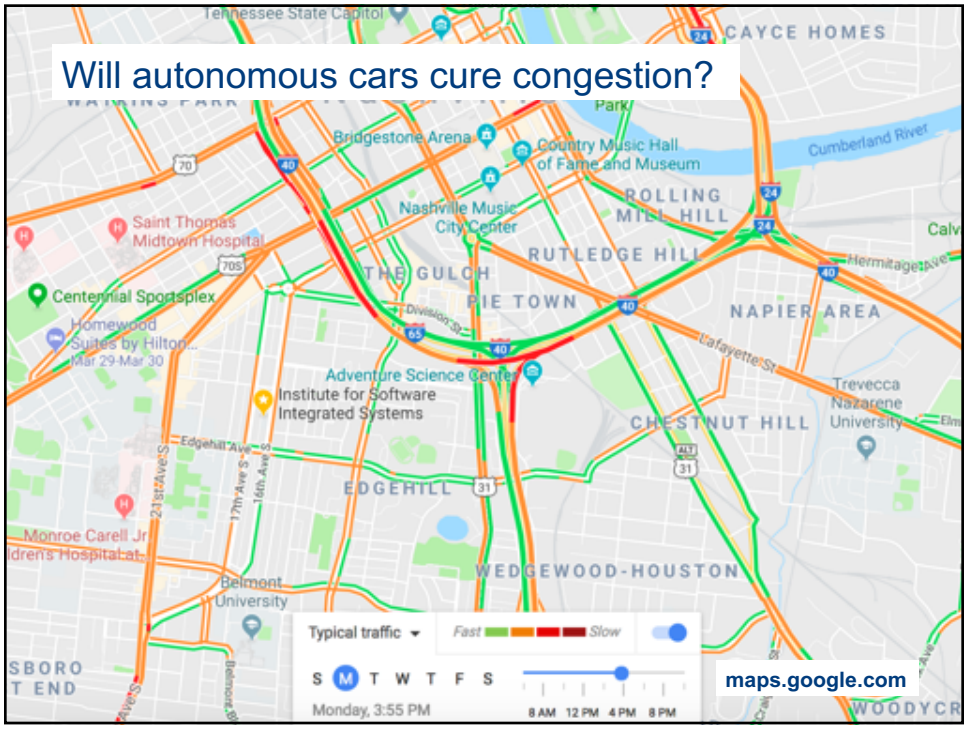
Control of traffic composed of humans and automated vehicles

Dan Work

Associate Professor
Civil & Environmental Engineering
Electrical Engineering & Computer Science
Institute for Software Integrated Systems
Vanderbilt University

Joint work with:
Rafi Stern (TU Munich; Minnesota FA19), Maria Laura Delle Monache (Inria Grenoble),
Benedetto Piccoli (Rutgers), Benni Seibold (Temple),
Roman Lysecky & Jonathan Sprinkle (Arizona)

[National Science Foundation grant numbers: CNS-1446435, CNS-1446690, CNS-1446702, CNS-1446715]



Will automated vehicles increase travel demand?

VANDERBILT

Probably.

Chauffer Experiment

- Give people a chauffer and see what happens
- Overall: 76% more miles traveled and longer trips
- Retirees: 3x increase in evening driving 2x longer trips.
- Millennials: ¾ of cohort increased miles.
- 20% "ghost trips" (e.g., to pick up children, friends)

[Joan Walker/Science Magazine, 2017; CEO Chariot 2018; GM 2018]

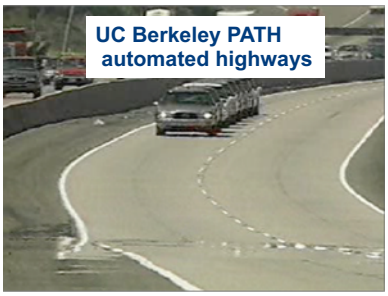
Can autonomous cars improve roadway capacity?

VANDERBILT

YES.

Automated Highways

- Need cars that talk, coordinate, and drive with high speeds and small gaps
- Up to 2-3x freeway capacity increase (in ideal conditions)
- *Main idea.* Move people/goods close together at high speeds

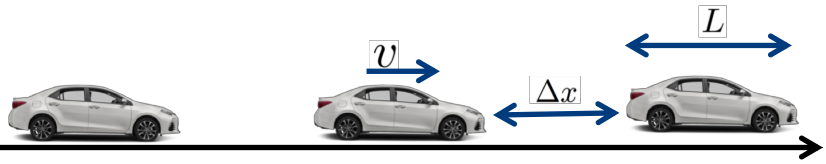


KTH Truck platoons

COMPANION

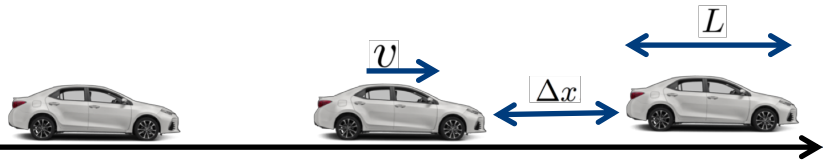
[Shladover et al. 94; Johansson et al. 15]

How to determine road capacity for platoons?



- Assume cars of length L follow with a space gap of Δx
- The spacing is: $s = \Delta x + L$
- The density of traffic is: $\rho = 1/s$. Density is typically measured in veh/mi or veh/km.
- The speed of each vehicle is v.
- The flow of traffic is: $q = \rho v$, or equivalently: $q = \frac{v}{\Delta x + L}$

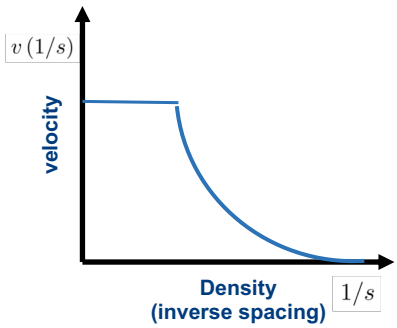
How to determine road capacity for platoons?

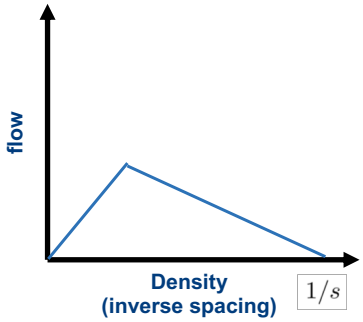


- The flow of traffic is: $q = \rho v$, or equivalently $q = \frac{v}{\Delta x + L}$
- Flow is measured in veh/hr (e.g., 2,000 veh/hr/lane)
- The maximum possible flow is called the *capacity*
- We can increase the flow by increasing the speed or reducing the space gap.

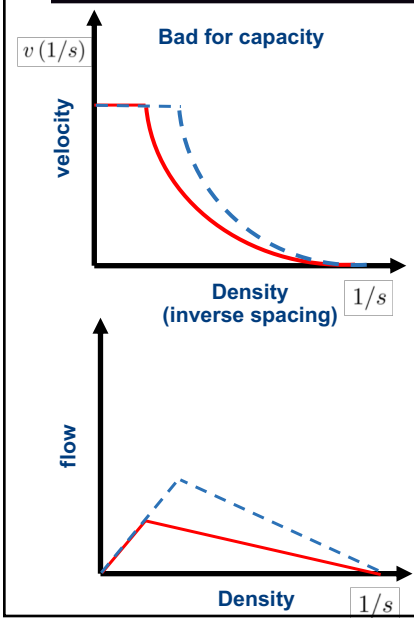
Typical models for humans

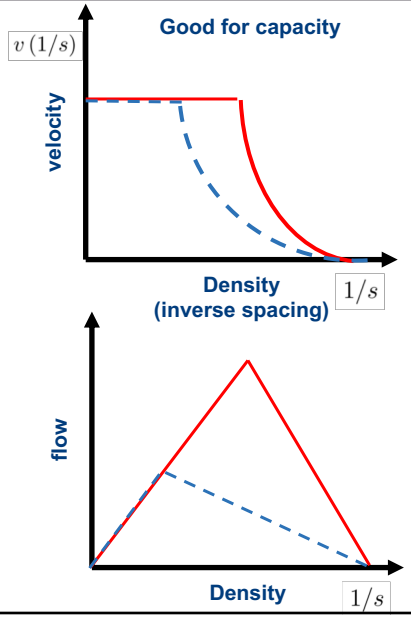
- Speed and spacing are typically related. Consequently flow and spacing are related too:





Possible models for AVs (exaggerated)





CARPOOL. Another way to move people together at high speeds

[The Late Late Show With James Corden]

CARPOOL. Another way to move people together at high speeds

[The Late Late Show With James Corden]

Taking the argument further…

72 people
(bike)

72 people
(car)

72 people
(bus)

[Münster planning department, 1991]

Taking the argument further…

72 people
(bike)

72 people
(autonomous car)

72 people
(bus)

[Münster planning department, 1991]

What to expect from a small number of autonomous vehicles (AVs)

- A few AVs will not eliminate traffic congestion
  - As long as demand exceeds supply…

What to expect from a small number of autonomous vehicles (AVs)

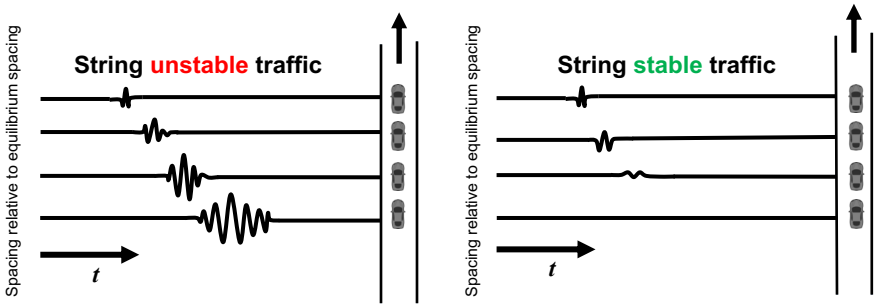
- AVs might not eliminate traffic congestion
  - As long as demand exceeds supply…
- CLAIM: A small number of automated vehicles can prevent "phantom jams" →

[Sugiyama et al. 2008]

Phantom jams occur on real roads too

[Joe Miroe (Youtube), 2017]

Phantom traffic jams: result of unstable traffic



Small variations are amplified by the vehicle behind

Small variations are dampened by the vehicle behind

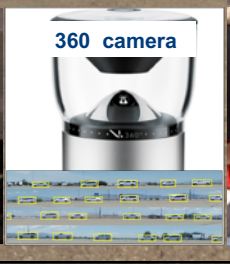
[e.g., Wilson and Ward, 2010]

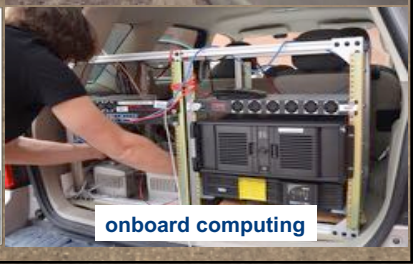
Experiments with only a single AV

- **Temperature: 107 F**
- 25 vehicles
- 30 drivers
- 15 support staff
- 280 bottles of water
- 15 cans of sun screen


U. of Arizona CAT Vehicle

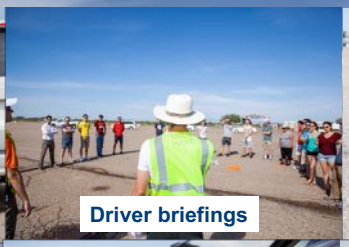
OBD-II scanners

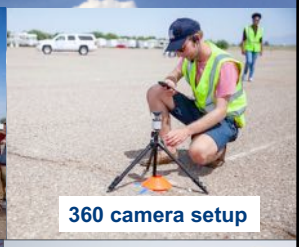

360 camera

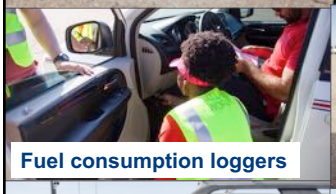

onboard computing

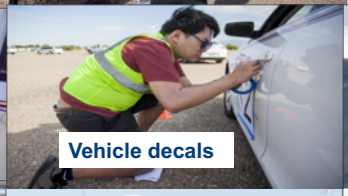
Experiment Logistics

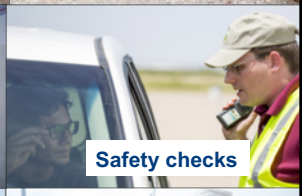

Vehicle alignment


Driver briefings


360 camera setup

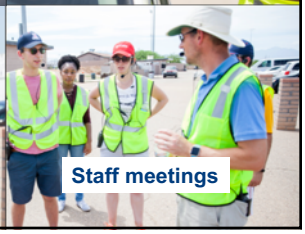

Fuel consumption loggers


Vehicle decals

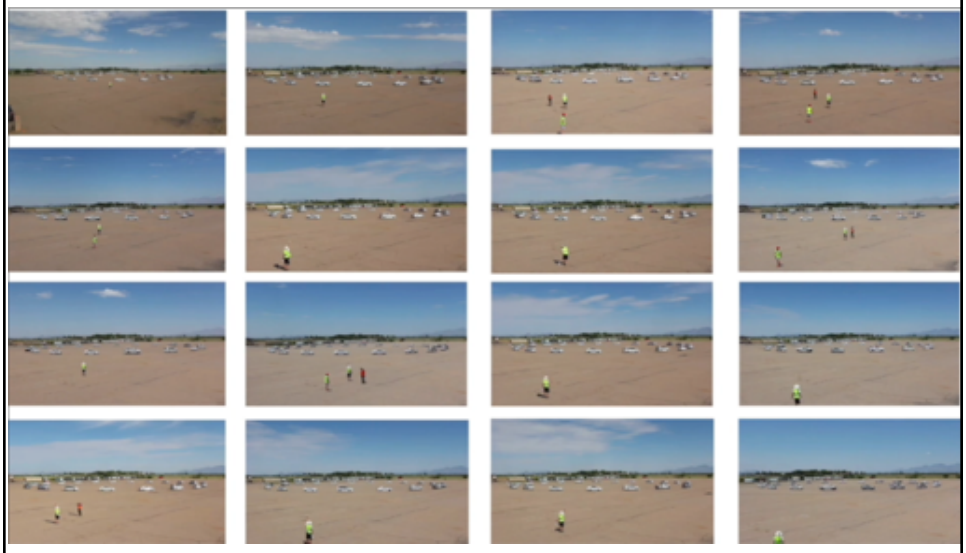

Safety checks


Managing the Arizona CAT Vehicle


Experiment adjustments


Staff meetings

Data collection: selected traffic experiments



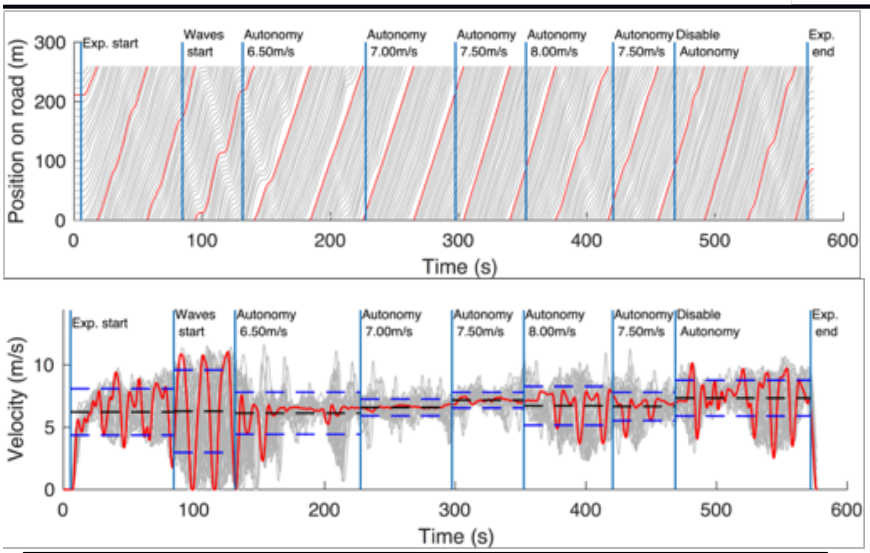
[Data in Wu et al. 2018]

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, Cui, Delle Monache, Bhadani, Bunting, Churchill, Hamilton, Haulcy, Pohlmann, Wu, Piccoli, Seibold, Sprinkle, & Work, 2017]

Experimental results



Velocity standard deviation: **80.8%**
Breaking events: **98.6%**
Fuel consumption: **42.5%**
Throughput: **14.1%**

Special thanks to the research and logistics team: Rafi Stern, Shumo Cui, Maria Laura Delle Monache, Rahul Bhadani, Matt Bunting, Miles Churchill, Nathaniel Hamilton, R'mani Haulcy, Hannah Pohlmann, Fangyu Wu, Benedetto Piccoli, Benni Seibold, and Jonathan Sprinkle (co-PIs)

Special thanks to the research and logistics team: Rafi Stern, Shumo Cui, Maria Laura Delle Monache, Rahul Bhadani, Matt Bunting, Miles Churchill, Nathaniel Hamilton, R'mani Haulcy, Hannah Pohlmann, Fangyu Wu, Benedetto Piccoli, Benni Seibold, and Jonathan Sprinkle (co-PIs)

The 6 levels of automation

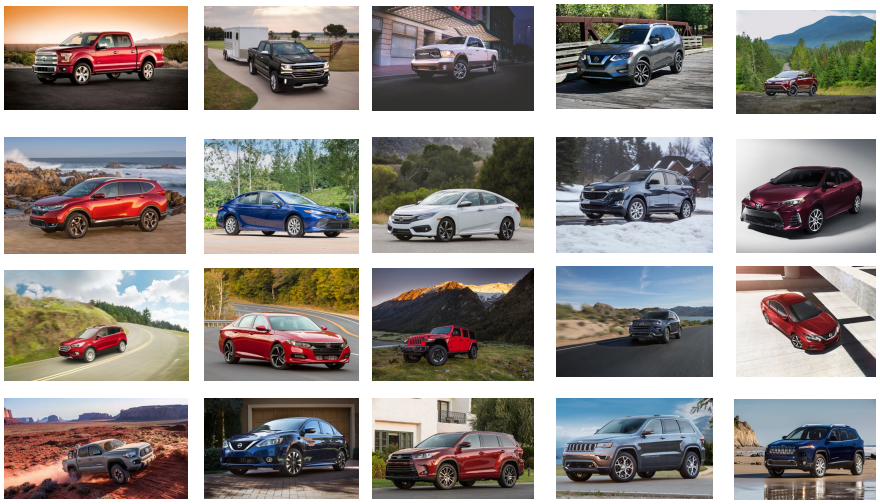
VANDERBILT

Level of automation	Steering and acceleration	Monitoring of environment	Intervention when needed	Robot in control
0 – No automation				Never (no robot)
1 – Driver assistance				Sometimes
2 – Partial automation				Sometimes
3 – Conditional automation				Sometimes
4 – High automation				Sometimes
5 – Full automation				Always

Increased automation

[Society of Automotive Engineers, 2018]

20 best selling vehicles

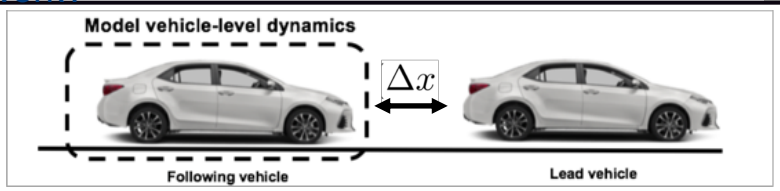


[Business insider, 2018]

16 best selling vehicles w/ level 1 automation

[Business insider, 2018]

How do adaptive cruise control systems work?



- The follower vehicle accelerates/decelerates according to:

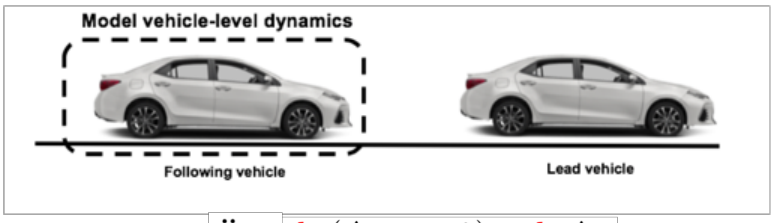
$$\ddot{x} = k_1(\Delta x - \tau \dot{x}) + k_2 \Delta v$$

Acceleration | Relax to constant time headway | Relax toward leader's velocity

- Where Δv is the lead vehicle velocity minus the follower vehicle velocity, $\dot{x}$; τ is the desired following time (e.g., in seconds), and k_1, k_2 are additional parameters

[Wilson & Ward, 2010; Gunter et al. 2019] 27

When will the ACC system create phantom jams?



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

Acceleration | Relax to constant time headway | Relax toward leader's velocity

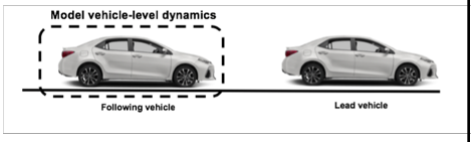
- Jams occur when the parameters are chosen such that

$$\frac{k_1}{(k_1\tau)^3}\left(\frac{(k_1\tau)^2}{2} + k_2 k_1 \tau - k_1\right) < 0$$

[Wilson & Ward, 2010; Gunter et al. 2019] 28

Are commercially implemented ACC string stable?

- **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



[Wilson & Ward, 2010; Gunter et al. 2019]

Candidate vehicles

- Need to test broad range of vehicles
- Selected seven vehicles from two manufactures to cover range of size and vehicle class


Vehicle A


Vehicle B


Vehicle C


Vehicle D

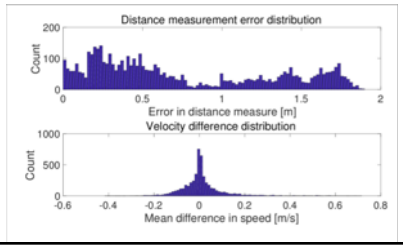

Vehicle E


Vehicle F

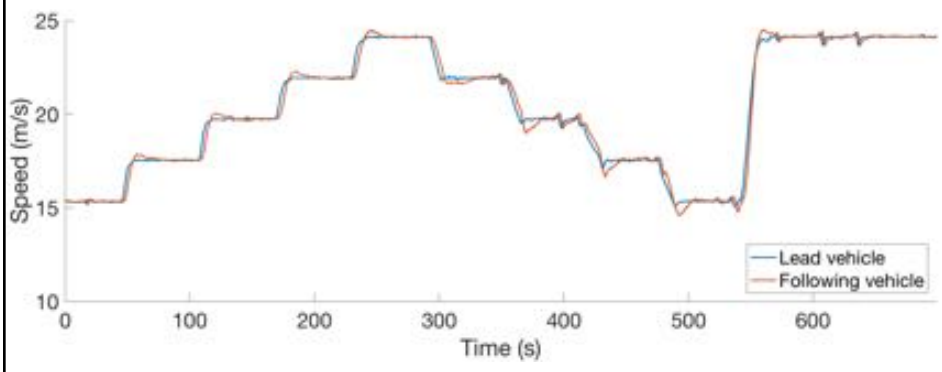

Vehicle G

Instrument vehicles with GPS

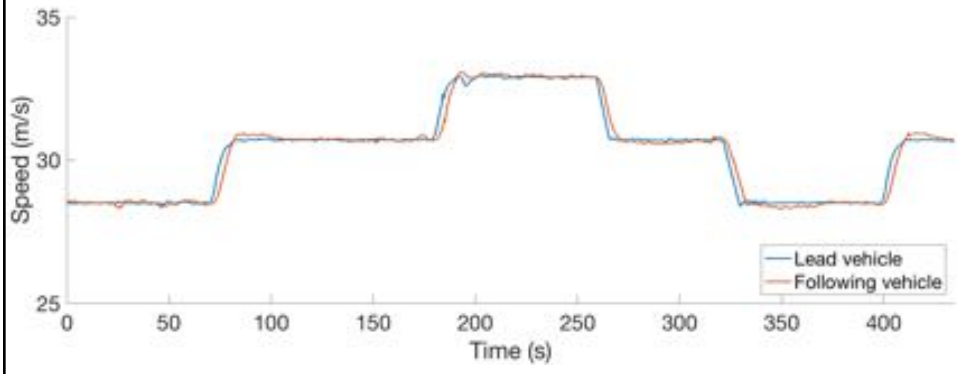
- Need high accuracy position and speed measurements
- Use GPS to track position throughout experiment
- 0.43 m ave. relative position error and 0.06 m/s speed error (0.2 mph)



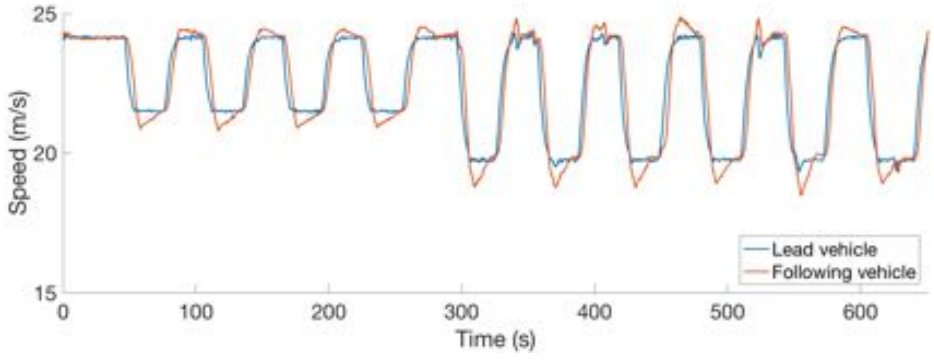
Test data: step test – steady state behavior



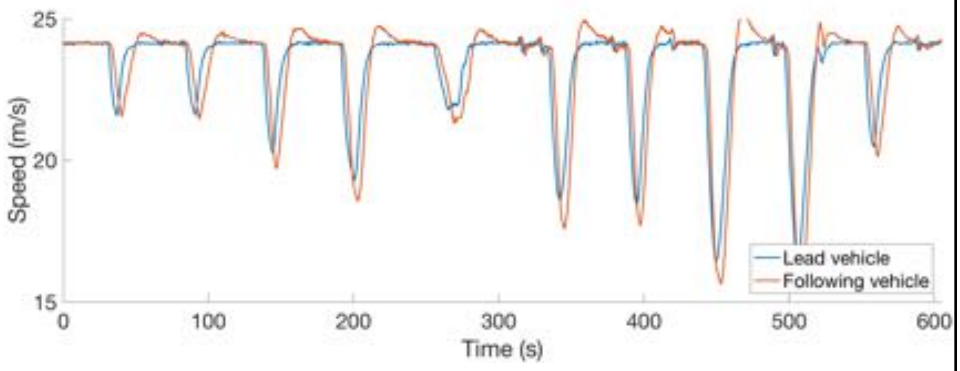
Test data: step test – steady state behavior



Test data: oscillatory test – transient behavior



Test data: dip test – transient behavior



Results

- Broad range of vehicles tested
- All tested vehicles are string unstable under both settings considered

Vehicle A

Vehicle B

Vehicle C

Vehicle D

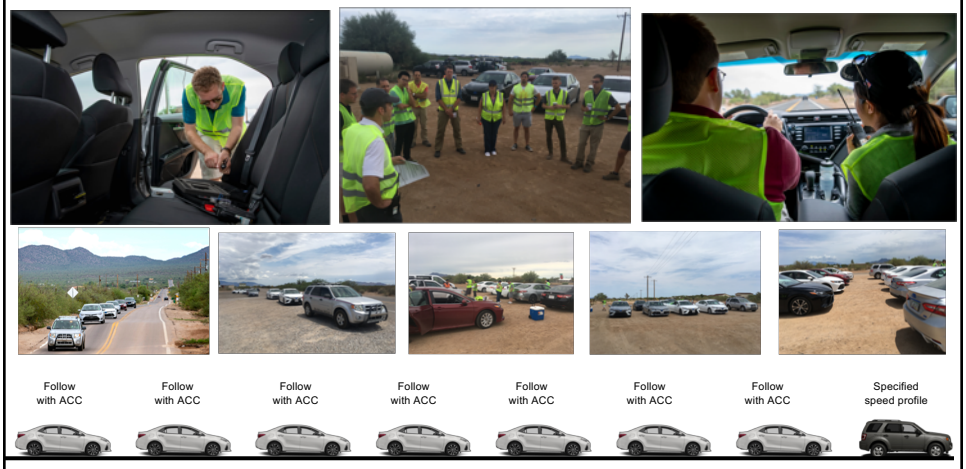
Vehicle E

Vehicle F

Vehicle G

Platoon experiment

- Collect data from a platoon of ACC vehicles to check validity of calibrated model



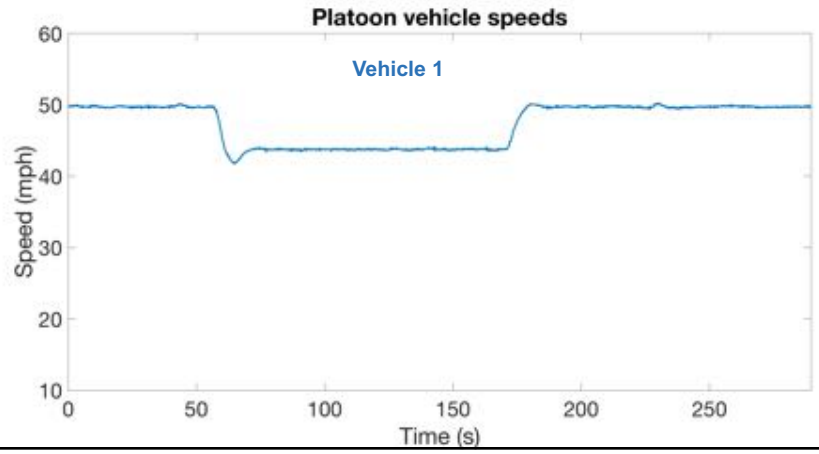
ADAPTIVE CRUISE CONTROL
PLATOON TESTS

THIS WORK SUPPORTED BY THE NATIONAL SCIENCE FOUNDATION PROJECT "CONTROL OF VEHICULAR TRAFFIC FLOW VIA LOW DENSITY AUTONOMOUS VEHICLES" UNDER AWARDS CNS-1446435, 1446690, 1446702, 1446715.

[Gunter, Gloudemans, Stern, McQuade, Bhadani, Bunting, Delle Monache, Lysecky, Seibold, Sprinkle, Benedetto, Work, 2019]

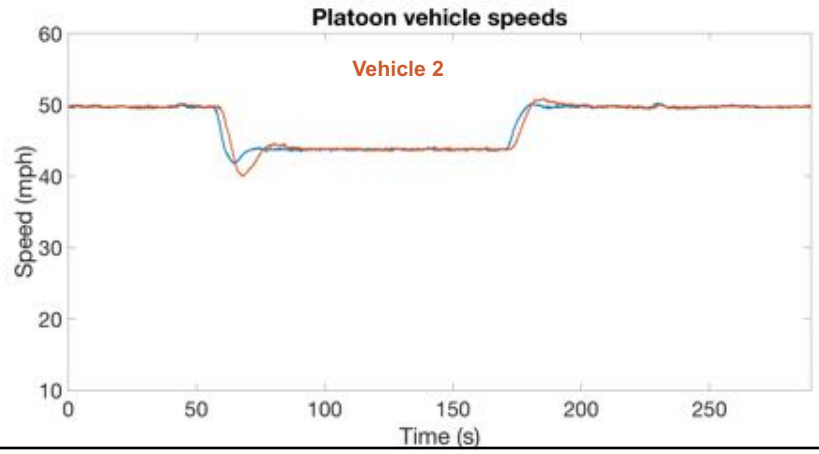
Validation of string unstable ACC platoons

- Lead vehicle at 50 mph and rapidly decelerates to 44 mph



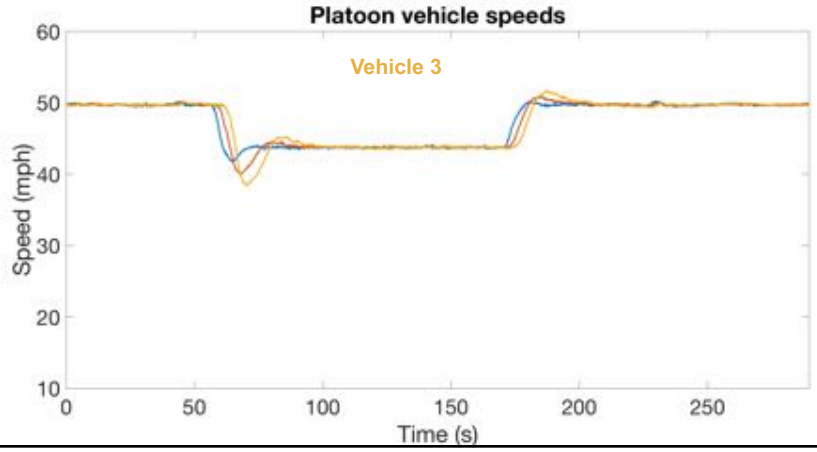
Validation of string unstable ACC platoons

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



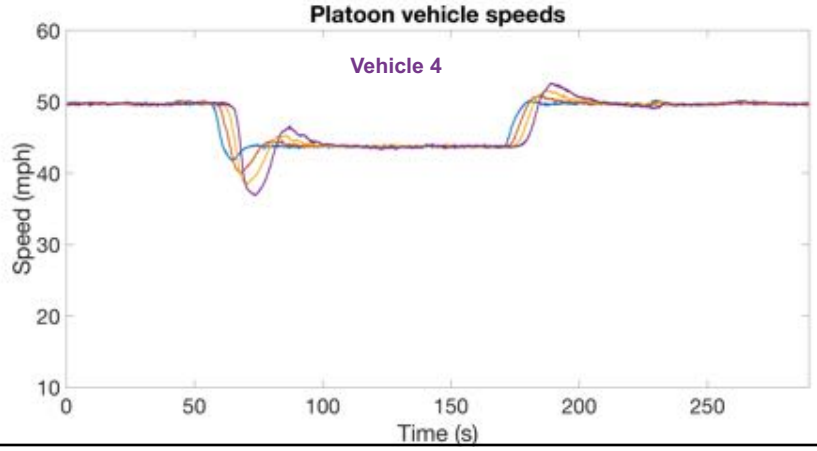
Validation of string unstable ACC platoons

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



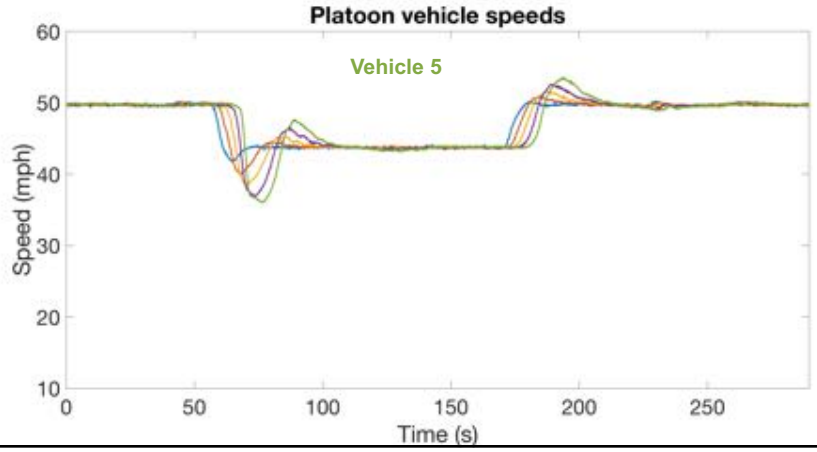
Validation of string unstable ACC platoons

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



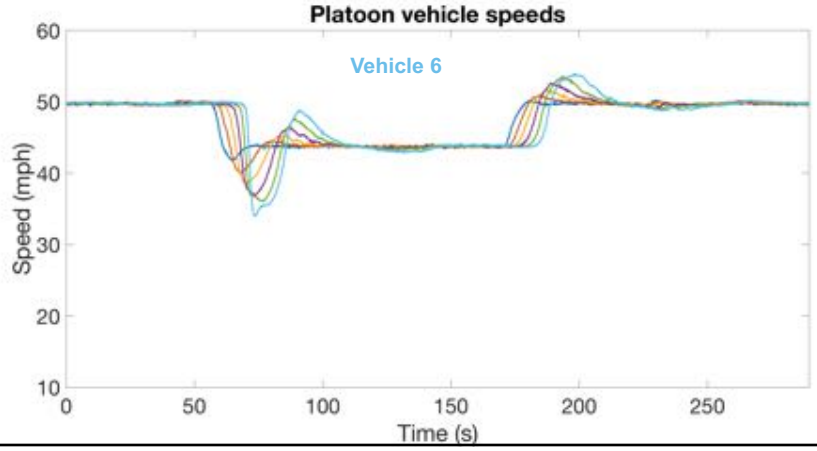
Validation of string unstable ACC platoons

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



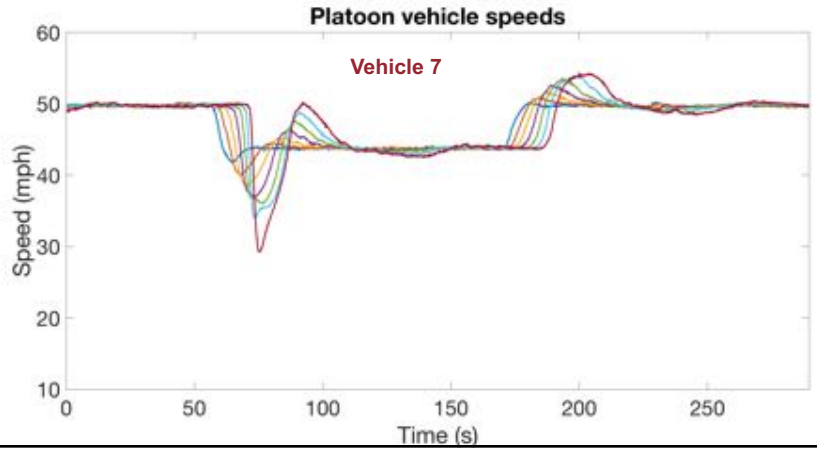
Validation of string unstable ACC platoons

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



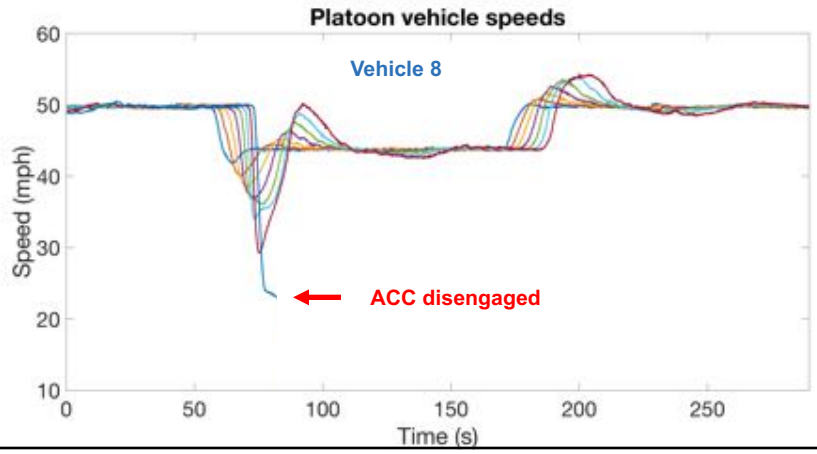
Validation of string unstable ACC platoons

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



Validation of string unstable ACC platoons

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



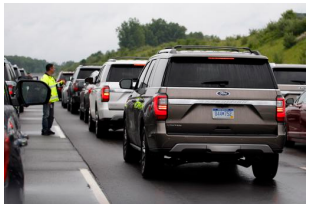
It is clear that all adaptive cruise control systems are created equal…

And they may outperform humans…

Welcome to Ford's Michigan Proving Ground

VANDERBILT



Overhead view of experiments

VANDERBILT

Take home messages

- Self driving cars won't solve all of our mobility problems
- But CAVs at moderate penetration rates can help smooth flow – experimentally demonstrated.
- Current autonomous vehicle systems have widely varying qualities, from a traffic perspective.

Team

Will Barbour

Derek Gloudemans

Yue Hu

Yanbing Wang

Caroline Janssen

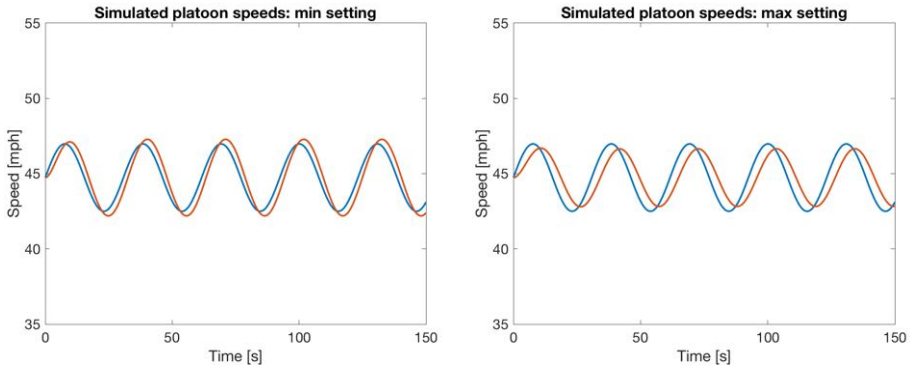
George Gunter

Control of traffic composed of humans and automated vehicles

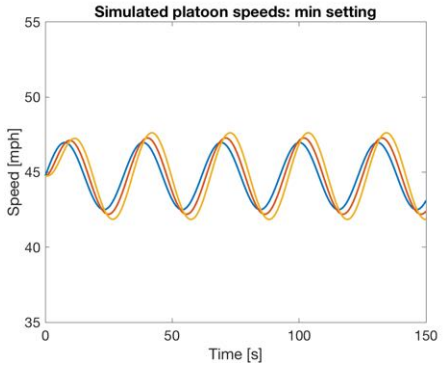
Dan Work
Associate Professor
Civil & Environmental Engineering
Electrical Engineering & Computer Science
Institute for Software Integrated Systems
Vanderbilt University

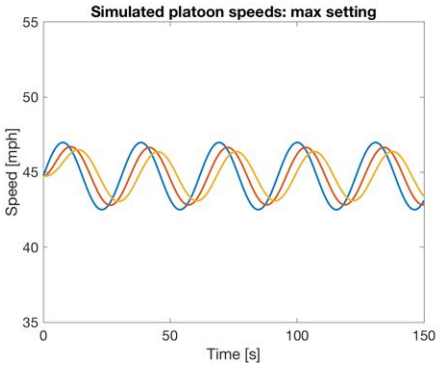
[Research sponsors: NSF, FHWA UTC, Siebel Energy Institute]

High performance electric vehicle platoon

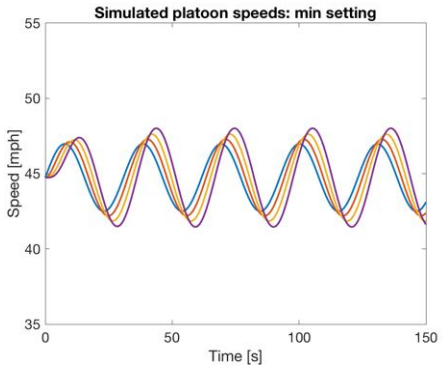


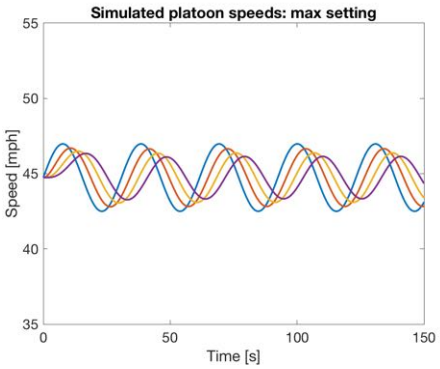
High performance electric vehicle platoon



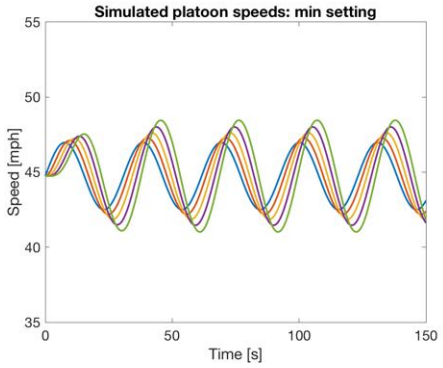


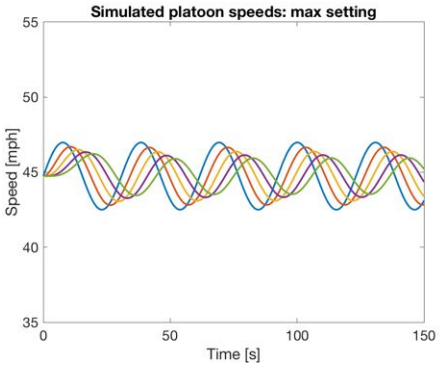
High performance electric vehicle platoon



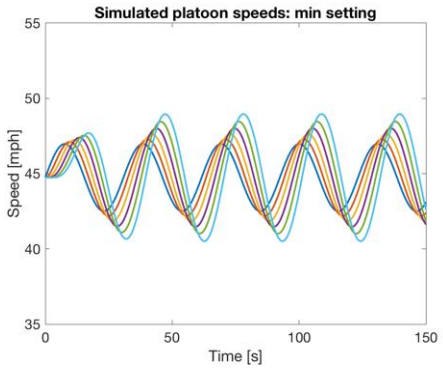


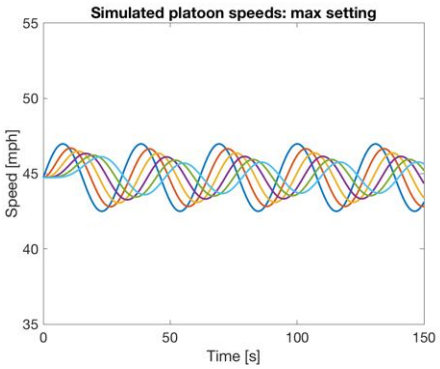
High performance electric vehicle platoon



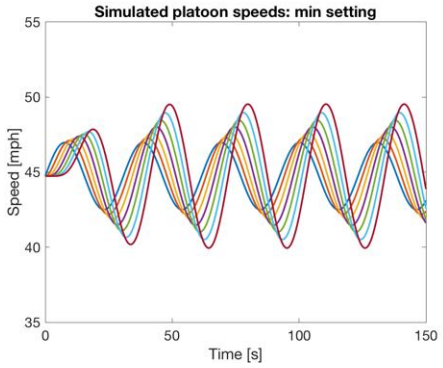


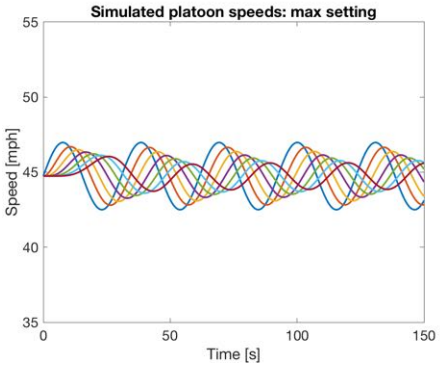
High performance electric vehicle platoon



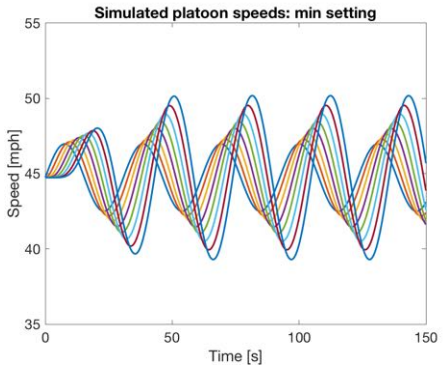


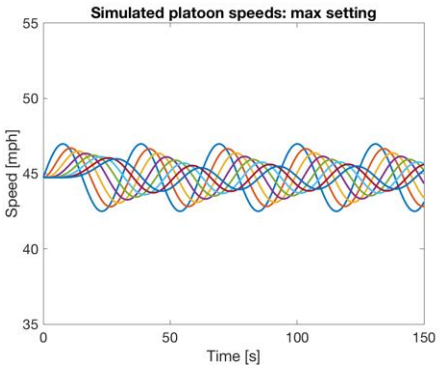
High performance electric vehicle platoon





High performance electric vehicle platoon





High performance electric vehicle platoon