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Dissipation of Emergent Traffic Waves in Stop-and-Go Traffic Using a Supervisory Controller

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Agenda

- Motivation
- Contribution
- Experiment setup
- Controller Design
  - Approach and Implementation
- Results
  - Simulation and Real-world experiment
- Conclusion

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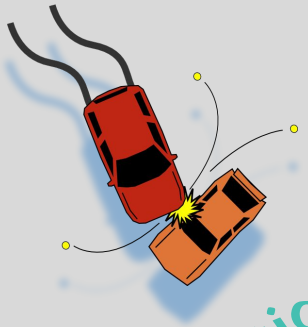
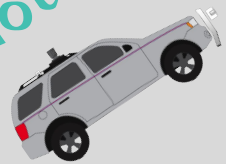
Safety for humans in mixed traffic: autonomous vehicles + human driven vehicles

Urban stop and go traffic



Motivation



Traffic waves

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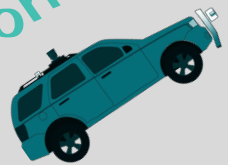
Design of controller for AVs to alleviate the adverse effect of traffic congestion and address human safety in mixed traffic.

Demonstrate that controlling small number of vehicles autonomously increases the traffic-flow rate and positively impacts stop-and-go urban traffic.

Contribution



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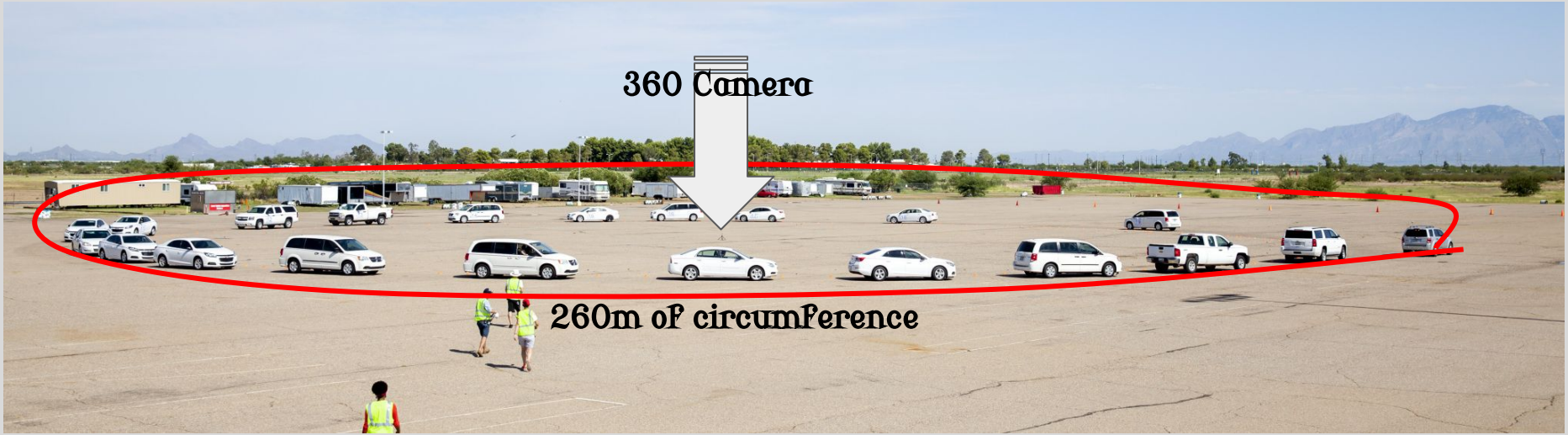
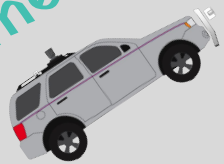
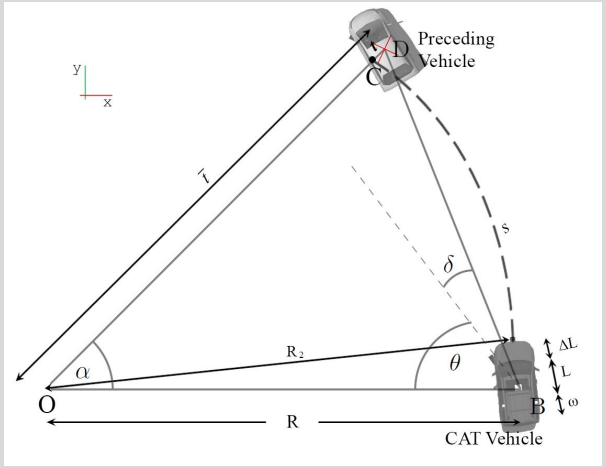


Experimental Setup





ROS

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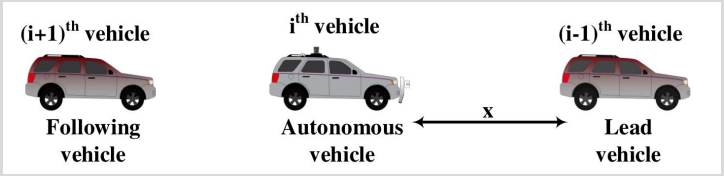
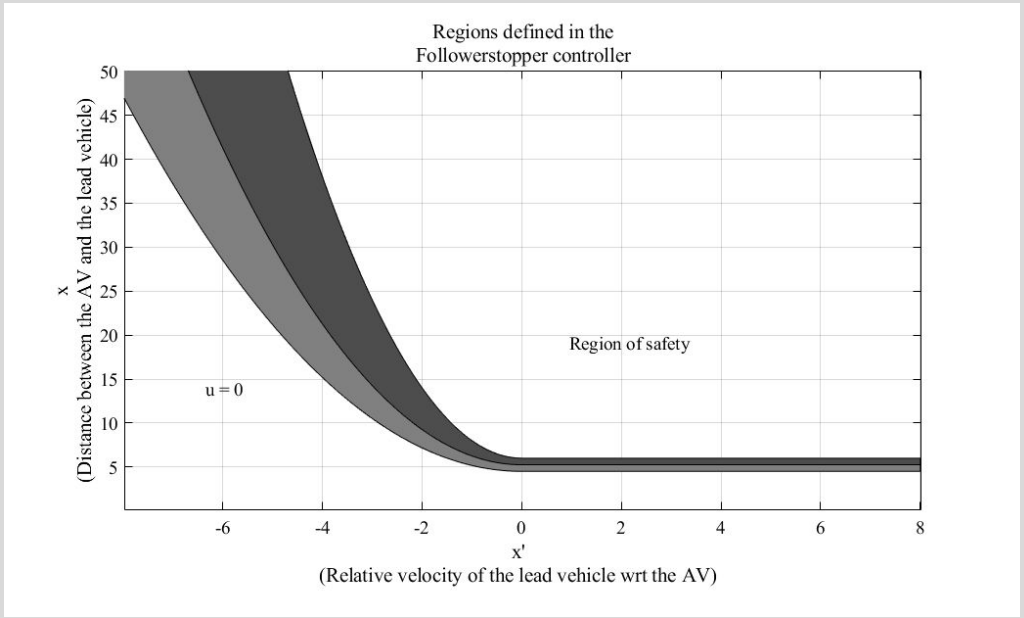
Weighted sum of reference and lead vehicle's velocity to design the velocity controller!





Controller Design

$$u = \begin{cases} 0, & \text{if } \mathbf{x} \le \mathbf{x}_1 \\ v\frac{\mathbf{x}-\mathbf{x}_1}{\mathbf{x}_2-\mathbf{x}_1}, & \text{if } \mathbf{x}_1 < \mathbf{x} \le \mathbf{x}_2 \\ v+(r-v)\frac{\mathbf{x}-\mathbf{x}_2}{\mathbf{x}_3-\mathbf{x}_2}, & \text{if } \mathbf{x}_2 < \mathbf{x} \le \mathbf{x}_3 \\ r, & \text{if } \mathbf{x}_3 < \mathbf{x} \end{cases}$$

$$v = \min(\max(v_{\text{lead}}, 0), r)$$

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$$u = \begin{cases} 0, & \text{if } \mathbf{x} \le \mathbf{x}_1 \\ v\frac{\mathbf{x}-\mathbf{x}_1}{\mathbf{x}_2-\mathbf{x}_1}, & \text{if } \mathbf{x}_1 < \mathbf{x} \le \mathbf{x}_2 \\ v+(r-v)\frac{\mathbf{x}-\mathbf{x}_2}{\mathbf{x}_3-\mathbf{x}_2}, & \text{if } \mathbf{x}_2 < \mathbf{x} \le \mathbf{x}_3 \\ r, & \text{if } \mathbf{x}_3 < \mathbf{x} \end{cases}$$

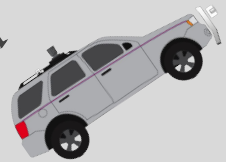
$$v = \min(\max(v_{\text{lead}}, 0), r)$$

Uses kinematic equations to design piecewise linear control: spacing between cars varies as a function of square of relative velocity

$$\mathbf{x}_j = \omega_j + \frac{1}{2\alpha_j}(\dot{\mathbf{x}}^*)^2 \text{ for j = 1, 2, 3}$$

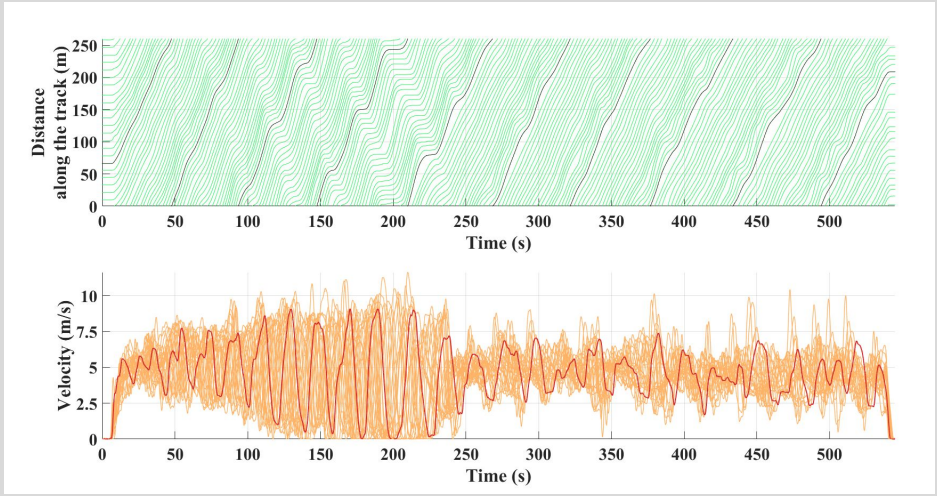
$$\dot{\mathbf{x}}^* = min(\dot{\mathbf{x}}, 0)$$

Controller Design Approach



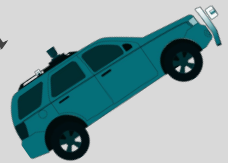
$\mathbf{x}_3$ triggers controlled behavior.
$\mathbf{x}_1$ is minimum safe distance AV should always maintain.
Reference velocity $\mathbf{r}$ comes from some other controller.
We called the resulting piecewise controller **Followerstopper controller**.

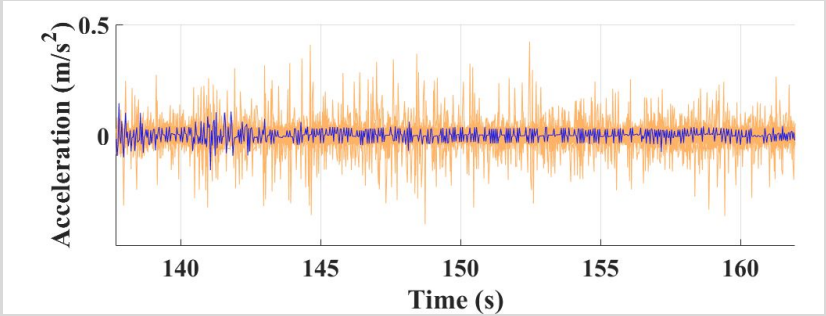
Data driven approach to human driver characterization



Human driving leads to traffic waves with oscillatory velocity profile but acceleration are bounded within ± 0.5 m/s^2

Controller Design Approach





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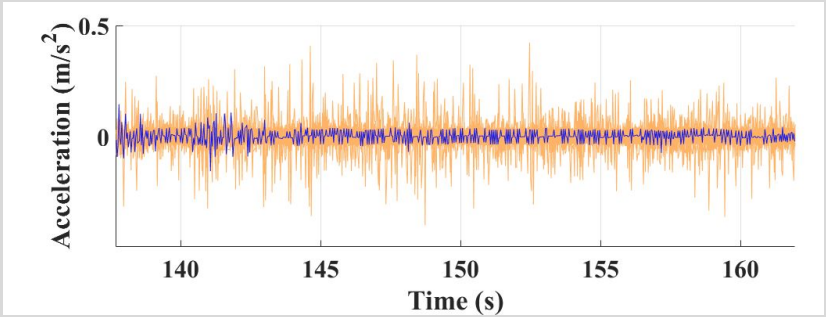
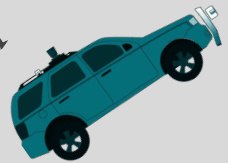
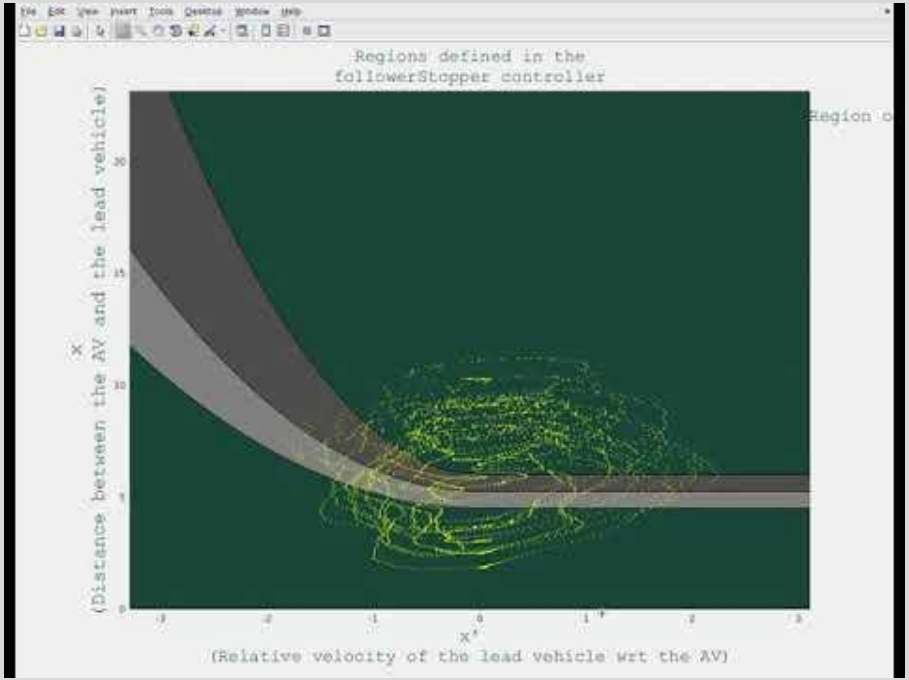
Based on human driving data we chose $a_1 = 0.5 m/s^2$ and $\omega_1 = 4.5$ m; $a_3 = 1.5 m/s^2$ and $\omega_3 = 6.0$ m; $a_2 = (a_1 + a_3)/2$ and $\omega_2 = (\omega_1 + \omega_3)/2$ for smooth transition when switching regions for safety and wave-dampening effect.



Controller Design Approach



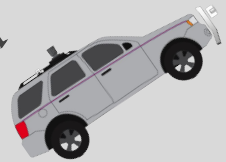
Phase-space animation showing how relative distance between a car and its preceding vehicle varies when a human drivers operates a vehicle in stop and go traffic.



Human driving behavior on phase space plot

https://youtu.be/iNqjZrMYHX4

Controller Design Approach



There are number of events when a human driver crosses safe distance x_1. These situations may potentially lead to collision and require evasive maneuvers.

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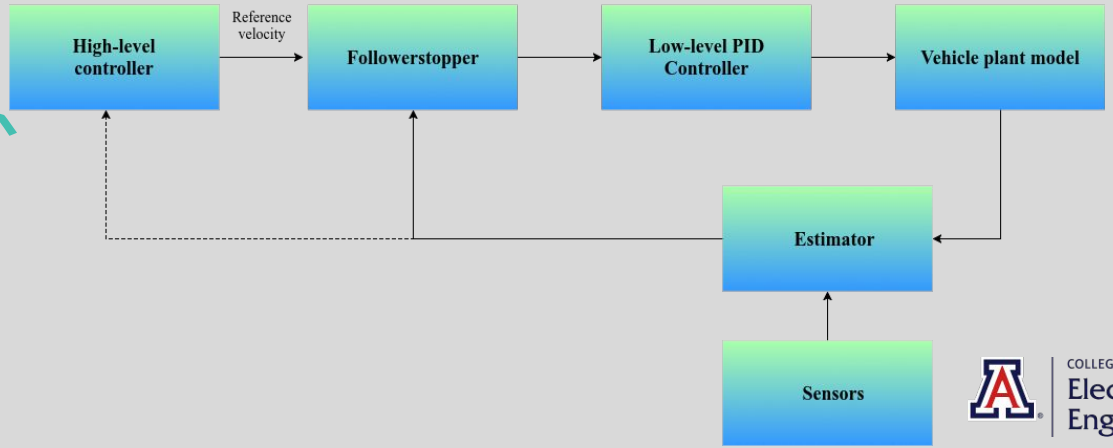
Controller design used model-based engineering for implementation ...

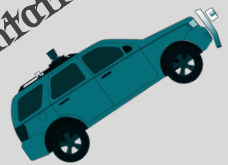
... and code-generation ...

... with the first order plant model and PID controlled dynamics valid in the range of 8-10m/s

$k_p = 44.6218$
$k_i = 72.7801$
$k_d = 0.84327$



Controller Design Implementation



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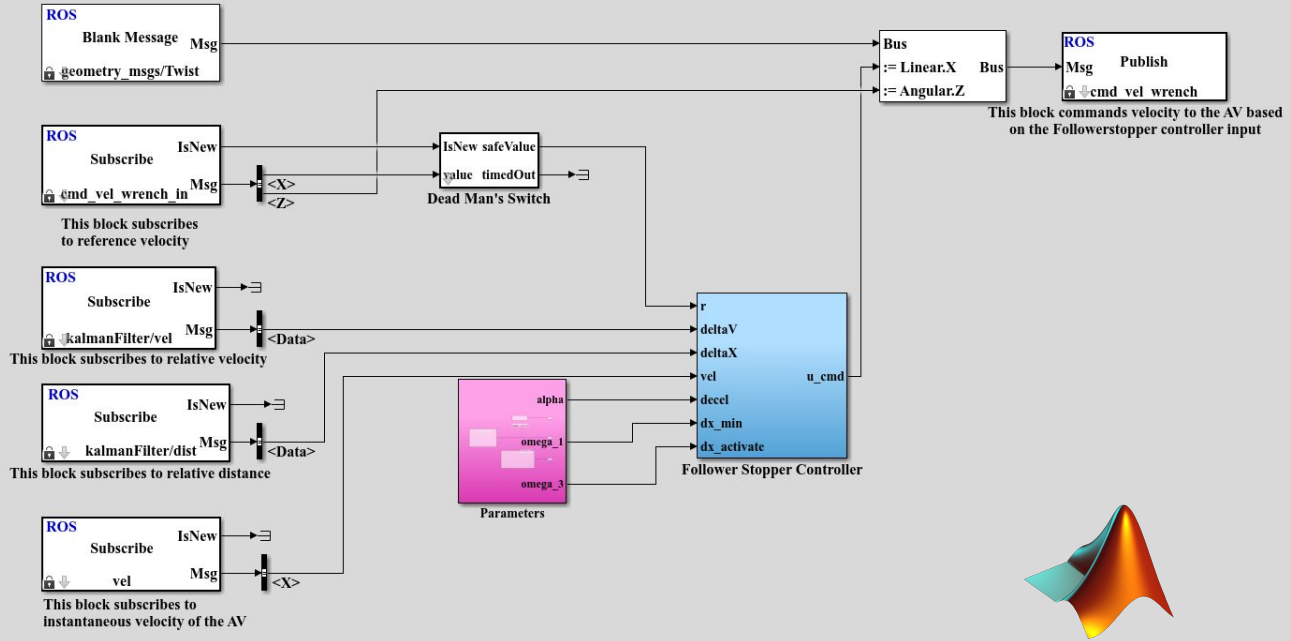
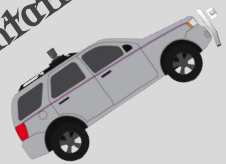
Code For deployment on real hardware is one-click away.



Controller Design Implementation



Code-generation method allowed us to design controller at block level while reducing debug time. Additionally, we didn't need to write separate code for simulation and hardware-implementation in real autonomous vehicle. This further cuts overall design time.

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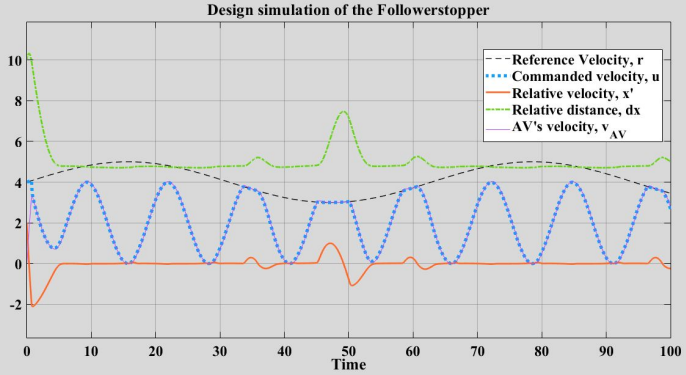
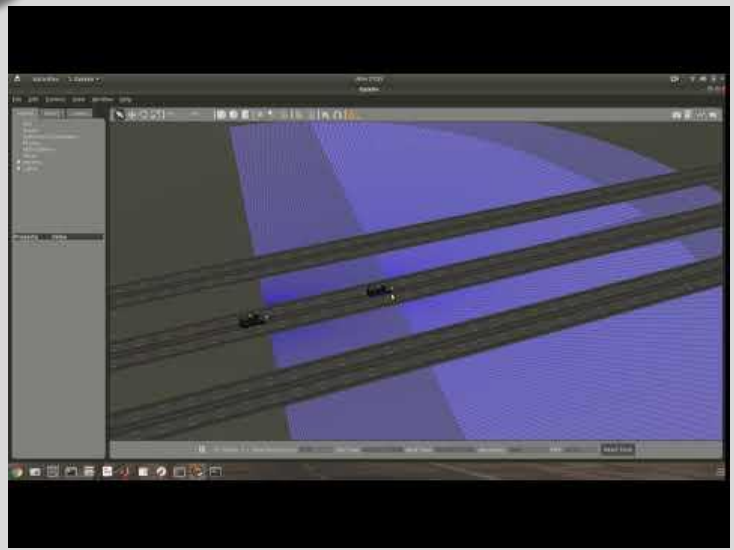
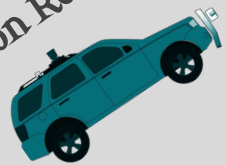
Simulation with synthetic data. Reference velocity input r and lead vehicle velocity inputs are sinusoidal. Minimum relative distance satisfies required safe distance requirements as defined in the controller definition.





Results

Simulation Results



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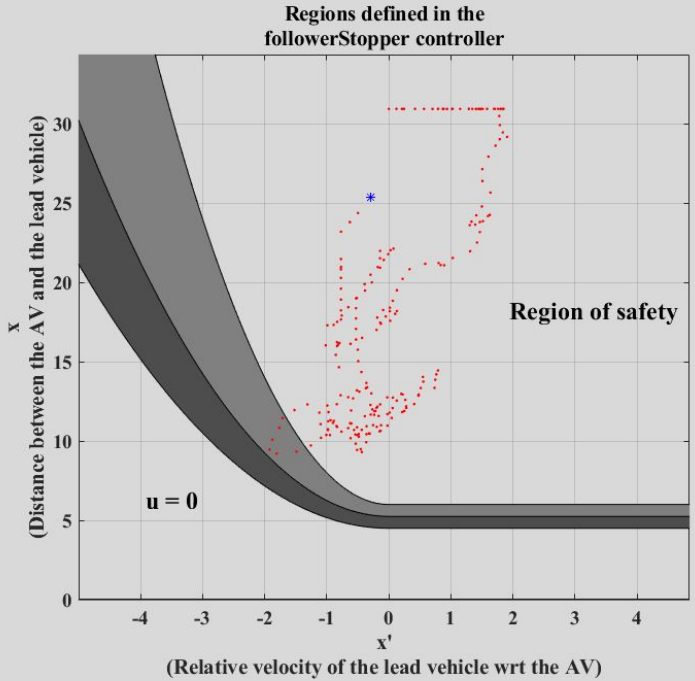
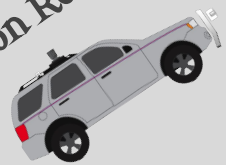
Lead-vehicle driving using joystick in Gazebo simulation to imitate human driving and Following vehicle uses Followerstopper to follow the leader



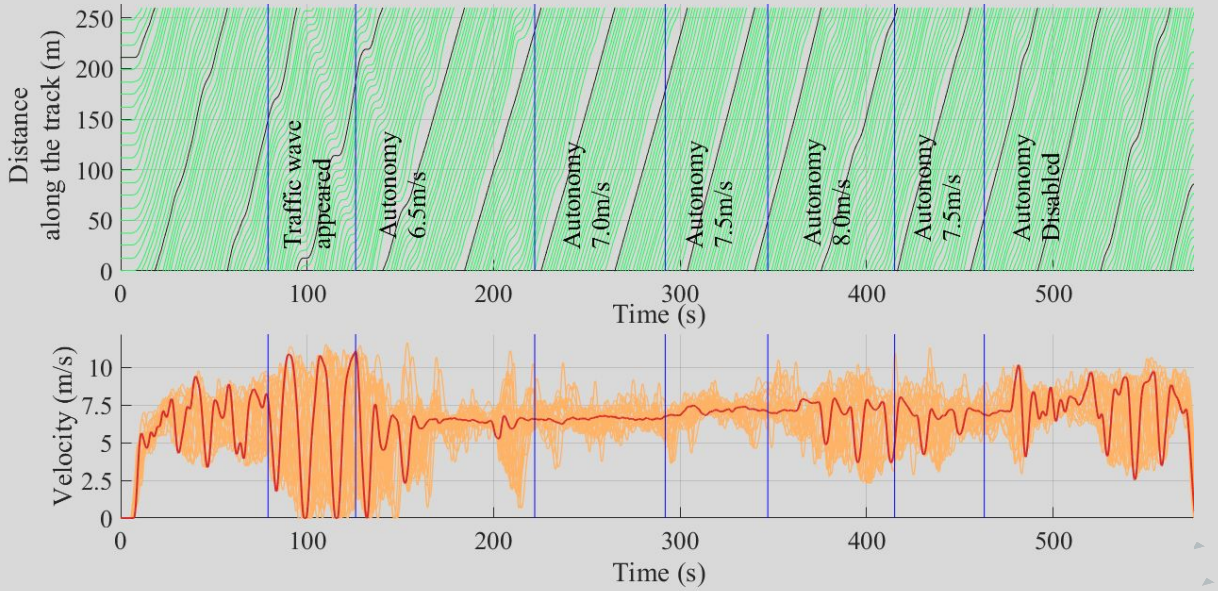
Results

Simulation Results



We conducted experiments with 21 vehicles on ring road in Tucson, Arizona.
One vehicle out of 21 was autonomous vehicle, operating autonomously using **Followerstopper.**

The Followerstopper velocity controller was activated at **t = 126s** into the experiment. We observed wave-dampening effect when Followerstopper was activated for the AV. Remaining 20 vehicles were still under human control to imitate stop-and-go traffic.



Results
Experiment Results

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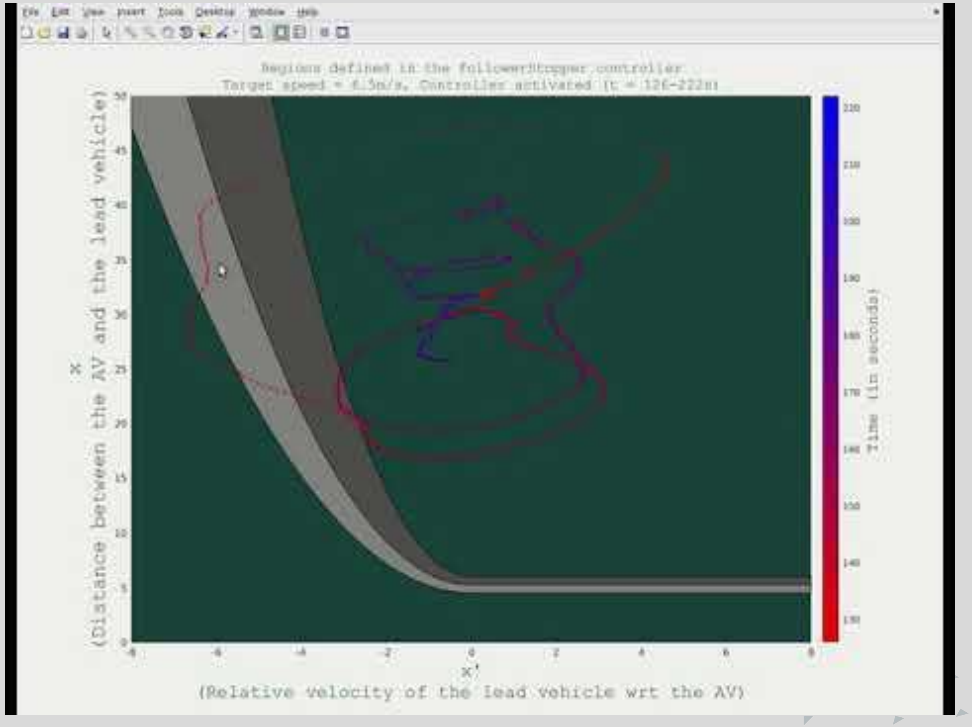
Let's look at the phase space evolution for controller-assisted driving with reference velocity of 6.5m/s.

In controller-assisted driving, AV never leaves too little or too large gap and rebounds to safe region whenever there is too large a gap for given relative velocity.

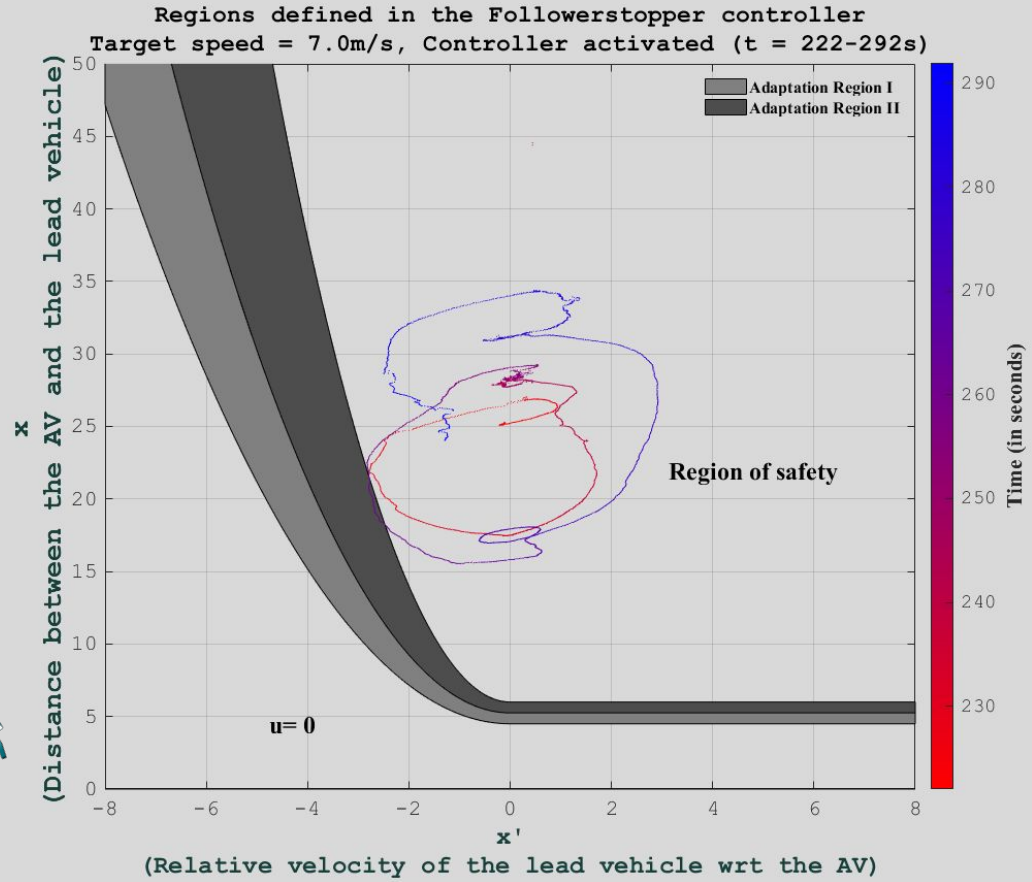


Results

Experiment Results

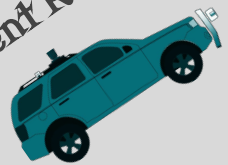
https://youtu.be/V5ADfpS9FiI

Best performance in terms of wave-dampening was achieved for reference velocity of 7.0 m/s.



Results

Experiment Results



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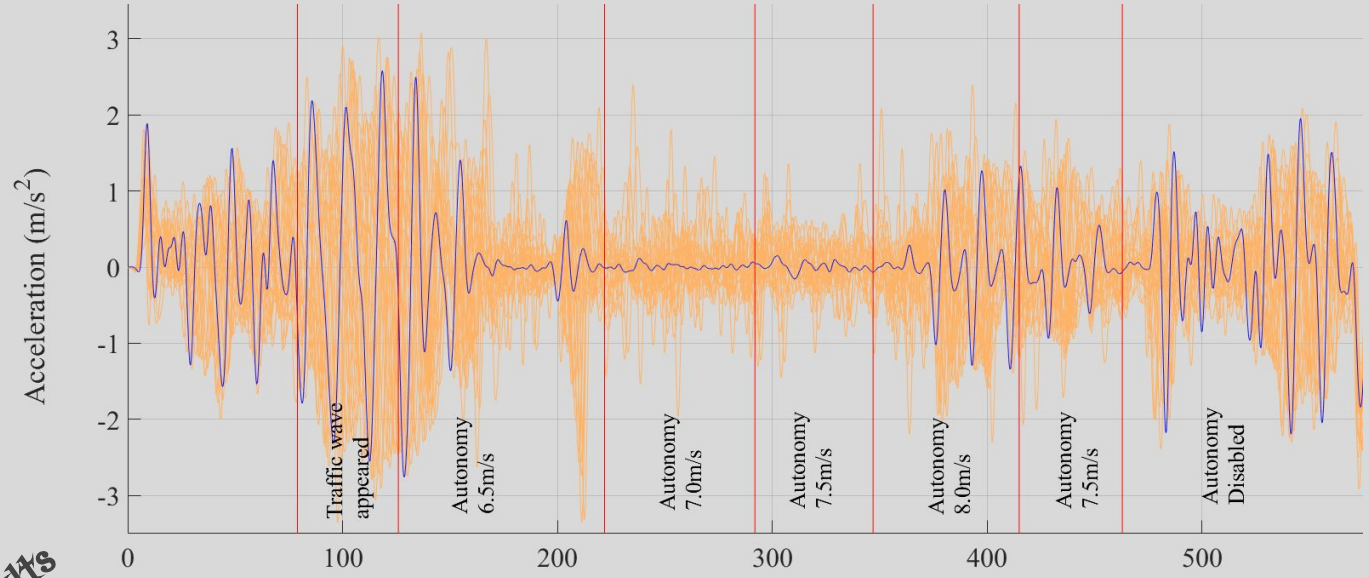
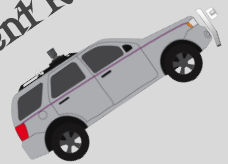
Finally, we look at acceleration profile of vehicles involved in the experiment. When one of the vehicle is in autonomous mode, there is visible reduction in acceleration of all vehicles involved in the experiment. Disabling autonomous mode brings back oscillations in acceleration profile.



Results
Experiment Results



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Relevant publication to the experiment: Stern, R. E., Cui, S., Delle Monache, M. L., Bhadani, R., Bunting, M., Churchill, M., ... & Seibold, B. (2018). ***Dissipation of stop-and-go waves via control of autonomous vehicles: Field experiments.*** Transportation Research Part C: Emerging Technologies, 89, 205-221.

Related work in this series: Delle Monache, M. L., Liard, T., Rat, A., Stern, R., Bhadani, R., Seibold, B., ... & Piccoli, B. (2017). ***Feedback control algorithms for the dissipation of traffic waves with autonomous vehicles.***

https://www.youtube.com/watch?v=2mBjYZTeaTc

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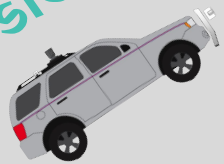
Conclusion and Discussions

The presented work demonstrated that even a very simple supervisory controller, if design carefully can regulate velocity to reduce traffic congestions.

Sets standard for velocity controller intended to controller autonomous vehicles in human-av mixed traffic: **AV driving should behave like human but a bit smarter.**

AV velocity controller doesn't need other vehicles to know that they are following an AV in order to dissipate traffic waves aka congestions.



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What is missing?

In an upcoming work in this series, we will provide a mathematical foundation and formal analysis of followerstopper controller on why it worked.

Conclusion and Discussions

Thank you!

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Questions?

Download slides at https://goo.gl/Z519gL

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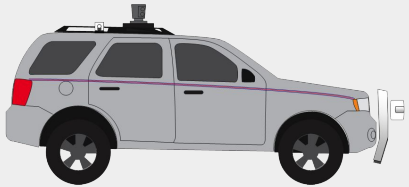

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