Controlling mixed human and autonomous traffic

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Joint work with: George Gunter, Maria Laura Delle Monache, Benedetto Piccoli, Benjamin Seibold, Jonathan Sprinkle, Fangyu Wu, and Daniel Work

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Broader context: impacts of autonomous vehicles

- What will happen to VMT?
  - If pooled autonomous shuttles become common: VMT decrease
  - If AV becomes a chauffeur: VMT increases
- What will happen to land use?
  - If no more need for parking: cities become denser
  - If we enable extreme commuters: cities become more sprawling
- What happens to safety?
  - Benefits even before all vehicles are fully autonomous

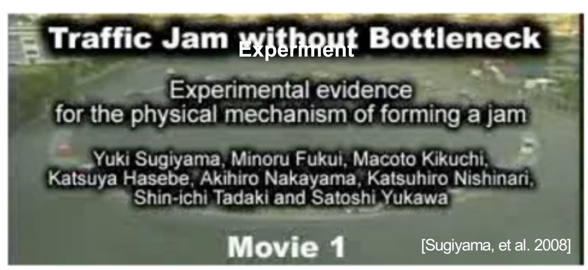





[Samaranayake, et al. 2017; Levin and Boyles, 2015; Walker, et al. 2017; Wadud, MacKenzie, Leiby, 2015; Anderson, et al. 2014; Fragnat and Kockelman, 2015]

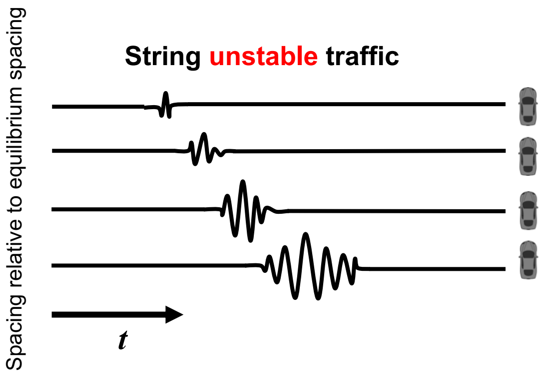
How will increased vehicle autonomy influence traffic flow?

Phantom traffic jams: real jams that happen for no apparent reason – observed in the wild, recreated in the lab

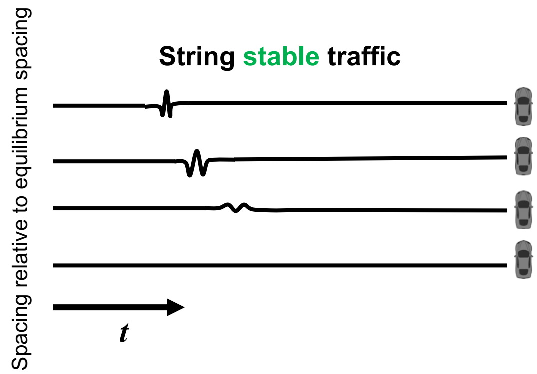


Video link:
https://youtu.be/7wm-pZp_mi0

Phantom traffic jams: result of unstable traffic



Small perturbations from the equilibrium spacing will amplify as the propagate along the platoon of vehicles



Small perturbations from the equilibrium spacing will dissipate as the propagate along the platoon of vehicles

[Wilson and Ward, 2010]

Outline of today’s talk

- How to collect data on phantom traffic jams?
  - Experimental design and data collection
- Can autonomous vehicles dampen traffic waves?
  - Traffic control via AVs
- How will driver assist features impact traffic stability?
  - Mathematical models
  - Stability analysis

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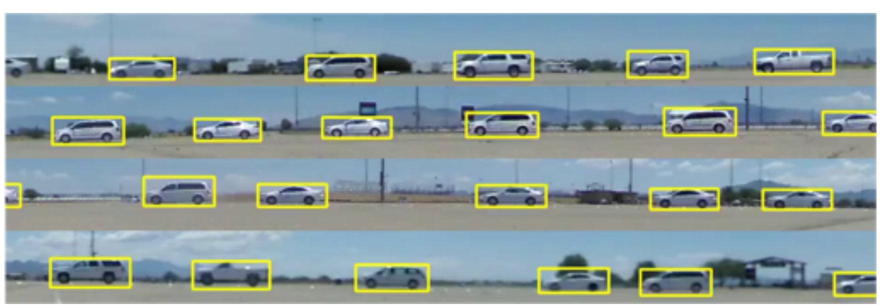
Research question:

How can we reliably collect experimental data to observe the development of phantom traffic jams?

Goal: track vehicle trajectories to study phantom jams

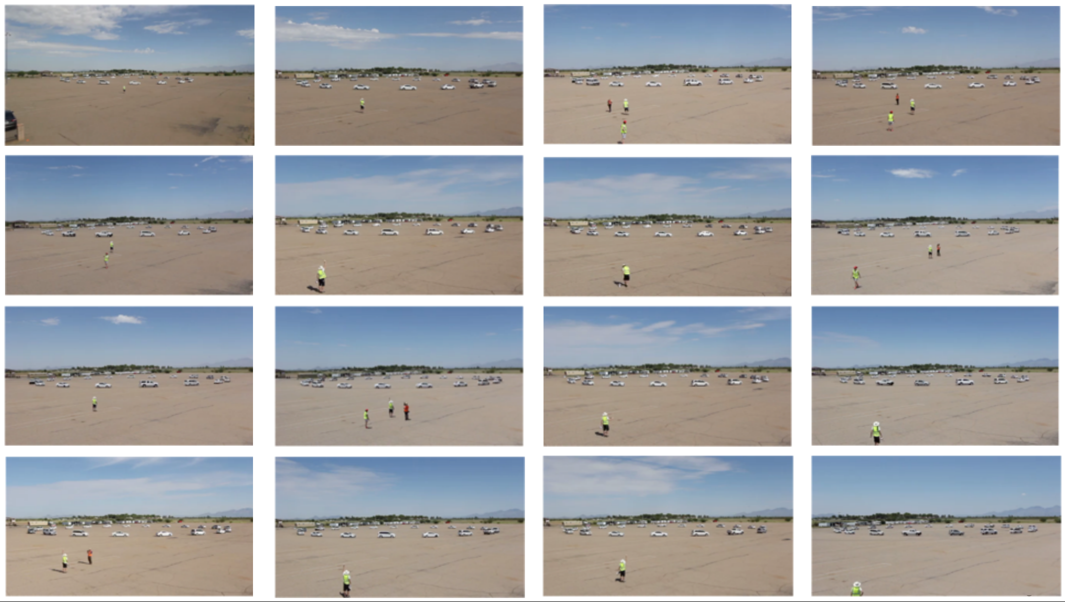
Solution: Use a VSN360 360° panoramic camera to film experiments from the center of a circular track.
Measure fuel consumption with OBD-II scanner.



[Wu, Stern, et al., 2019]

Data collection: selected traffic experiments

- 19 experiments
- 4 days of testing
- 25 vehicles
- 30 drivers
- 15 support staff
- Quantified increased fuel consumption with stronger waves
- 97% data success rate
- All data freely available online



[Wu, Stern, et al., 2019]

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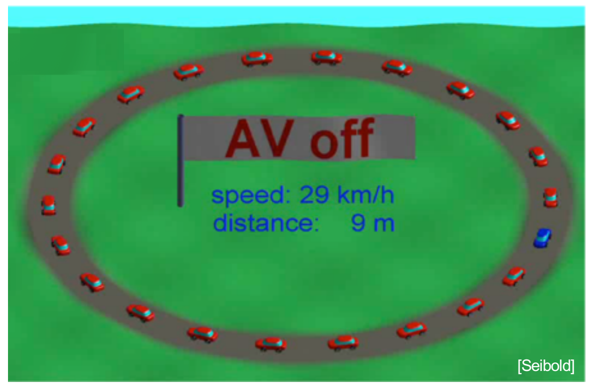
Research question:

How will the presence of a small number of autonomous vehicles influence traffic stability? Can they be controlled to benefit the traffic flow?

Designing AV controllers to eliminate phantom jams

Test controller in simulation:



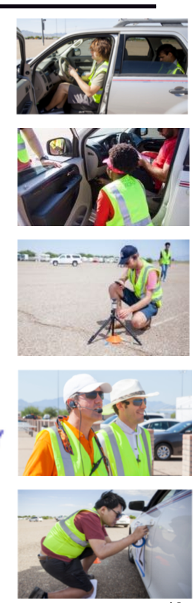
- **Goal:** drive AV "mostly" like a human
- **Control intuition:** AV drives with "as close to constant velocity" as possible

[Stern, et al., 2018]

Experimental demonstration that changing the dynamics of one vehicle can eliminate phantom jams

Dissipation of stop-and-go traffic waves via control of a single autonomous vehicle

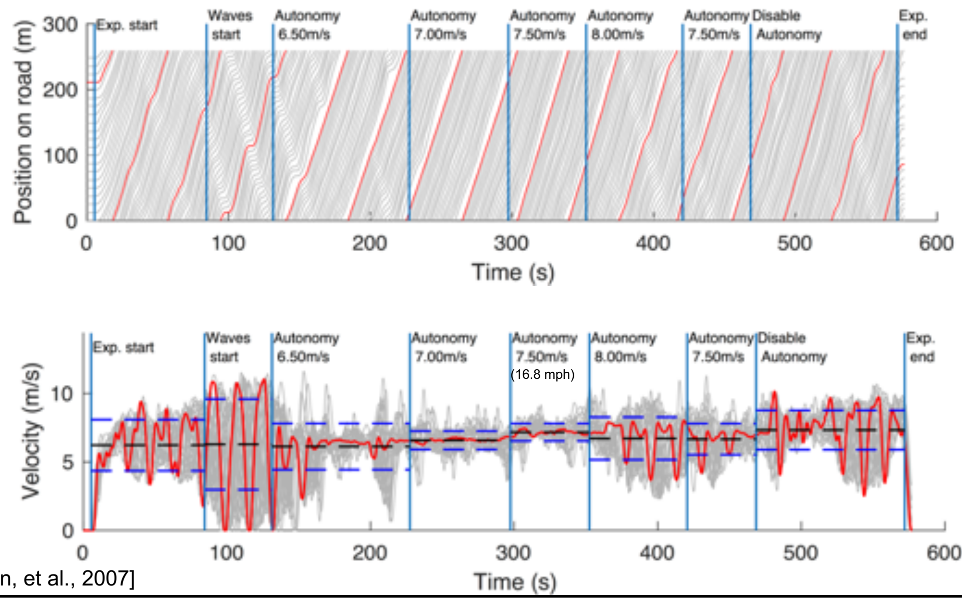
ILLINOIS UNIVERSITY OF ILLINOIS AT URBANA-CHAMPAIGN   RUTGERS   TEMPLE UNIVERSITY   THE UNIVERSITY OF ARIZONA



[Stern, et al. 2017]

Video link: https://youtu.be/2mBjYZTeaTc

Experimental results



Total braking events: **98.6%**

Throughput: **14.1%**

Fuel consumption: **39.8%**

[Stern, et al., 2007]

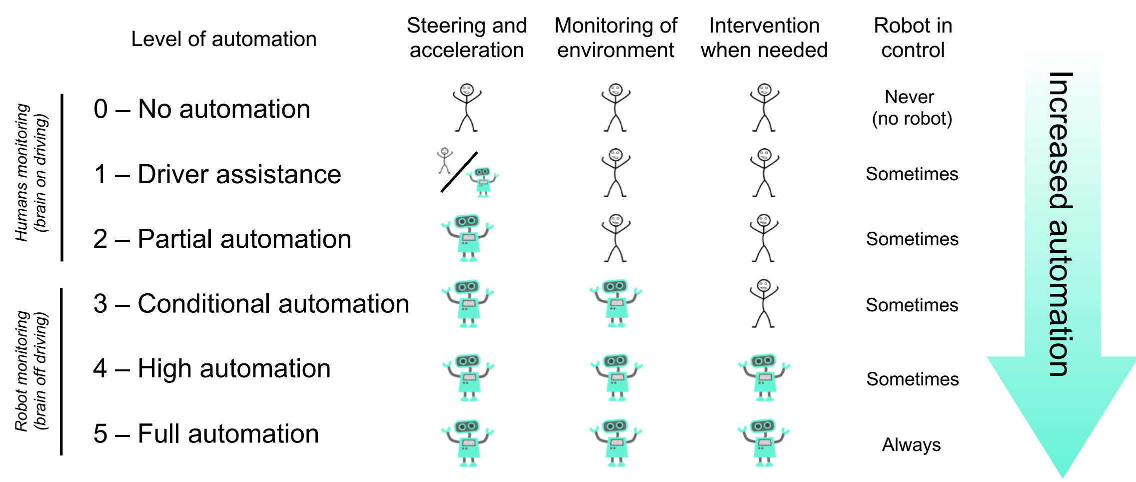
Outline of today's talk

- How to collect data on phantom traffic jams?
  - Experimental design and data collection
- Can autonomous vehicles dampen traffic waves?
  - Traffic control via AVs
  - Impact on vehicle emissions
- How will driver assist features impact traffic stability?
  - Mathematical models
  - Stability analysis

Research question:

How will commercially-available ACC systems impact traffic stability?

Not all AVs are the same

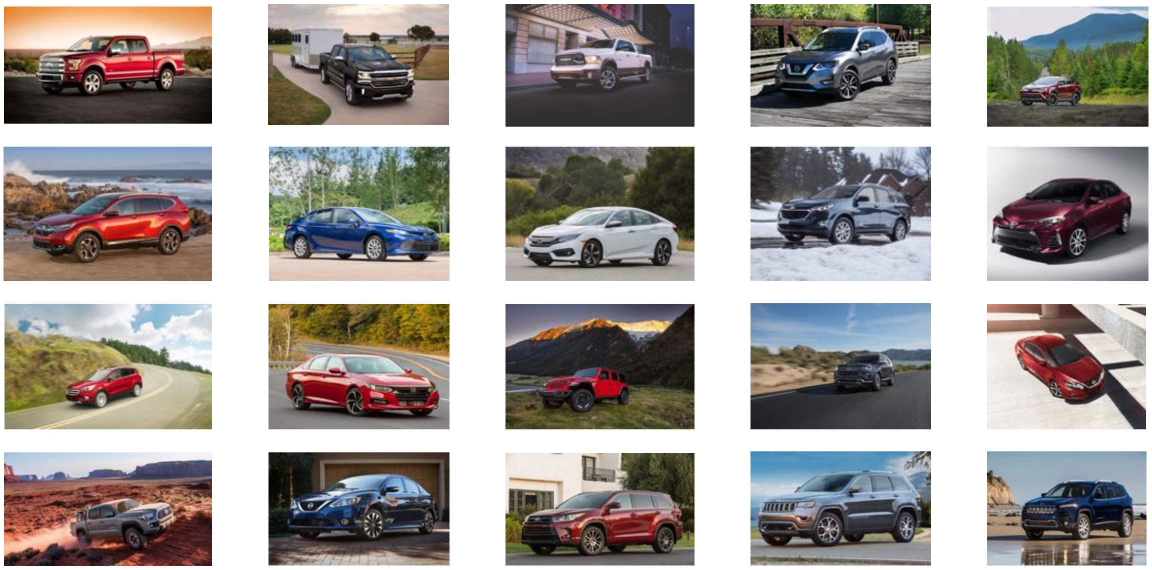


[Society of Automotive Engineers, 2018]

Level 1 AV: Adaptive cruise control

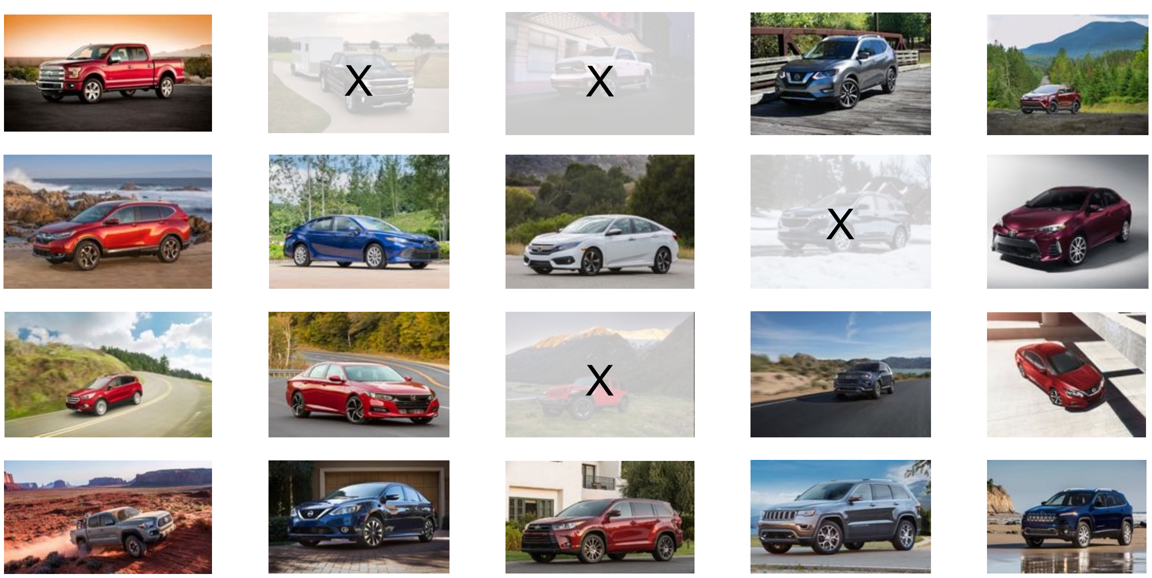
- *Adaptive cruise control* (ACC) maintains desired speed when safe, and drives slower, as needed, to maintain safe headway
- First versions became commercially available in the mid 1990s
- Historically: Premium feature, cost ~$2,800

20 best selling vehicles



[Business insider, 2018]

16 best selling level-one autonomous vehicles



[Business insider, 2018]

Modelling traffic flow

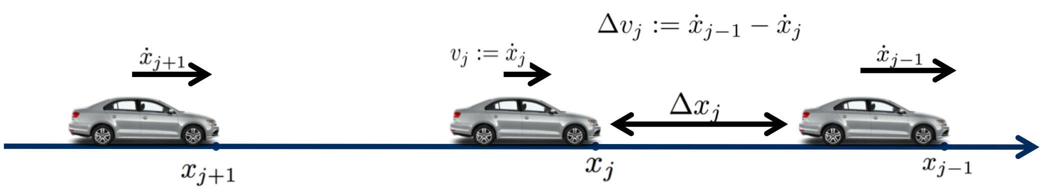
- To study ACC stability, first need framework to model traffic flow
- Model this traffic flow using an ordinary differential equation for acceleration:

$$\underbrace{\ddot{x}_j}_{\text{Acceleration of vehicle } j} = f(\underbrace{\Delta x_j}_{\text{Space in front of vehicle } j}, \underbrace{\Delta v_j}_{\text{Relative speed in front of vehicle } j}, \underbrace{\dot{x}_j}_{\text{Speed of vehicle } j})$$

Rational driving constraints:

$$\underbrace{\frac{\partial f}{\partial \Delta x}}_{\text{More space: speed up}} := f_{\Delta x} \geq 0, \quad \underbrace{\frac{\partial f}{\partial \Delta v}}_{\text{Lead vehicle faster: speed up}} := f_{\Delta v} \geq 0, \quad \underbrace{\frac{\partial f}{\partial v}}_{\text{Higher speeds: less acceleration}} := f_v \leq 0$$

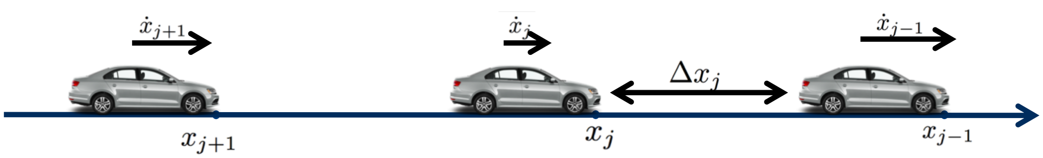
- Can be used for traffic simulation and analysis



[Gipps, 1956; Treiber, Hennecke, Belbing, 2000; Bando 1996, etc.]

String stability of traffic models: a standard approach

- **System equilibrium: occurs when all cars have constant velocity (zero acceleration)**
- Start with a car following model $\ddot{x}_j = f(\Delta x_j, \Delta v_j, \dot{x}_j)$ at equilibrium $f(\Delta x^*, 0, v^*) = 0$

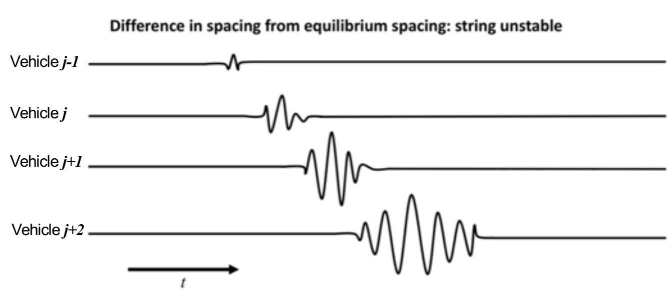


- Introduce small perturbations from this equilibrium:

$$\Delta x_j = \Delta x^* + \Delta \tilde{x}(t)$$
$$v_j = v^* + \tilde{v}(t)$$

- Consider a small perturbation from the equilibrium:

Do successive vehicles have to overreact such that the disturbance grows?



[Wilson and Ward, 2010]

String stability of traffic models: a standard approach

- Linearize the model around the equilibrium: $f_{\Delta v} = \frac{\partial f}{\partial \Delta v}$ $\quad f_{\Delta x} = \frac{\partial f}{\partial \Delta x}$ $\quad f_v = \frac{\partial f}{\partial v}$

- Insert this perturbation into the system dynamics to see how this perturbation propagates through the system:

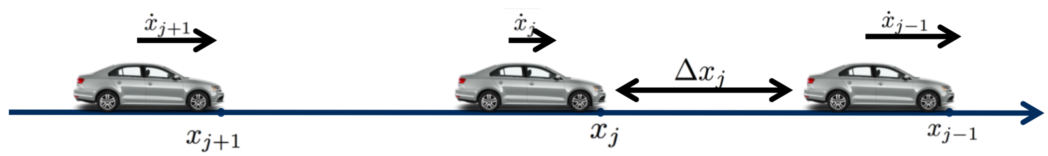
$$\Delta\ddot{\tilde{x}}_j + (f_{\Delta v} - f_v)\Delta\dot{\tilde{x}}_j + f_{\Delta x}\Delta\tilde{x}_j = f_{\Delta v}\Delta\dot{\tilde{x}}_{j-1} + f_{\Delta x}\Delta\tilde{x}_{j-1}$$

- To study how the perturbation evolves, replace RHS with forcing function ***F(t)*** and consider frequency domain

- Transfer function perturbation dynamics: $\mathcal{S}_j(z) = \frac{\mathcal{F}(z)}{z^2 + (f_{\Delta v} - f_v)z + f_{\Delta x}}$

$\mathcal{S}_j(z)$ - Laplace transform of $\Delta\tilde{x}_j$

$\mathcal{F}(z)$ - Laplace transform of ***F(t)***



[Wilson and Ward, 2010]

Traffic string stability: transfer function approach

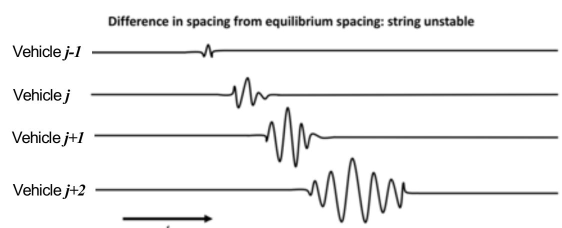
For a generic car following model $\ddot{x}_j = f(\Delta x_j, \Delta v_j, \dot{x}_j)$ at equilibrium $f(\Delta x^*, 0, v^*) = 0$

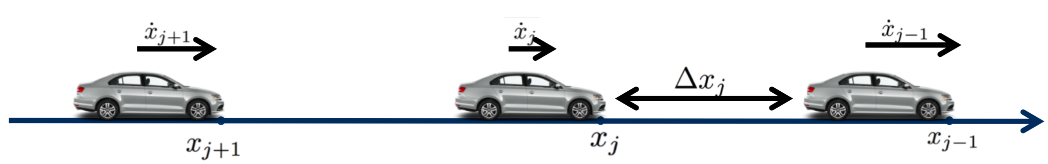
Stability depends on the growth rate of a perturbation:

$$\lambda_2 = \frac{f_{\Delta x}}{f_v^3}\left(\frac{f_v^2}{2} - f_{\Delta v}f_v - f_{\Delta x}\right)$$

If $\lambda_2 < 0$ the car following model is *string stable*

If $\lambda_2 > 0$ the car following model is *string unstable*

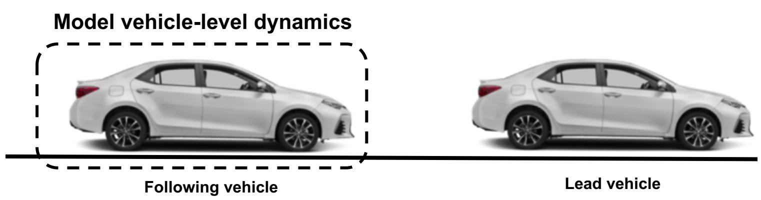




[Wilson and Ward, 2010]

Modeling ACC behavior

- **Goal:** *model ACC behavior to assess string stability of actual ACC systems*
- Want to model overall system behavior, not actual controller on vehicle
  - Want to know system-level traffic behavior
  - ACC controller depends on internal state, may not be possible to model
- Can use results to simulate stability of overall flow



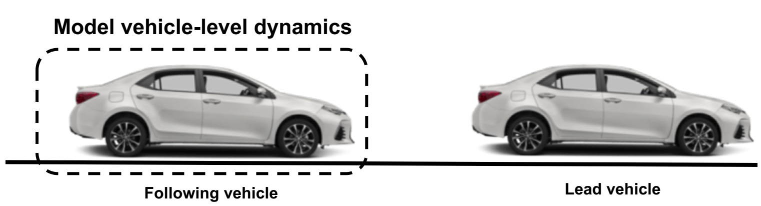
Optimal velocity relative velocity model (OVRV)

- Common assumption: headway-based controller
- Constant time headway OV with RV term:

$$\underbrace{\ddot{x}}_{\text{Acceleration}} = f(\Delta x, \Delta v, \dot{x}) = \underbrace{\overset{\text{Model parameter}}{k_1}(\Delta x - \overset{\text{Model parameter}}{\tau}\dot{x})}_{\text{Relaxation toward "optimal" velocity}} + \underbrace{\overset{\text{Model parameter}}{k_2}\Delta v}_{\text{Relaxation toward leader's velocity}}$$

Recall

$$\lambda_2 = \frac{f_{\Delta x}}{f_v^3}\left(\frac{f_v^2}{2} - f_{\Delta v} f_v - f_{\Delta x}\right)$$



[Milanes and Shaldover, 2014; Xiao, Wang, and van Armen, 2017]

Stability of the optimal velocity relative velocity model

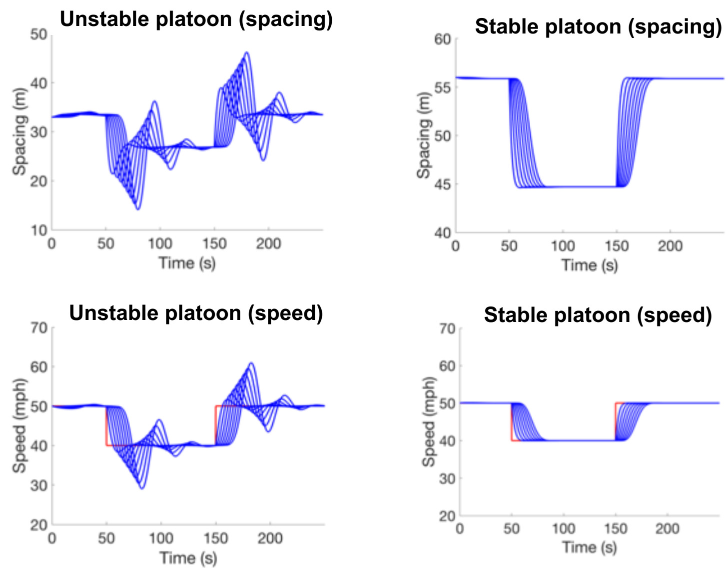
- OVRV can be stable or unstable depending on parameter values

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

$$f_{\Delta x} = k_1, \quad f_v = -k_1 \tau, \quad f_{\Delta v} = k_2$$

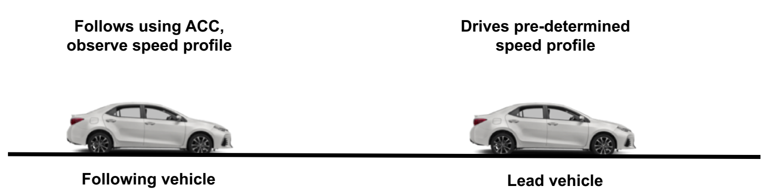
$$\lambda_2 = \frac{k_1}{-k_1^3 \tau^3} \left(\frac{k_1^2 \tau^2}{2} + k_1 k_2 \tau - k_1 \right)$$

- Instability also seen in speed profile



ACC system identification

- **Goal:** observe behavior or ACC vehicle as a function of the input signal from the lead vehicle in an experiment
- **Experimental setup:**
  - Drive lead vehicle with specified trajectory
  - Measure reaction of following vehicle when ACC engaged



Modeling ACC behavior

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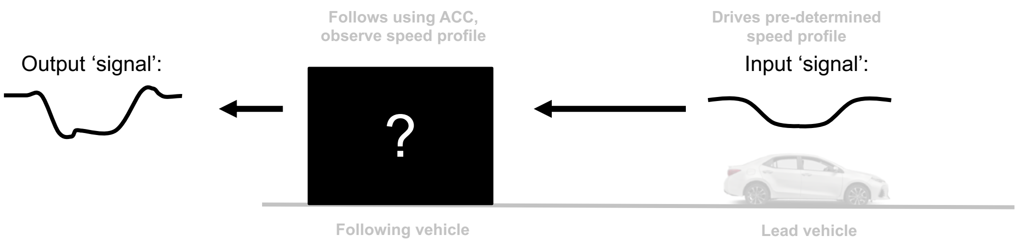
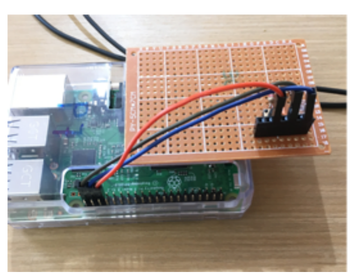


Instrument vehicles with GPS

- Need high accuracy position and speed measurements
- Use GPS to track position throughout experiment
- Sub-meter precision on position and 0.1 m/s speed accuracy (0.2 mph)



Test broad range of vehicles

- Need to test broad range of vehicles
- However, accessing all possible ACC vehicles on the market is not feasible
- Selected seven vehicles from two manufactures to cover range of size and vehicle class

Vehicle A

Vehicle B

Vehicle C

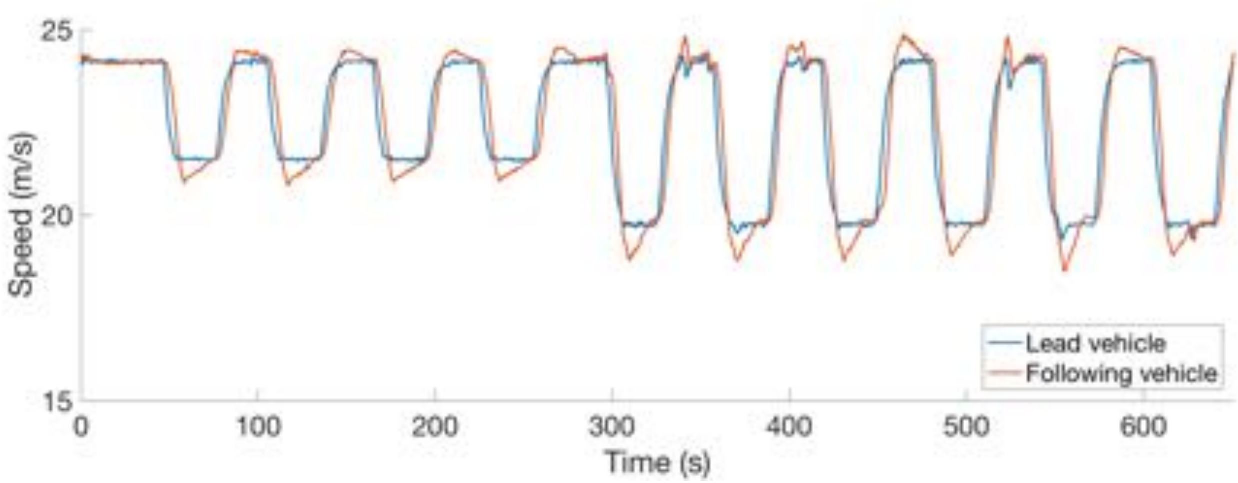
Vehicle D

Vehicle E

Vehicle F

Vehicle G

Test data: oscillatory test – transient behavior

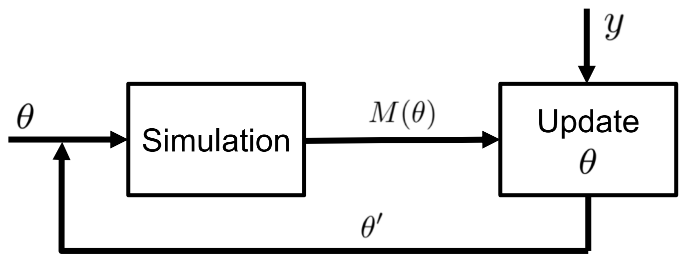


[Gunter, et al., 2019, ArXiv, dataset available]

Calibration approach: simulation-based optimization

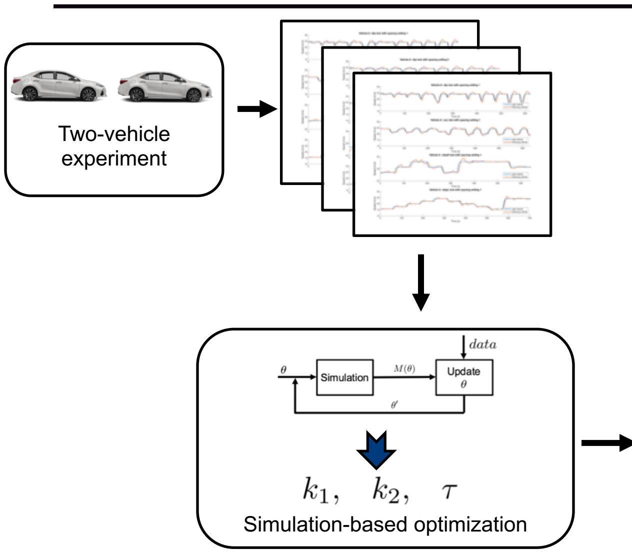
- Calibrate parameter values by minimizing headway error between simulation and data:

$$\min_{\theta} \underbrace{y}_{\text{Data collected in experiment}} - \underbrace{M(\theta)}_{\text{Simulation result using parameters } \boldsymbol{\theta}}$$



[Gunter, et al., 2019, ArXiv]

Microscopic model calibration

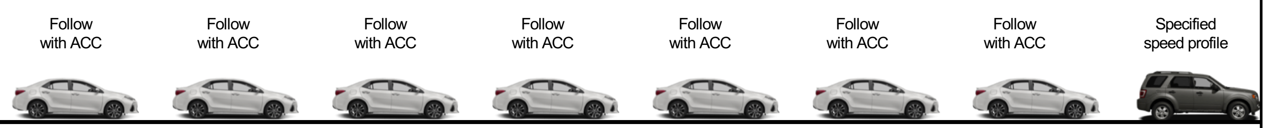


Vehicle	Following	k_1	k_2	τ	MAE (s)	λ_2
A	min	0.0535	0.0645	1.44	0.109	5.33
A	max	0.0353	0.0645	2.78	0.113	0.934
B	min	0.0704	0.157	1.41	0.0489	3.60
B	max	0.0169	0.123	2.50	0.0600	2.44
C	min	0.0379	0.140	1.57	0.0751	5.04
C	max	0.0225	0.107	2.84	0.0655	1.18
D	min	0.0512	0.0945	1.49	0.0810	4.77
D	max	0.0281	0.116	2.71	0.0679	1.04
E	min	0.0583	0.0958	1.54	0.0539	3.64
E	max	0.0666	0.0261	2.36	0.0365	0.860
F	min	0.0848	0.0652	1.42	0.0686	3.39
F	max	0.0447	0.0615	2.25	0.0578	1.46
G	min	0.0803	0.0657	1.46	0.0647	3.25
G	max	0.0472	0.0584	2.24	0.0482	1.41

[Gunter, et al., 2019, ArXiv]

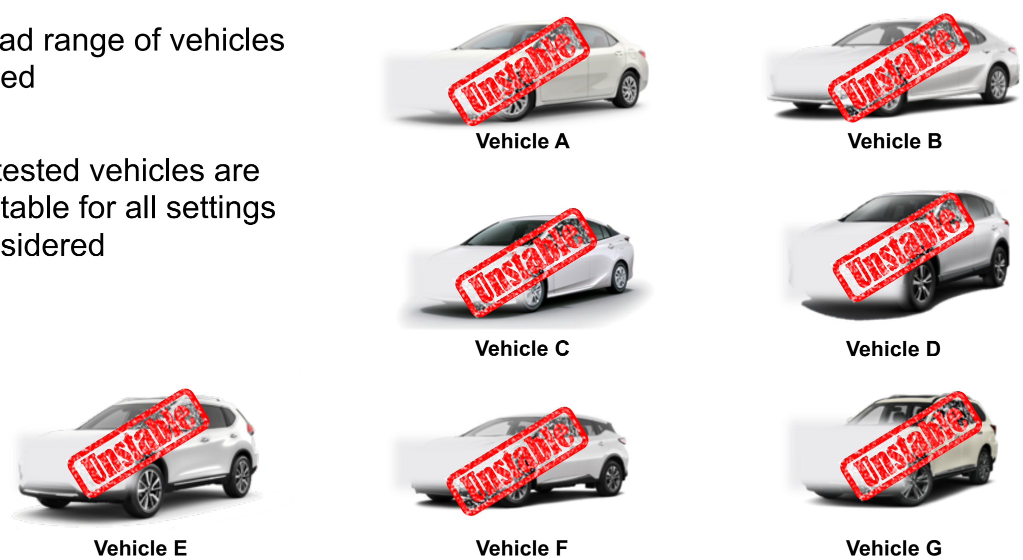
Platoon experiment

- Understanding platoon behavior is important for real traffic [Knoop, et al., 2019]
- Collect data from a platoon of ACC vehicles to check validity of calibrated model



Test broad range of vehicles

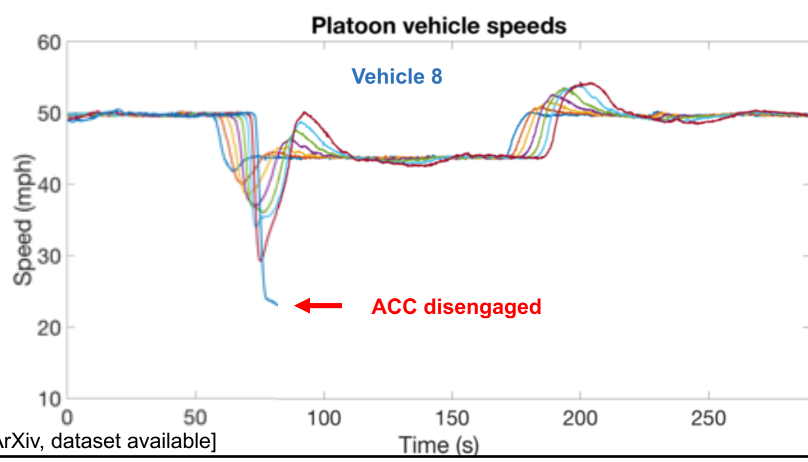
- Broad range of vehicles tested
- All tested vehicles are unstable for all settings considered



[Gunter, et al., 2019, ArXiv]

Do ACC vehicles dampen waves?

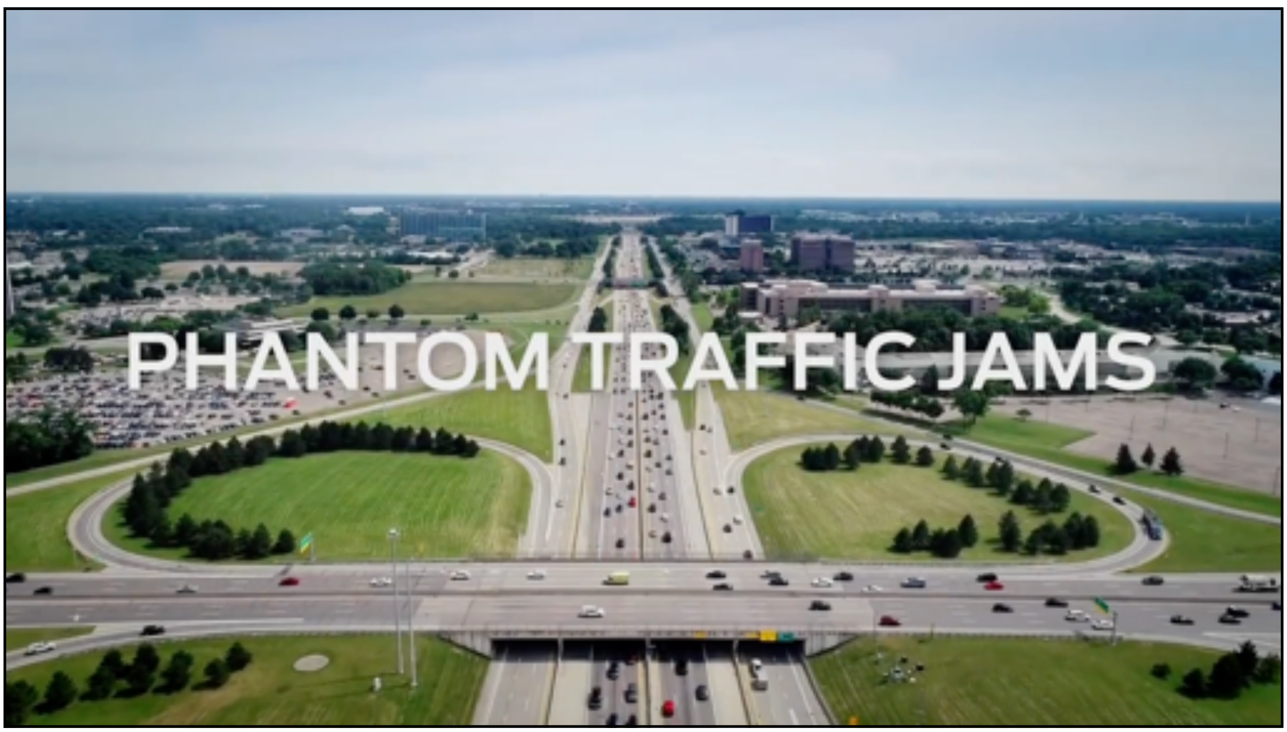
- Lead vehicle at 50 mph and rapidly decelerates to 44 mph
- Following vehicles use ACC to follow in a platoon



[Gunter, et al., 2019, ArXiv, dataset available]

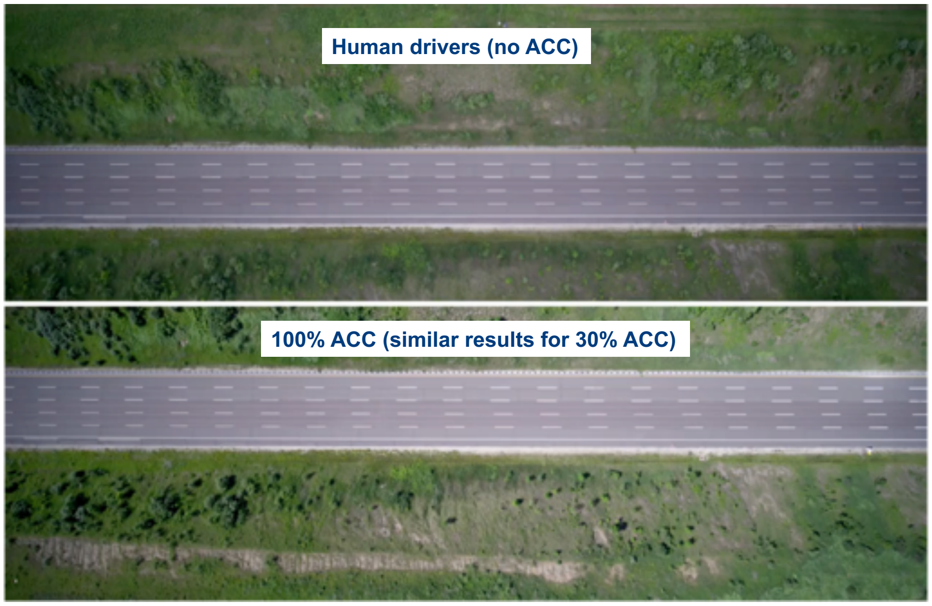
How does ACC compare to typical driving

- The ACC vehicles tested were all unstable under all parameter settings tested
- However, human driving behavior is also unstable
- Worked with Ford to test how current ACC systems compare to typical driving conditions



Video link: https://youtu.be/2GYfXxVn2Oc

Overhead view of experiments



Summary of today’s talk

- How to collect data on phantom traffic jams?
  - Collected experimental data on a ring road
  - Data available online for research
- Can autonomous vehicles dampen traffic waves?
  - A single AV can dampen traffic waves in human-piloted traffic if properly designed
- How will driver assist features impact traffic stability?
  - ACC is the first step toward an autonomous future
  - Tested a wide range of ACC vehicles and modeled their response
  - All tested vehicles are string unstable

Controlling mixed human and autonomous traffic

Raphael Stern
Assistant Professor, University of Minnesota
October 27, 2019

Joint work with: George Gunter, Maria Laura Delle Monache, Benedetto Piccoli, Benjamin Seibold, Jonathan Sprinkle, Fangyu Wu, and Daniel Work

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