Controlling Stop and Go Traffic with a Single Autonomous Vehicle: Experimental Results

July 14, 2017

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Raphael Stern
Fangyu Wu
Miles Churchill
Daniel Work

RUTGERS UNIVERSITY | CAMDEN

Maria Laura Delle Monache
Benedetto Piccoli

THE UNIVERSITY OF ARIZONA

Rahul Bhadani
Matt Bunting
Jonathan Sprinkle

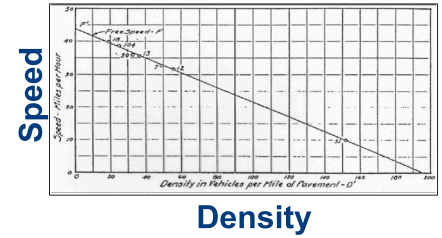
TEMPLE UNIVERSITY

Shumo Cui
Hannah Pohlmann
Benjamin Seibold

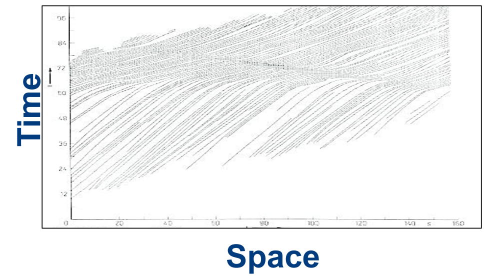
This material is based upon work supported by the National Science Foundation under Grant No. 1446702.

Data drives understanding in transportation

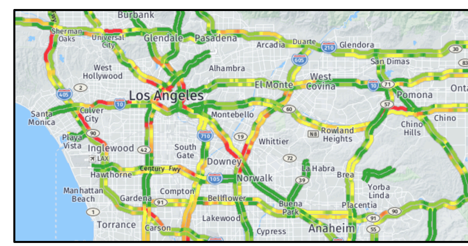
- 1935 – Greenshields collected traffic data on highway
  - Density vs. Speed



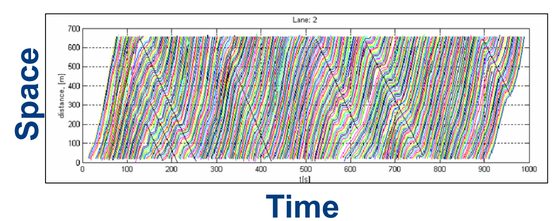
- 1974 – Treiterer and Myers used aerial photography to track traffic waves
  - Tracking waves along the highway



- 2001 – PEMS dataset
  - Use inductive loop detectors for traffic counts



- 2003 – NGSIM data
  - Instrumental for calibration of microscopic traffic models for shock waves

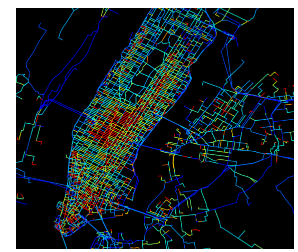


Transformative datasets

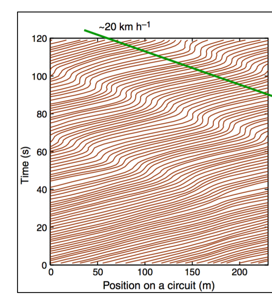
- 2006 – Naturalistic Driving Study
  - Collected vehicle data of naturalistic driving

- 2012 – U. Michigan V2V deployment
  - 2700+ V2V and V2I equipped vehicles and roadside units deployed in Ann Arbor, MI

- 2013 – New York City taxi dataset
  - Used to understand large-scale mobility in the city



2008 – Sugiyama, et al. experiment
Demonstrated that traffic waves emerge in absence of external bottlenecks



[Donovan & Work, 2016; VTTI 2006; UMTRI 2012; Sugiyama, et al., 2008]

Autonomous vehicles have come a long way

Ford concept AV, 1962

DARPA Urban Grand Challenge, 2007

Tesla Model S Autopilot, 2015

- AV technology has reached a point where it is feasible to test on large scales

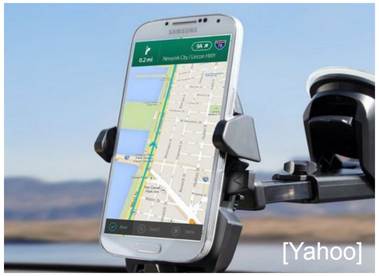
Questions: How will AVs behave in traffic with other human drivers? Can AVs be used to benefit human-piloted traffic? Need data to answer these questions.

How technology has shaped transportation

- Classical estimation pre ~2010
  - Dedicated sensors at fixed locations


[Car Connection]

- Modern estimation today
  - 1-5% GPS penetration


[Yahoo]

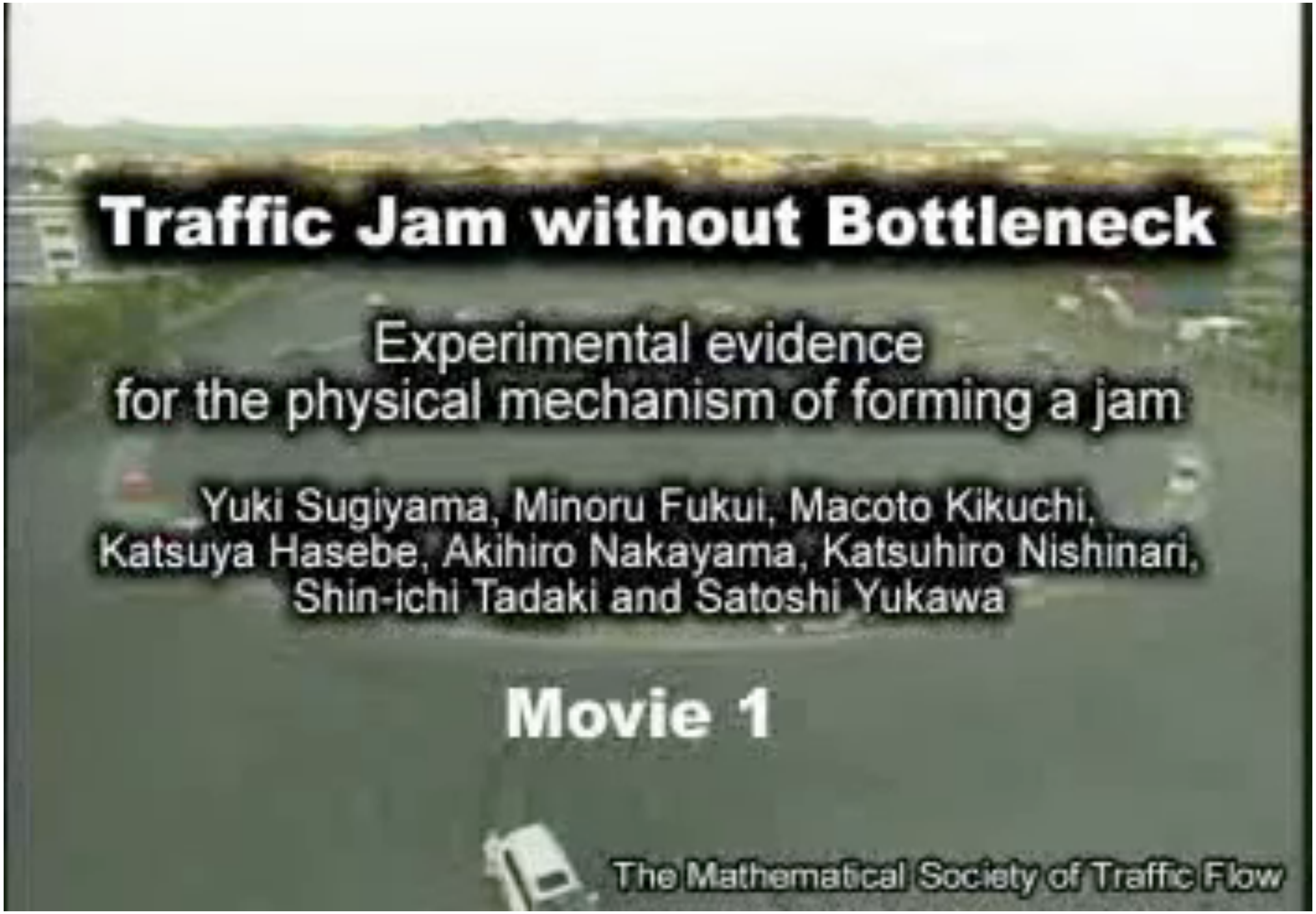
- Traffic control today
  - Dedicated actuation at fixed locations


[Wikimedia]

- Future traffic control ~2020+
  - Mobile actuation with a few autonomous vehicles


[Google]

Traffic waves arise dynamically



[Sugiyama, et al., 2008]

Sugiyama: contributions and limitations

- Contribution
  - Demonstrated traffic waves arise in absence of external bottlenecks

- Limitations
  - No engine data recorded
  - No fuel consumption data recorded
  - Difficult to identify impact on fuel consumption

Experimental goals

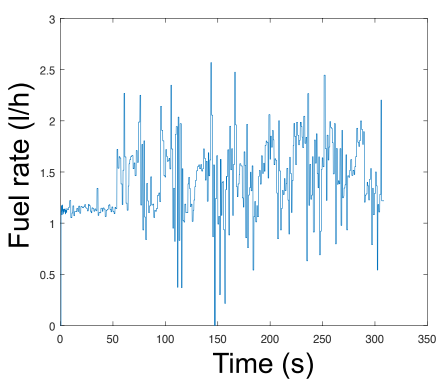
Goal: collect data of oscillatory traffic that includes:

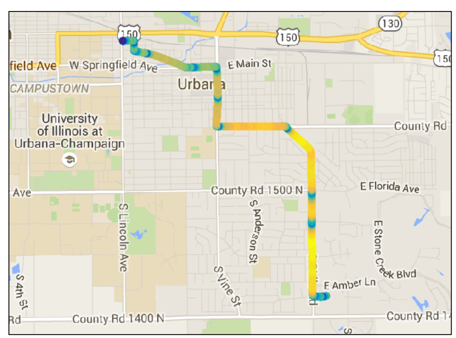
- Vehicle trajectories
- Fuel consumption
- Complete fleet information

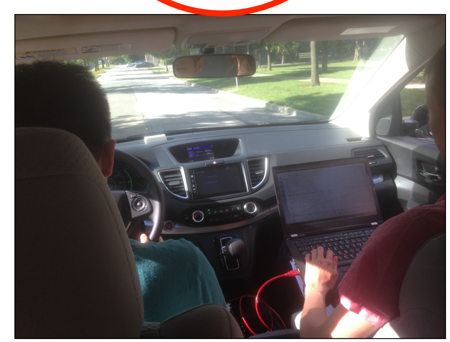
Measuring vehicle performance

Goal: collect data on vehicle performance and fuel consumption to enable research on the link between oscillatory traffic and emissions.

- OBD-II scanners and tablets tested
- Can collect fuel consumption data



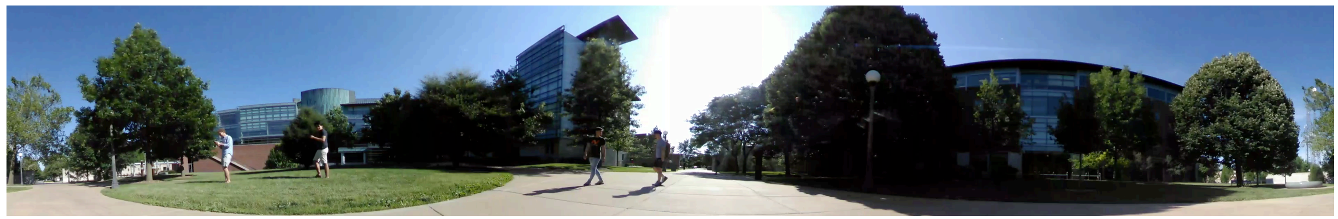




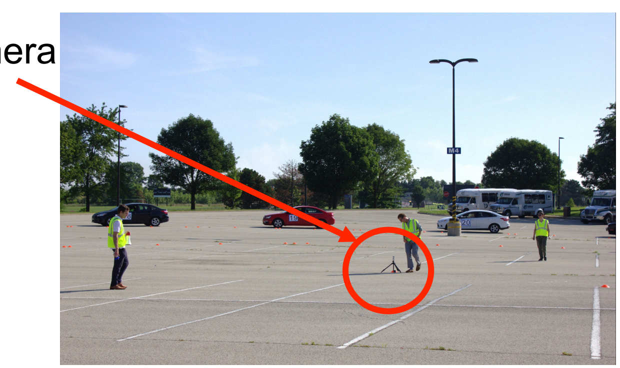
Key feature: collecting OBD-II data enables understanding of fuel consumption in oscillatory conditions

Collecting vehicle trajectories

Goal: accurately track vehicle trajectories using a repeatable method.



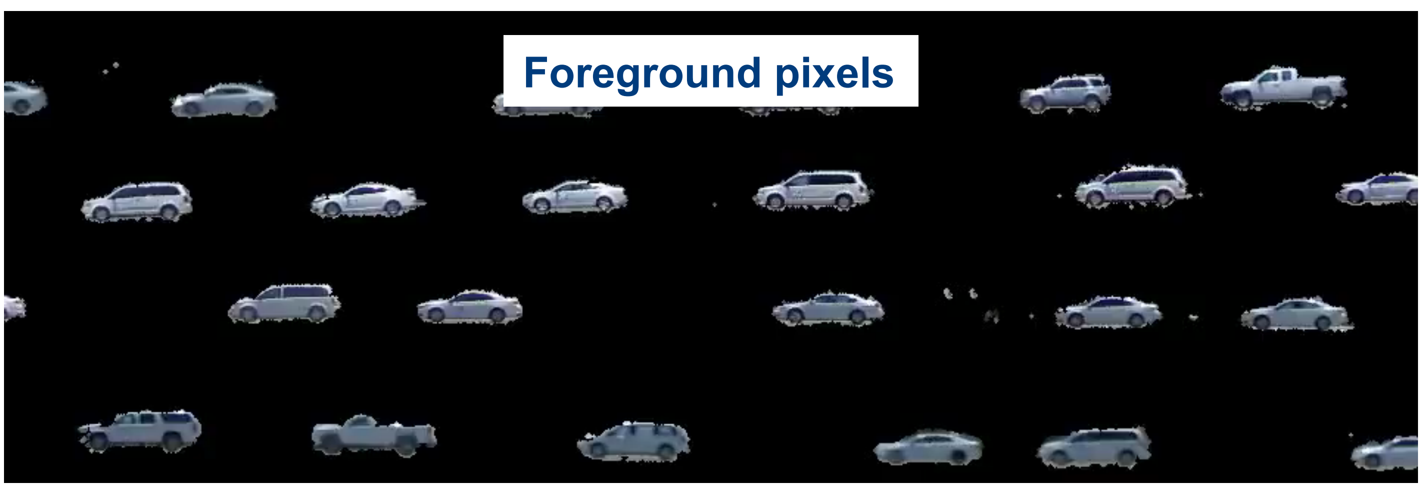
V360 camera



Solution: Use a VSN360 360° panoramic camera to film experiments from the center of a circular track

Extracting vehicle trajectories from 360 video

- Step 1: Identify Background
  - Filter moving pixels using *dense optical flow*
  - Subtract background image from each frame to find vehicle pixels

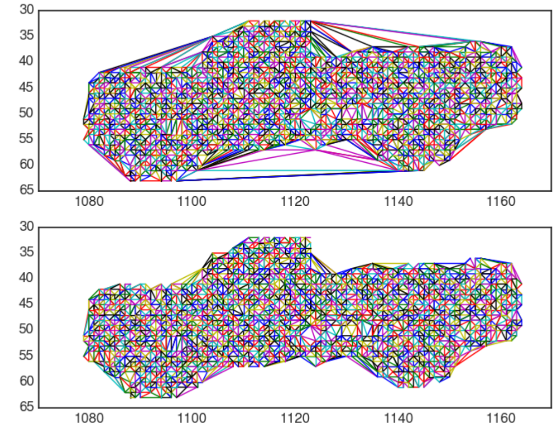


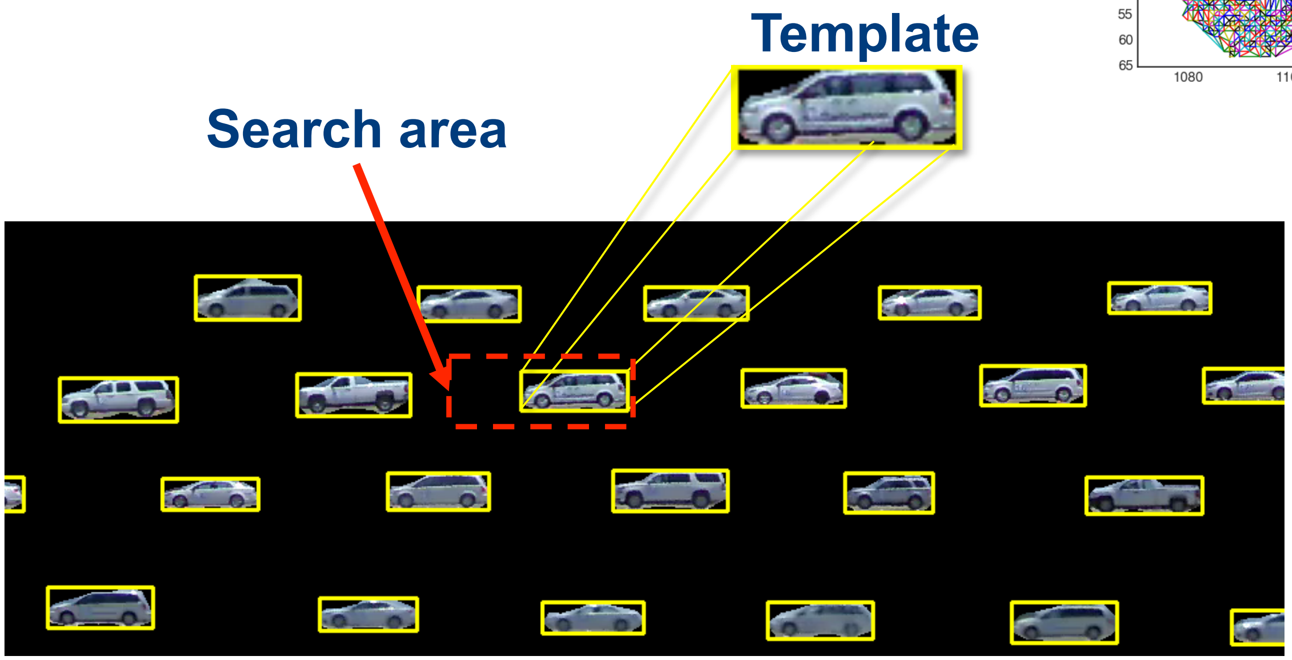
[Wu, et al. 2017]

Extracting vehicle trajectories from 360 video

- Step 2: Cluster foreground pixels
  - Construct a template for each vehicle
- Step 3: Tracking
  - Match template frame by frame

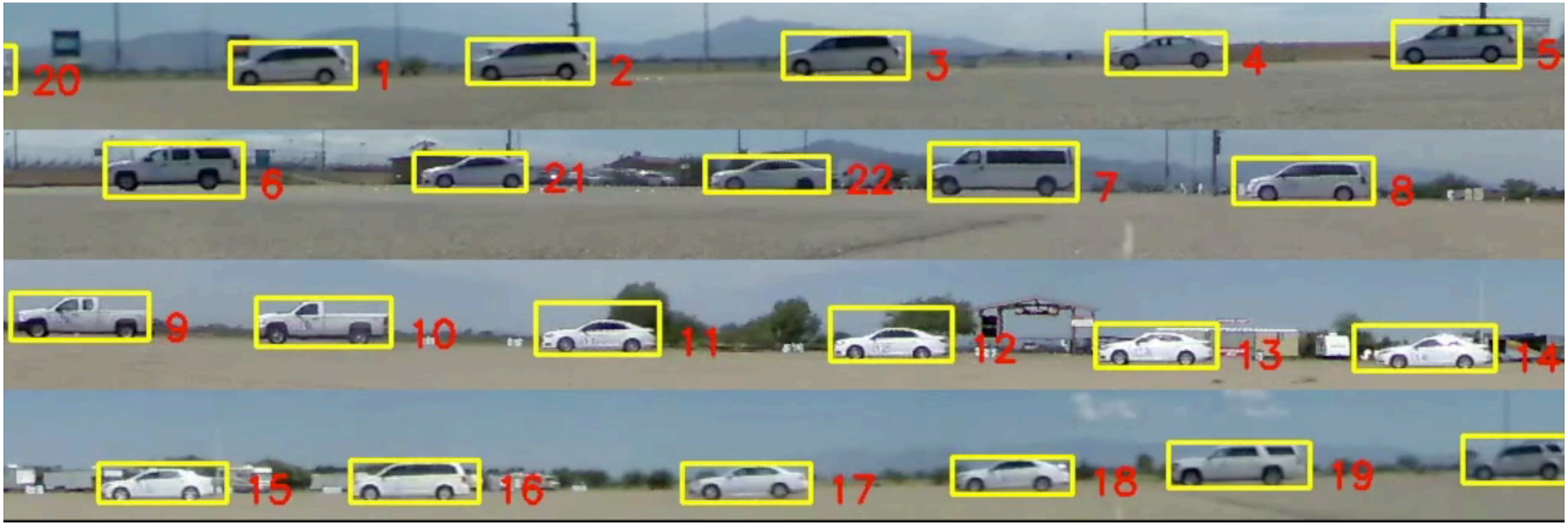
Template refinement from pixel cluster





[Wu, et al. 2017]

Extracting vehicle trajectories from 360 video



- Position Accuracy: 1.5 pixels (0.11 meters) matched with human-annotated data
- Velocity Accuracy: 0.09 m/s (0.2 mph)

Result: Computer vision enables precise vehicle tracking throughout the experiment

Experimental logistics


Setting track


Expect the unexpected


Safety briefing

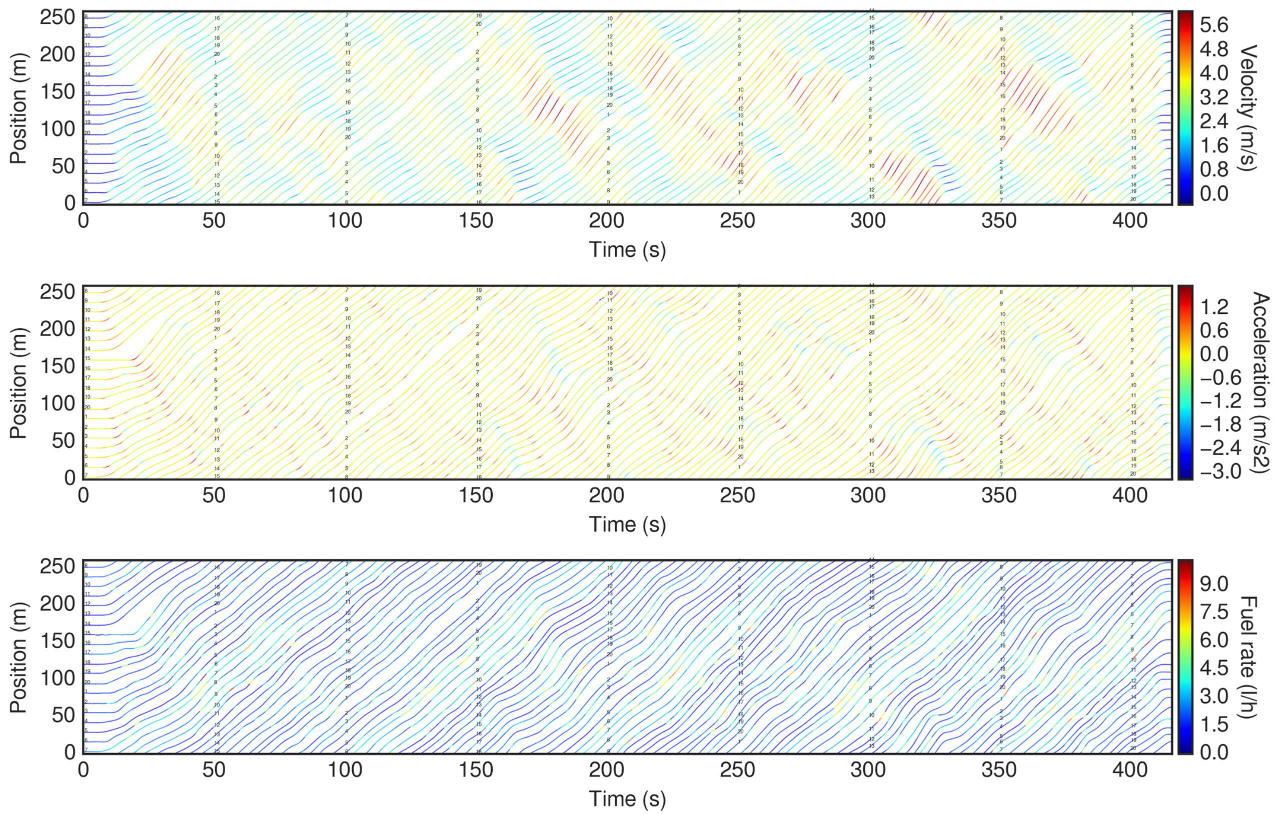

Experiment start


Experiment setup

Total of 20 experiments conducted to re-produce traffic waves

Experimentally reproducing traffic waves

- Collected a total of 20 five to 10-minute experiments to observe traffic behavior
- Extracted vehicle trajectories and accelerations from video footage
- Collected OBD-II data (fuel consumption, engine speed, etc.) from all experiments



Contribution: Data demonstrates repeatability of traffic waves and enables systematic study of oscillatory traffic and affects on fuel consumption and emissions.

[Wu, et al. 2017]

Can a single AV change the traffic state?

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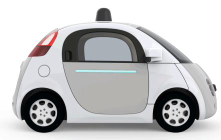

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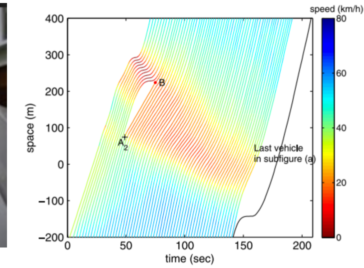
Question: Can an AV be used to dampen traffic waves and reduce fuel consumption and emissions?

Efforts in traffic control

- Single vehicle control
  - Motion planning; deep learning; etc.
- Variable speed limit control
  - Use VSL to dampen waves (e.g. SPECIALIST)
- Platooning
  - Connected and controlled cars, trucks, etc.
- Mixed traffic with AVs
  - Traffic signal free intersections; load balanced routing; simulating CACC and ACC technologies in the steam, etc.



[Shladover 1995; Ioannou et al. 1993; Buehler et al. 2009; He et al. 2017; Jin and Orosz 2014; Davis 2004; Besselink & Johansson, 2017; Hegyi et al. 2008; Rios-Torres & Malikopoulos 2016; Swaroop & Hedrick 1996; Talebpour & Mahmassani 2016]

Traffic string stability

Traffic string stability is defined in terms of how a perturbation from equilibrium is propagated upstream

Let $\Delta x = x_{j+1} - x_j$, consider a car following law

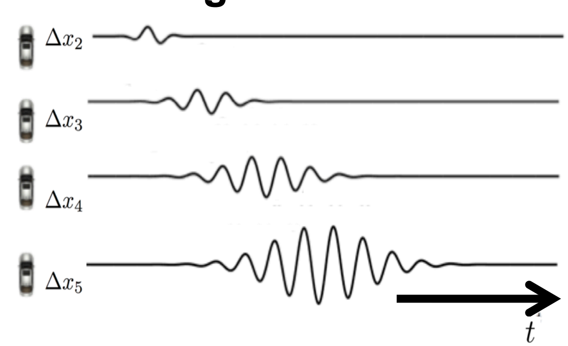
$$\ddot{x} = f(\Delta x_j, \dot{x}_{j+1} - \dot{x}_j, \dot{x}_j)$$

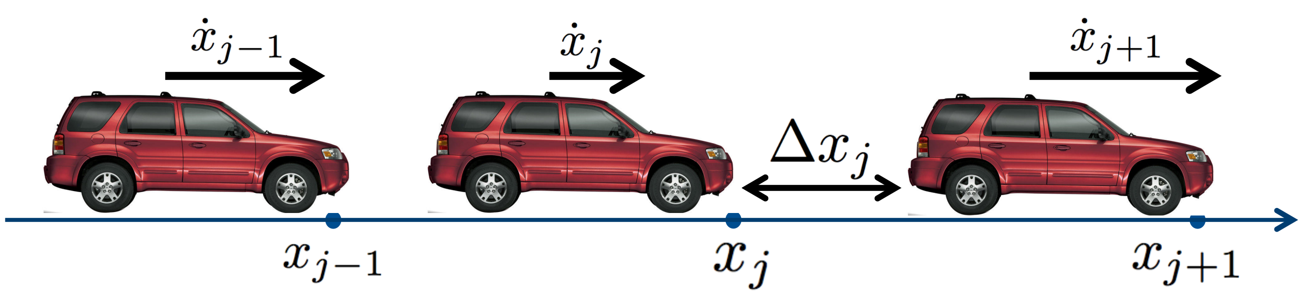
Compute perturbation growth rate

$$\lambda = \frac{\frac{\partial f}{\partial \Delta x_j}}{\left(\frac{\partial f}{\partial \dot{x}_j}\right)^3} \left(\frac{1}{2} \left(\frac{\partial f}{\partial \dot{x}_j} \right)^2 - \frac{\partial f}{\partial (\dot{x}_{j+1} - \dot{x}_j)} \frac{\partial f}{\partial \dot{x}_j} - \frac{\partial f}{\partial \Delta x} \right)$$

If $\lambda < 0$ the car following model is *string stable*
If $\lambda > 0$ the car following model is *string unstable*

String unstable traffic





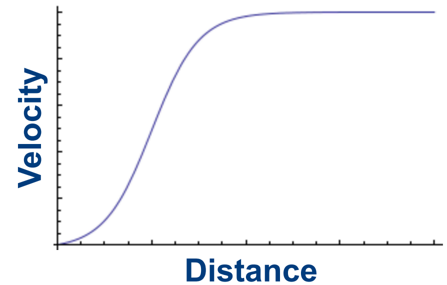
[Wilson & Ward, 2010]

Example model of human piloted traffic

- Model of human drivers

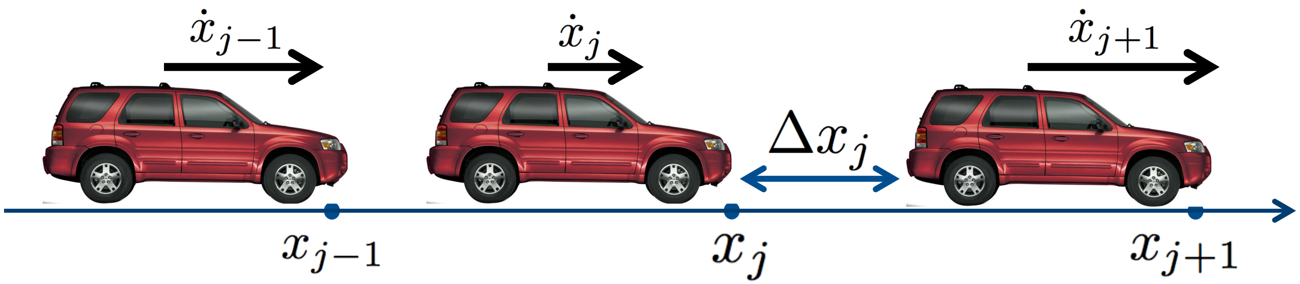
  Acceleration of vehicle j:

$$\ddot{x}_j = \underbrace{a \cdot \left(V\left(\Delta x_j\right) - \dot{x}_j\right)}_{\text{relax towards optimal velocity}} + \underbrace{b \cdot \frac{\dot{x}_{j+1} - \dot{x}_j}{\Delta x_j^2}}_{\text{relax towards leader's velocity}}$$



$$V(\Delta x_j) = V_m \frac{\tanh(\Delta x_j / d_0 - 2) + \tanh(2)}{1 + \tanh(2)}$$

$$\mathbf{z} = \begin{bmatrix} x_1 \\ \dot{x}_1 \\ x_2 \\ \dot{x}_2 \\ \vdots \\ x_N \\ \dot{x}_N \end{bmatrix}$$



Modelling human drivers

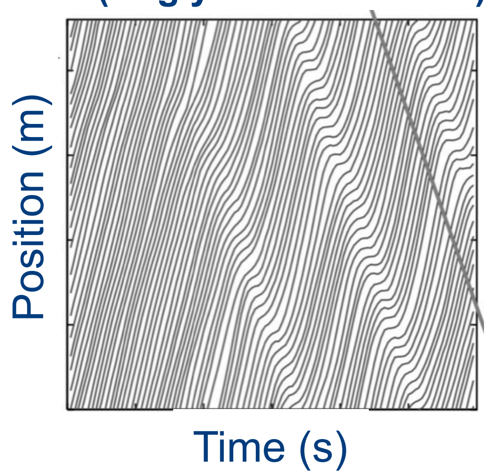
$$\ddot{x}_j = a \cdot \left(V\left(\Delta x_j\right) - \dot{x}_j\right) + b \cdot \frac{\dot{x}_{j+1} - \dot{x}_j}{\Delta x_j^2}$$

relax towards optimal velocity

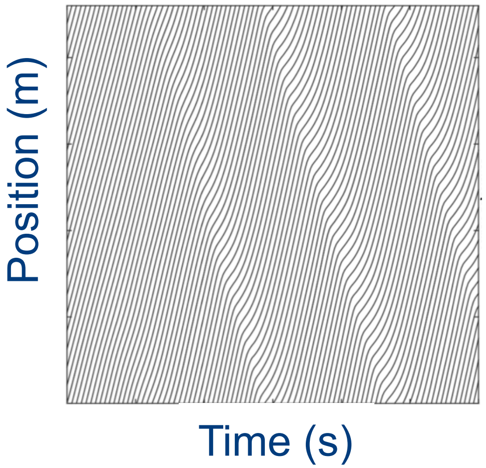
relax towards leader's velocity

Calibrate model parameters using parameter sweep to match macroscopic properties of data from Sugiyama, et al.:

Vehicle trajectories (Sugiyama et al. 2008)



Vehicle trajectories (simulation)



Stability analysis continued

- Linear *string stability* analysis around equilibrium flow of calibrated OV-FTL model:

$$\ddot{x}_j = a \cdot \left(V\left(\Delta x_j\right) - \dot{x}_j\right) + b \cdot \frac{\dot{x}_{j+1} - \dot{x}_j}{\Delta x_j^2}$$

Compute partial derivatives

$$\frac{\partial f}{\partial \Delta x_j} = a V_m \frac{\mathrm{sech}^2\left(2 - \frac{\Delta x_j}{d_0}\right)}{2 + 2\tanh(2)} \qquad \frac{\partial f}{\partial(\dot{x}_{j+1} - \dot{x}_j)} = \frac{b}{\Delta x_j^2} \qquad \frac{\partial f}{\partial \dot{x}_j} = -a$$

- Stability depends on sign of: $\lambda = \frac{\frac{\partial f}{\partial \Delta x_j}}{\left(\frac{\partial f}{\partial \dot{x}_j}\right)^3}\left(\frac{1}{2}\left(\frac{\partial f}{\partial \dot{x}_j}\right)^2 - \frac{\partial f}{\partial(\dot{x}_{j+1} - \dot{x}_j)}\frac{\partial f}{\partial \dot{x}_j} - \frac{\partial f}{\partial \Delta x}\right)$

- In case of calibrated OV-FTL model: $\lambda = 0.60 > 0$

Calibrated OV-FTL model is unstable

Feedback control of the AV

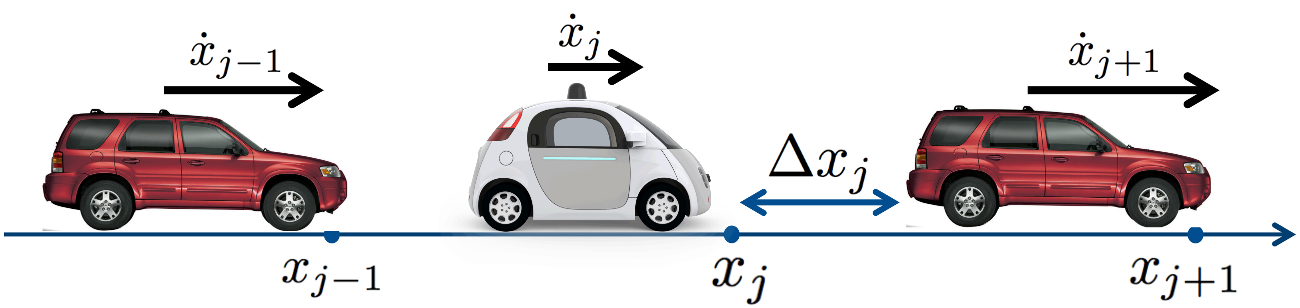
- Model of an autonomous vehicle
  Acceleration of vehicle j:

$$\ddot{x}_j = a \cdot (V(\Delta x_j) - \dot{x}_j) + b \cdot \frac{\dot{x}_{j+1} - \dot{x}_j}{\Delta x_j^2} + c \cdot (u_{\text{eq}} - \dot{x}_j)$$

relax towards optimal velocity

relax towards leader's velocity

relax towards equilibrium velocity



- Small deviations from human driving
- Stability of traffic flow depends on the entire system

A possible stabilizing control

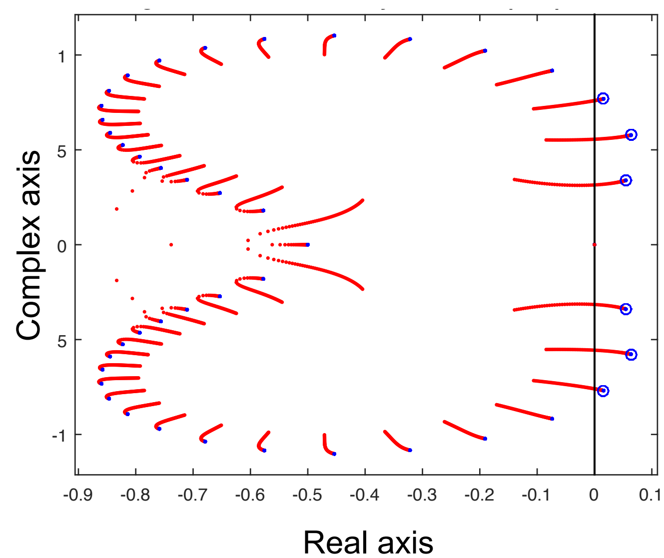
$$\ddot{x}_j = \underbrace{a \cdot (V(\Delta x_j) - \dot{x}_j)}_{\text{relax towards optimal velocity}} + \underbrace{b \cdot \frac{\dot{x}_{j+1} - \dot{x}_j}{\Delta x_j^2}}_{\text{relax towards leader's velocity}} + \underbrace{c \cdot (u_{\text{eq}} - \dot{x}_j)}_{\text{relax towards equilibrium velocity}}$$

$$\begin{cases} \dot{\mathbf{z}} = \mathbf{A}\mathbf{z} + \mathbf{B}u \\ u = \mathbf{F}\mathbf{z} - u_{eq} \end{cases}$$

Only control velocity of AV

$$\mathbf{B} = \begin{bmatrix} 0 \\ 1 \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix} \qquad \mathbf{F}^\top = \begin{bmatrix} 0 \\ -c \\ 0 \\ 0 \\ \vdots \\ 0 \\ 0 \end{bmatrix}$$

- Linearize system about equilibrium
- Determine gain required to stabilize the system around the equilibrium



Intuition: AV drives with as constant a speed as possible.

Experimental testbed: CAT Vehicle

- Used the University of Arizona *Cognitive Autonomous Test* (CAT) Vehicle

- Fully-autonomous Ford Escape Hybrid

- Possible to test control algorithms in Gazebo simulation and in the field

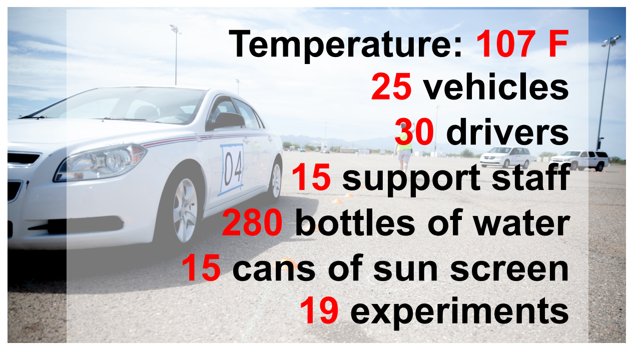
Experimentally demonstrate wave dampening


Vehicle decals


Driver briefings


Tech setup


Fuel consumption loggers




Safety checks


Managing the CAT Vehicle


Experiment adjustments


Staff meetings

Dampening waves in experiment

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

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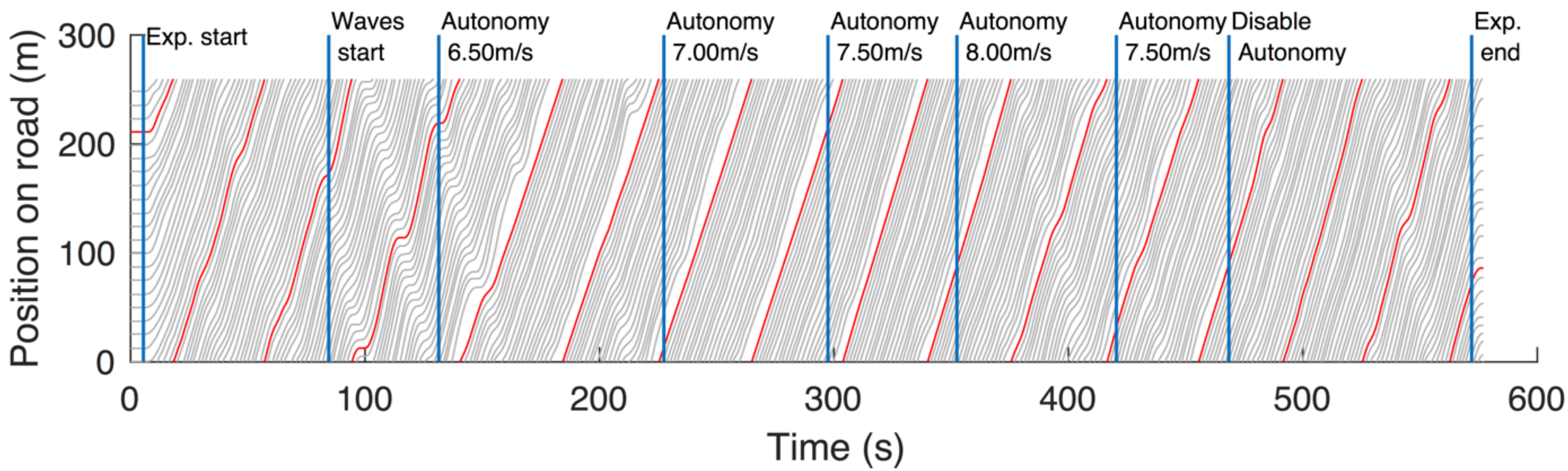
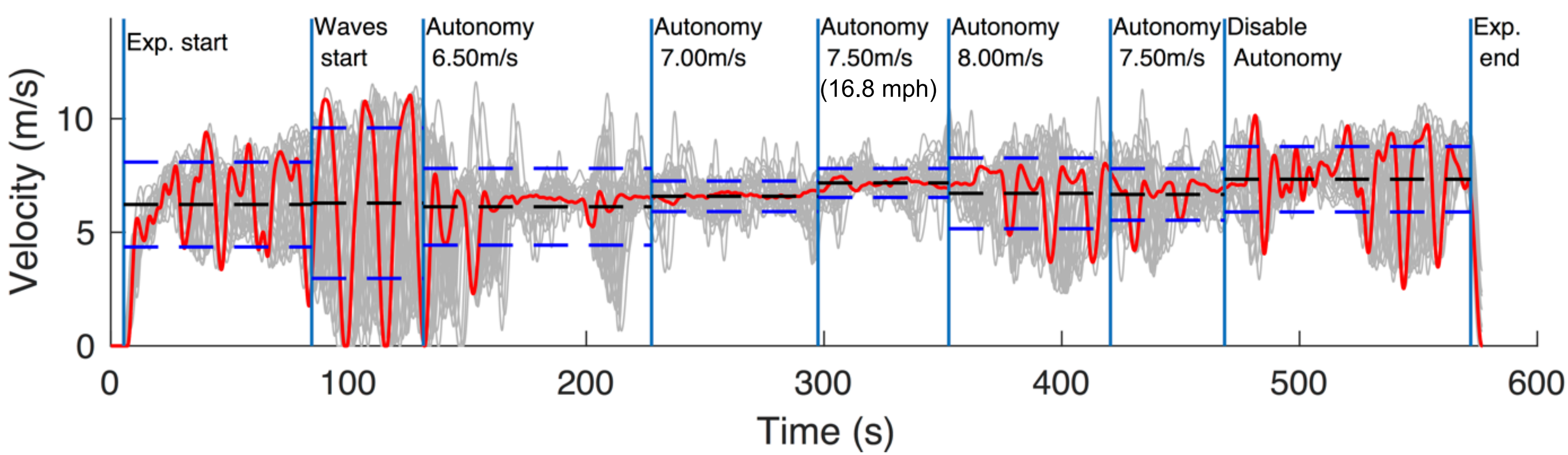
Experimental results





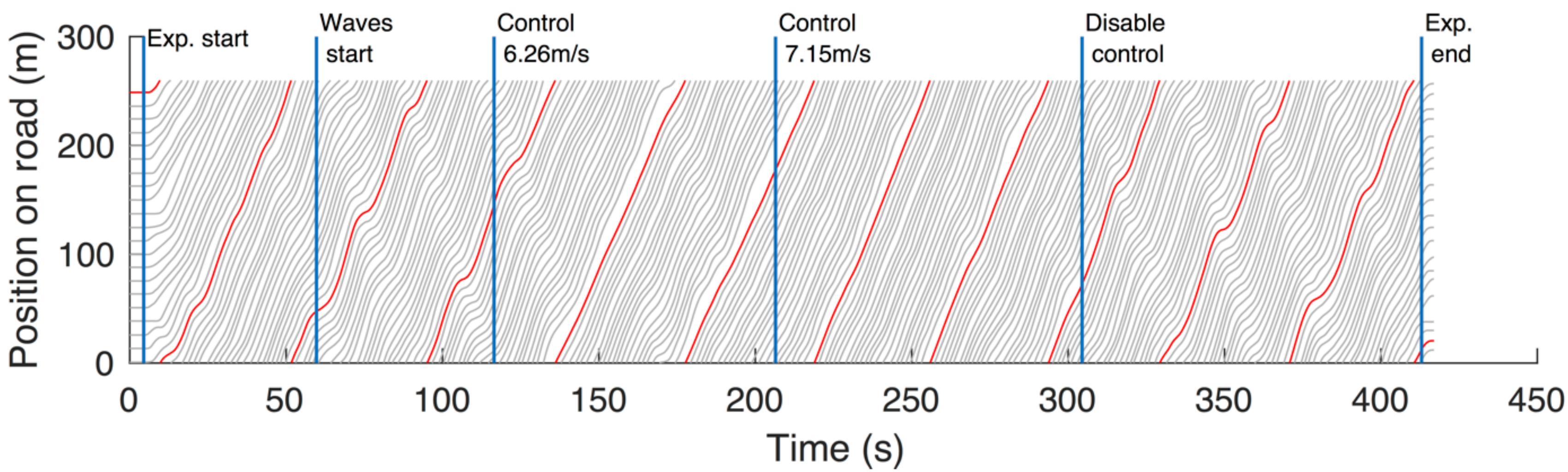
Total velocity standard deviation: **80.8%** ⬇ Fuel consumption: **42.5%** ⬇

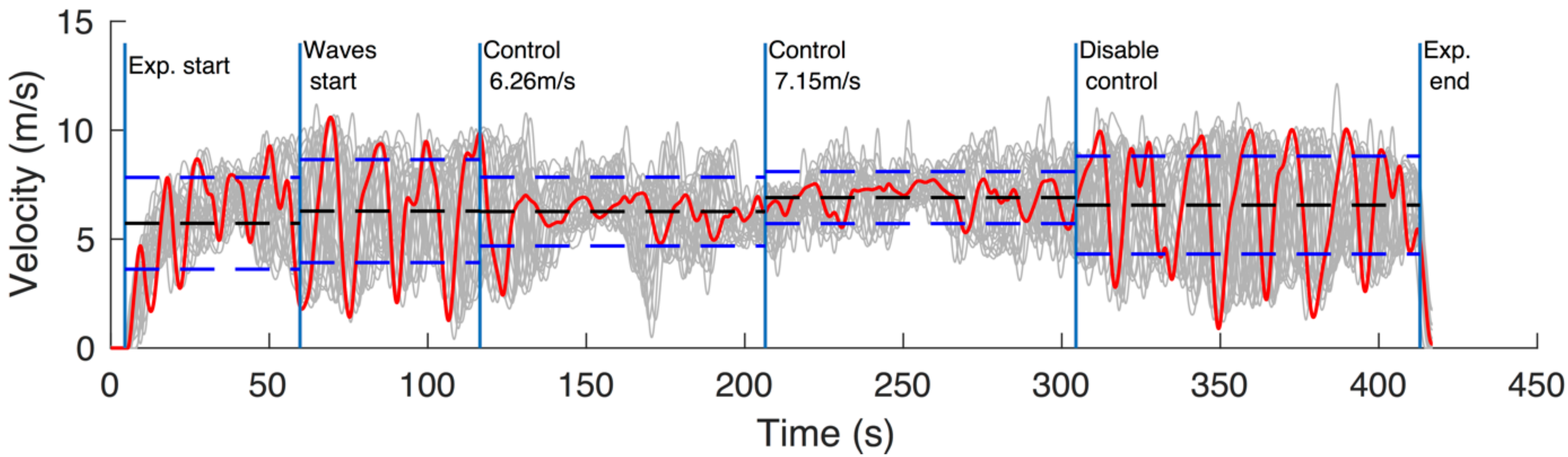
Total braking events: **98.6%** ⬇ Throughput: **14.1%** ⬆

Experimental results: Robot Matt

Control algorithm: instruct Robot Matt via two-way radio to drive with a constant speed.

Experimental results: Robot Matt



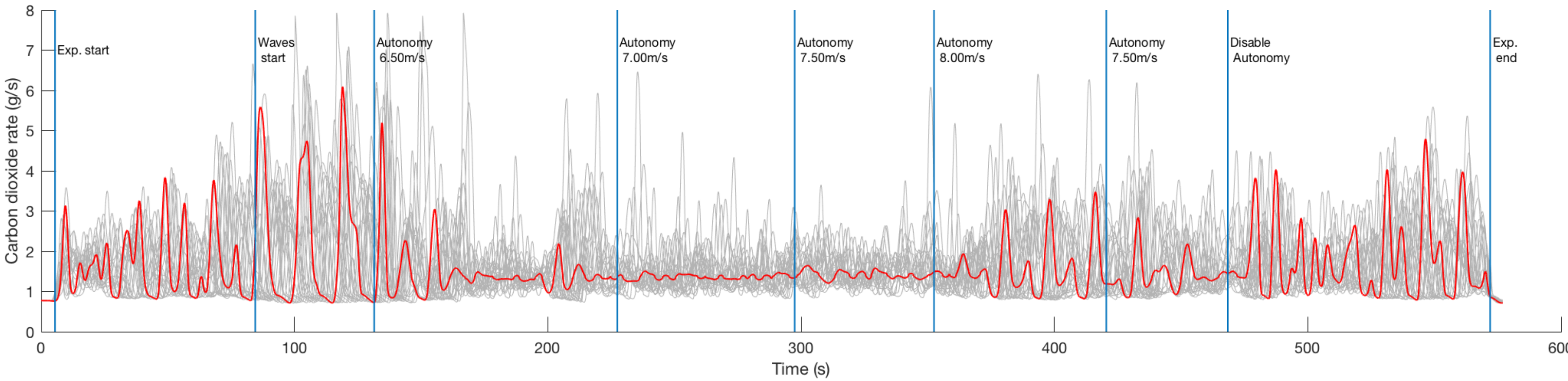


Total velocity standard deviation: **49.5%** ⬇ Fuel consumption: **22.1%** ⬇

Total braking events: **76.2%** ⬇ Throughput: **9.8%** ⬆

Evaluating emissions reduction

- How does stop-and-go traffic influence emissions?
- Detailed trajectories enables emissions estimation
- Use the VT-Micro model to estimate emissions based on each vehicle's velocity and acceleration



Carbon dioxide: **21.1**	Carbon monoxide: **12.5%**	Hydrocarbons: **16.2%**

Summary

- Designed experimental protocol to observe oscillatory traffic
- Designed controller to stabilize traffic flow
- Demonstrated wave dampening in simulation and in an experiment
- Investigated impact on emissions

Special thanks to the experimental crew: 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, Jonathan Sprinkle, and Dan Work.

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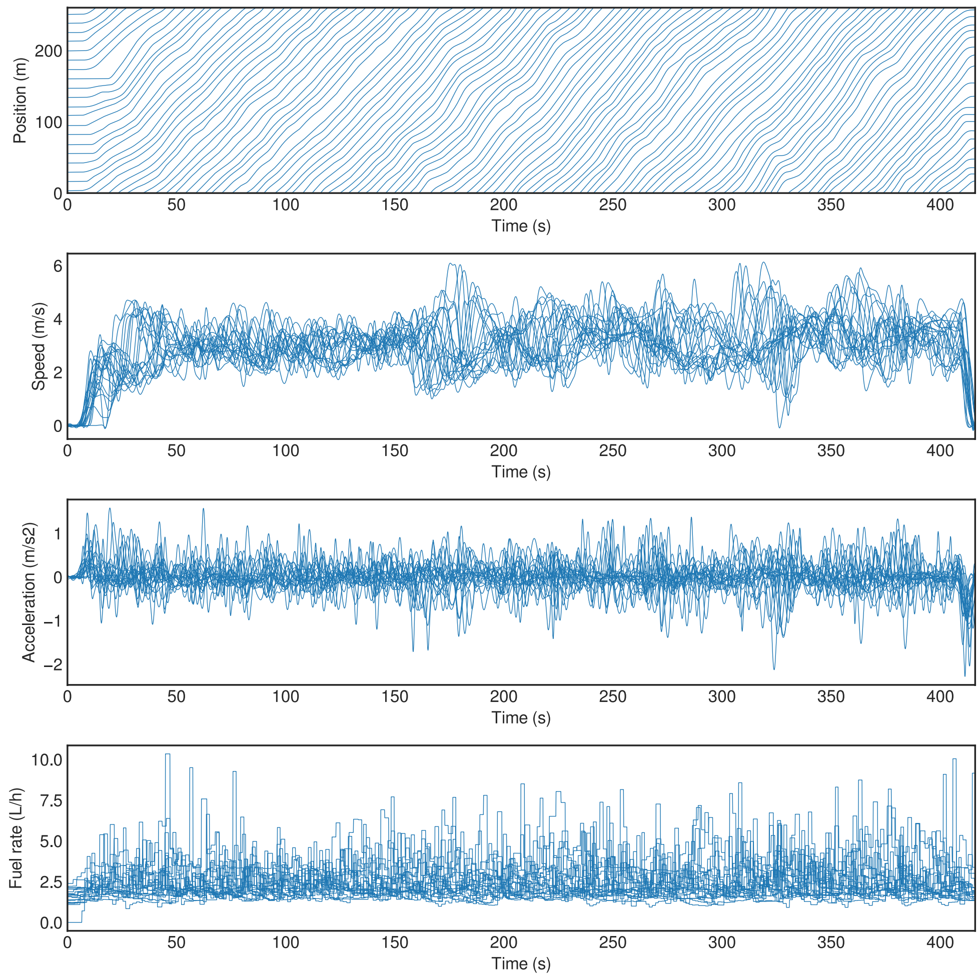

Contribution: Data demonstrates repeatability of traffic waves and enables systematic study of oscillatory traffic and affects on fuel consumption and emissions.

Wave dampening controller

Goal: command the AV to drive at the desired velocity, *U*

Consider three regions:

1. A safe region where $v^{\mathrm{cmd}} = U$
2. A stopping region, where zero velocity is commanded
3. An adaptation region (in two parts), where average of lead vehicle and desired velocity is commanded

$$v^{\mathrm{cmd}} = \begin{cases} 0 & \text{if } \quad \Delta x \le \Delta x_1 \\ v \frac{\Delta x - \Delta x_1}{\Delta x_2 - \Delta x_1} & \text{if } \Delta x_1 < \Delta x \le \Delta x_2 \\ v + (U - v) \frac{\Delta x - \Delta x_2}{\Delta x_3 - \Delta x_2} & \text{if } \Delta x_2 < \Delta x \le \Delta x_3 \\ U & \text{if } \Delta x_3 < \Delta x \, . \end{cases}$$

$$v = \min(\max(v^{\mathrm{lead}}, 0), U)$$

Δx_1, Δx_2, Δx_3 , are safety distance parameters