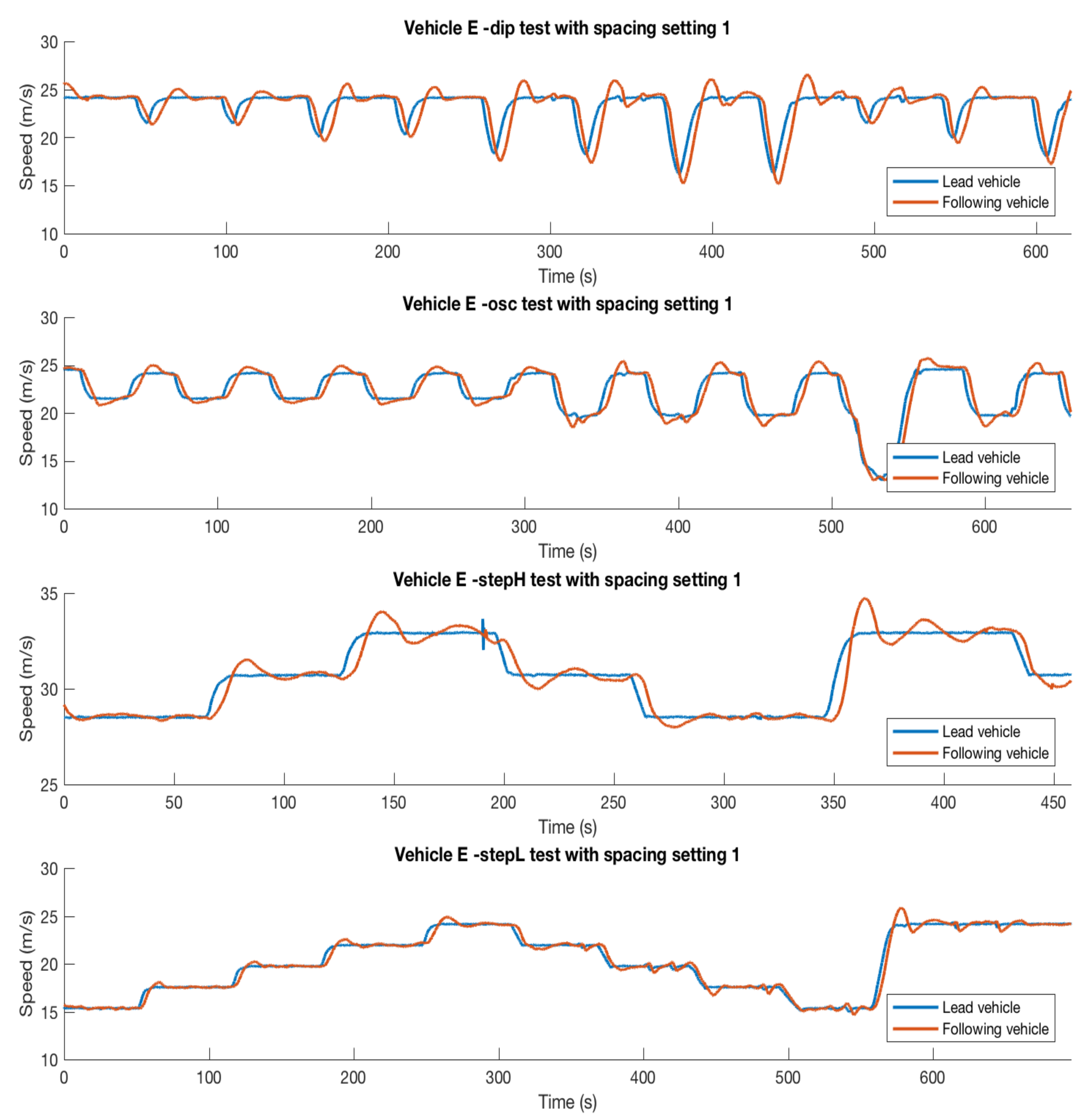


Platoons of vehicles were driven in a series of testing events, taking place in Tucson AZ, in order to record stability of ACC vehicles.

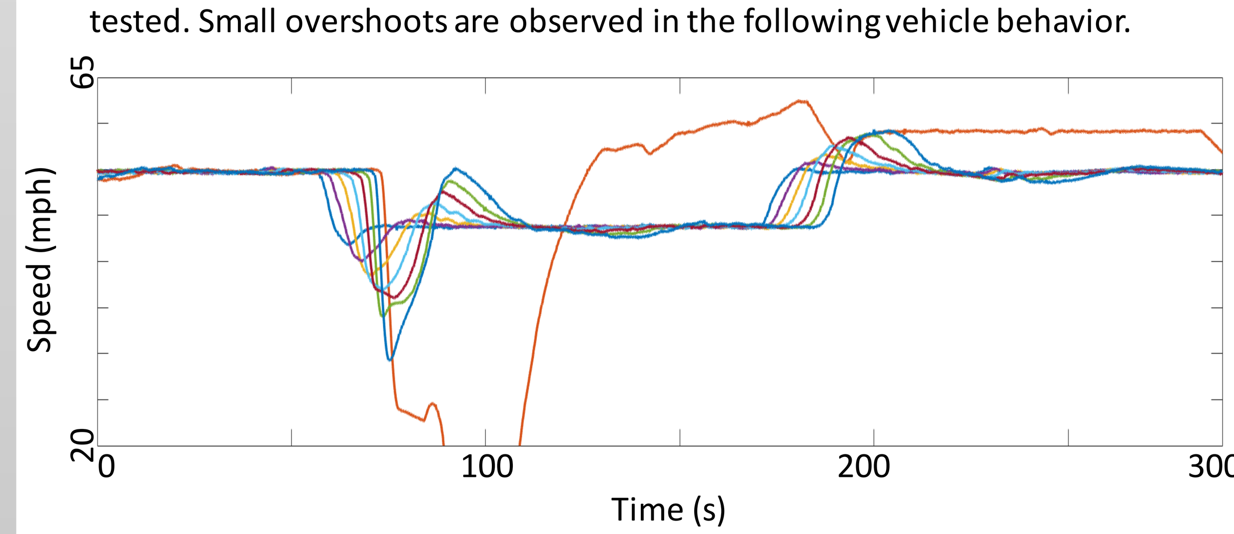
The CAT Vehicle at the University of Arizona, which can be driven autonomously, was used to create very precise traffic patterns.

## Experimental Data

- Conducted both two-vehicle tests and platoon tests
- Standardized testing protocol developed to identify instabilities in the ACC controller




GPS data from car following experiments conducted with all vehicles tested. Small overshoots are observed in the following vehicle behavior.




Speed data collected from platoon of 8 ACC vehicles showing clear overshoot in following vehicle behavior that amplifies upstream.

- Instability verified in platoon experiment with 8 vehicles

## ACC Vehicle Model

- Use a constant time headway second-order ODE to model vehicle acceleration as function of spacing, speed, and relative speed

$$\ddot{x} = f(s, v, \Delta v) = k_1(s - \tau v) + k_2(\Delta v)$$

Desired acceleration — Relaxation toward desired headway — Relaxation toward lead vehicle velocity

- Acceleration: $\ddot{x}$, spacing: $s$, speed: $v$, relative speed: $\triangle v$, headway: $\tau$, model parameters: $k_1$ and $k_2$

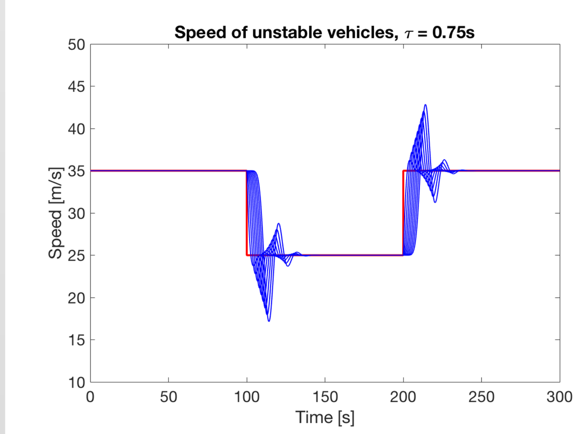
## Traffic String Stability

- String stability is is the mathematical way to quantify whether or not phantom jams will arise
- String stability tells if small perturbations from equilibrium amplify or decay as they propagate upstream
- Define ACC model partial derivatives:

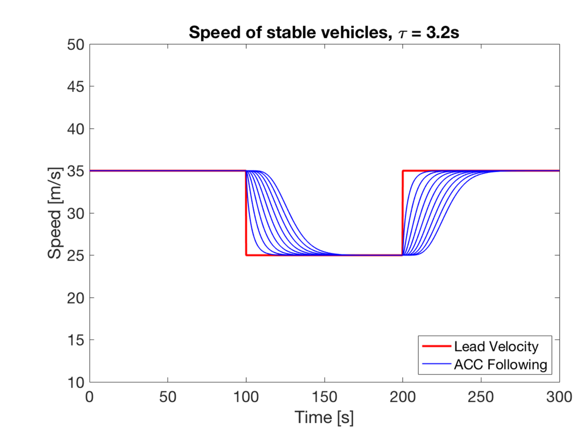
$$f_s = k_1 > 0, \quad f_{\Delta v} = k_2 > 0, \quad f_v = -k_1\tau < 0.$$

- String stability holds if:

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



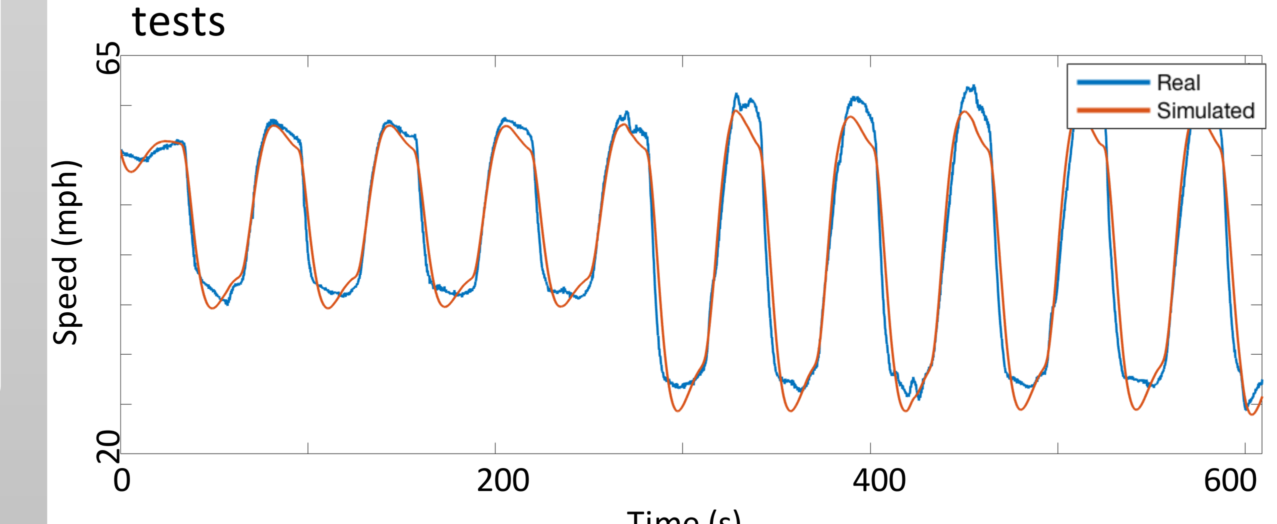

Platoon of string unstable vehicles showing amplification of disturbance.



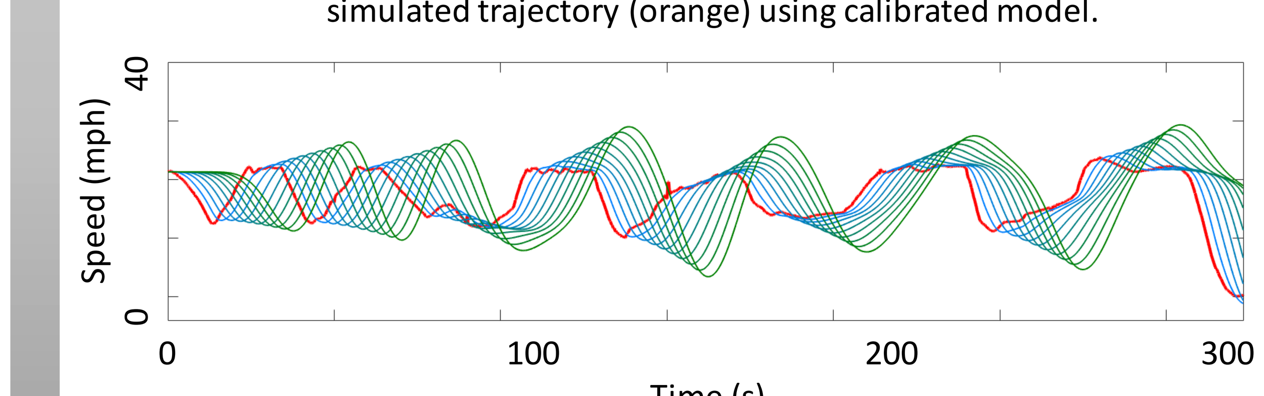

Platoon of string stable vehicles showing dissipation of disturbance.

## Model Calibration

- Calibrate model by selecting $k_1$, $k_2$ to minimize error between simulated headway and calibrated headway
- Simulation results show good agreement with collected vehicle trajectories for both two-vehicle tests and platoon tests




Vehicle speed profile of real trajectory (blue) and simulated trajectory (orange) using calibrated model.




Simulation of unstable platoon of ACC vehicles showing amplification of traffic waves through the platoon.

## Stability Results and Future Work

- Stability of tested vehicles analyzed by fitting car following model and determining sign of $\lambda_2$

| Vehicle | $k_1$ | $k_2$ | τ | Stability |
|---|---|---|---|---|
| Vehicle 1 | 0.0535 | 0.0645 | 1.44 | Unstable |
| Vehicle 2 | 0.0704 | 0.157 | 1.41 | Unstable |
| Vehicle 3 | 0.0379 | 0.140 | 1.57 | Unstable |
| Vehicle 4 | 0.0512 | 0.0945 | 1.49 | Unstable |
| Vehicle 5 | 0.0583 | 0.0958 | 1.54 | Unstable |
| Vehicle 6 | 0.0848 | 0.0652 | 1.42 | Unstable |
| Vehicle 7 | 0.0803 | 0.0657 | 1.46 | Unstable |

Calibrated parameter values for each vehicle and stability of the ACC system as computed using $\lambda_2$.

- All tested vehicles were observed to exhibit instabilities

## Research Outcomes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- M. L. Delle Monache, T. Liard , A. Rat, R. Stern, R. Bhadani, B. Seibold, J. Sprinkle, D. Work, B. Piccoli. "Feedback control algorithms for the dissipation of traffic waves with autonomous vehicles." Book: Computational Intelligence and Optimization Methods for Control Engineering, 2018.
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- R. Stern, Y. Chen, F. Wu, M. Churchill, D. Work. "Reducing Emissions Resulting from Stop-and-Go Traffic Waves using Automated Vehicles." Submitted to Transportation Research Part D: Transport and Environment, 2018.
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