Dissipation of Stop and Go Waves via Control of Autonomous Vehicles

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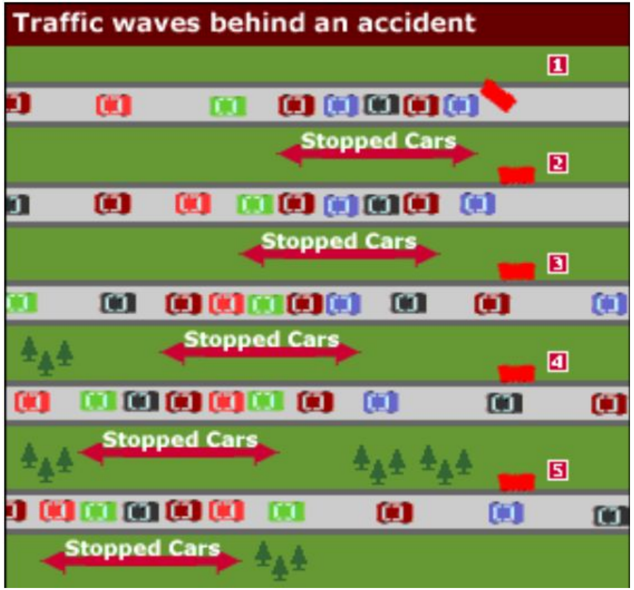
Outline

1. **Background**
2. System Dynamics
3. Algorithms
4. Experimental Setup
5. Results
6. Simulations
7. Conclusion
8. Future Work/Setbacks

Introduction

- Disruptions in the flow of vehicles that propagate backward through traffic, causing stop-and-go patterns.
- Reasons:
  - Driver behavior
  - Road conditions
  - Lane change
  - Capacity constraints
- Effects:
  - Congestion
  - Delays
  - Decreased fuel efficiency
  - Increased accident risks



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Simple Solutions

- Traffic flow control measures:
  - Ramp metering
  - Variable speed limits
- Improving road infrastructure
  - Adding lanes
  - Intersections
  - Optimizing traffic signal timings
- Driver education and awareness
- Public transportation
- Intelligent transportation systems

Existing Solutions

- Current traffic control strategies rely on fixed-location:
  - Variable speed advisory (VSA)
  - Variable speed limits (VSL)
- Strategies like "slow-in, fast-out"
- Newell's car following theory

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Prior Works (State of the Art)

Variable Speed Advisory (VSA):

- Real-time speed recommendations based on prevailing traffic conditions.
- Data collection devices installed to monitor traffic flow, weather conditions
- Calculated advisory speeds are communicated to drivers:
  - dynamic message signs
  - in-vehicle displays.

Variable Speed Limits (VSL):

- Posted speed limits: dynamically adjusted to match the actual traffic conditions
- Data collection devices to monitor traffic flow, congestion levels in real-time
- Optimal speed limits for specific road segment
- Speed limits updated on signage along the roadway

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Zhang Fangzhou, Lv Yang and Jiang Hui, "Studying on variable speed limit for expressway based on meteorological monitoring," *2014 IEEE Workshop on Advanced Research and Technology in Industry Applications (WARTIA)*, Ottawa, ON, Canada, 2014, pp. 370-373, doi: 10.1109/WARTIA.2014.6976272.

Main Contributions

- Literature does not offer a solution for wave dampening
- Ring-road experiments to dampen stop-and-go waves (setup of Sugiayama et al)
- Presenting two distinct control strategies:
  - Follower Stopper Control
  - PI controller with saturation
- Impact of Lagrangian actuators (AVs) in controlling traffic flow

Y. Sugiyama, M. Fukui, M. Kikuchi, K. Hasebe, A. Nakayama, K. Nishinari, S. ichi Tadaki, S. Yukawa, Traffic jams without bottlenecks – experimental evidence for the physical mechanism of the formation of a jam, New Journal of Physics 10 (3) (2008) 033001

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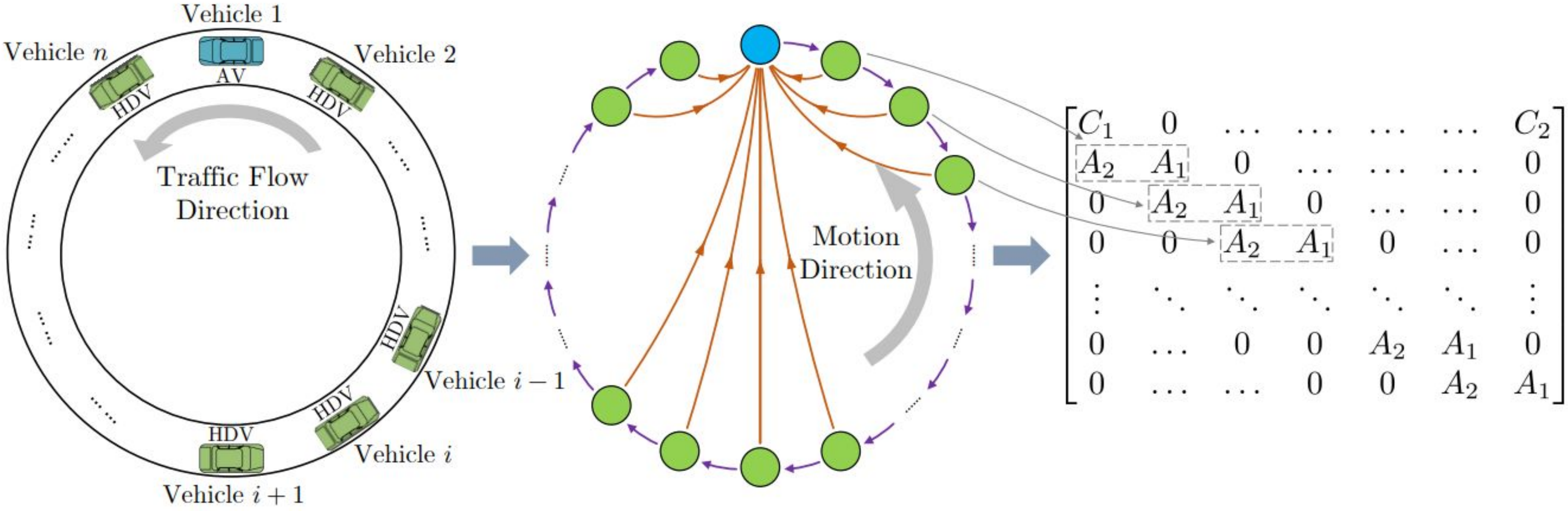
System Dynamics: CAT Vehicle



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System Dynamics

Human-driven Vehicle dynamics:

$$\dot{v}_i(t) = F(s_i(t), \dot{s}_i(t), v_i(t))$$

$$\begin{cases} \dot{\tilde{s}}_i(t) = \tilde{v}_{i-1}(t) - \tilde{v}_i(t), \\ \dot{\tilde{v}}_i(t) = \alpha_1 \tilde{s}_i(t) - \alpha_2 \tilde{v}_i(t) + \alpha_3 \tilde{v}_{i-1}(t) \end{cases}$$

$$\alpha_1 = \frac{\partial F}{\partial s}, \alpha_2 = \frac{\partial F}{\partial \dot{s}} - \frac{\partial F}{\partial v}, \alpha_3 = \frac{\partial F}{\partial \dot{s}}$$

$$\dot{x}(t) = Ax(t) + Bu(t)$$

$$A = \begin{bmatrix} C_1 & 0 & \dots & \dots & 0 & C_2 \\ A_2 & A_1 & 0 & \dots & \dots & 0 \\ 0 & A_2 & A_1 & 0 & \dots & 0 \\ \vdots & \ddots & \ddots & \ddots & \ddots & \vdots \\ 0 & \dots & 0 & A_2 & A_1 & 0 \\ 0 & \dots & \dots & 0 & A_2 & A_1 \end{bmatrix}, B = \begin{bmatrix} B_1 \\ B_2 \\ B_2 \\ \vdots \\ B_2 \end{bmatrix}$$

$$A_1 = \begin{bmatrix} 0 & -1 \\ \alpha_1 & -\alpha_2 \end{bmatrix}, \; A_2 = \begin{bmatrix} 0 & 1 \\ 0 & \alpha_3 \end{bmatrix},$$

$$C_1 = \begin{bmatrix} 0 & -1 \\ 0 & 0 \end{bmatrix}, \; C_2 = \begin{bmatrix} 0 & 1 \\ 0 & 0 \end{bmatrix}, \; B_1 = \begin{bmatrix} 0 \\ 1 \end{bmatrix}, \; B_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}$$

The system is stable if: $\alpha_2^2 - \alpha_3^2 - 2\alpha_1 \geq 0$

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Follower Stopper Controller

- Command a lower velocity based on the lead vehicle's velocity:

$$v_{cmd} < U \text{ (desired velocity)}$$

- Using the gap Δx and the velocity difference

$$\Delta v = d\Delta x/dt = v_{lead} - v_{AV}$$

the Δx–Δv phase space is divided into regions

  - a safe region: $v_{cmd} = U$
  - a stopping region: $v_{cmd} = 0$
  - an adaptation region (2 parts)

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Follower Stopper Controller

$$\Delta x_k = \Delta x_k^0 + \frac{1}{2d_k}(\Delta v_-)^2 , \quad \text{for } k = 1, 2, 3 .$$

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

$$v = \min(\max(v^{\text{lead}}, 0), U) \qquad \Delta v_- = \min(\Delta v, 0)$$

Δx^0_k : Δx–Δv phase intercept

d_k: deceleration rate.

v_{cmd} = 0, for short gaps and v_{cmd} = U, for large gaps

PI Saturation Controller

- CAT Vehicle's speed: average speed of the vehicles ahead
- Error: deviation from the average speed
- Saturation limits:
  - **Small gaps:** the lead vehicle's speed
  - **Larger gaps:** accelerates to catch up with the lead vehicle.

$$v^{\text{target}} = U + v^{\text{catch}} \times \min(\max(\frac{\Delta x - g_l}{g_u - g_l}, 0), 1)$$

$$v_{j+1}^{\text{cmd}} = \beta_j(\alpha_j v_j^{\text{target}} + (1 - \alpha_j) v_j^{\text{lead}}) + (1 - \beta_j) v_j^{\text{cmd}}$$

$$\alpha = \min(\max(\frac{\Delta x - \Delta x^s}{\gamma}, 0), 1)$$

$$\beta = 1 - \frac{1}{2}\alpha$$

Low Level Control: CAT Vehicle

- Multi-mode PID controller: gains for acceleration and braking
- v_{cmd} → gas and brake signals
- Controller gains → system identification of the CAT Vehicle.

$$a_{j+1} = \begin{cases} h_1(v_j, v_j^{\text{cmd}}) & \text{if } v_j^{\text{cmd}} - v_j > -0.25\,\frac{\text{m}}{\text{s}} \\ h_2(v_j, v_j^{\text{cmd}}) & \text{if } v_j^{\text{cmd}} - v_j \leq -0.25\,\frac{\text{m}}{\text{s}} \\ 0 & \text{otherwise}\ , \end{cases}$$

$$a_{j+1} \in [-100, 100]$$

When a < 0 the brake is depressed, a > 0 the accelerator is depressed.
h1: accelerate to and maintain the desired reference speed
h2: rapid speed reduction via the brake

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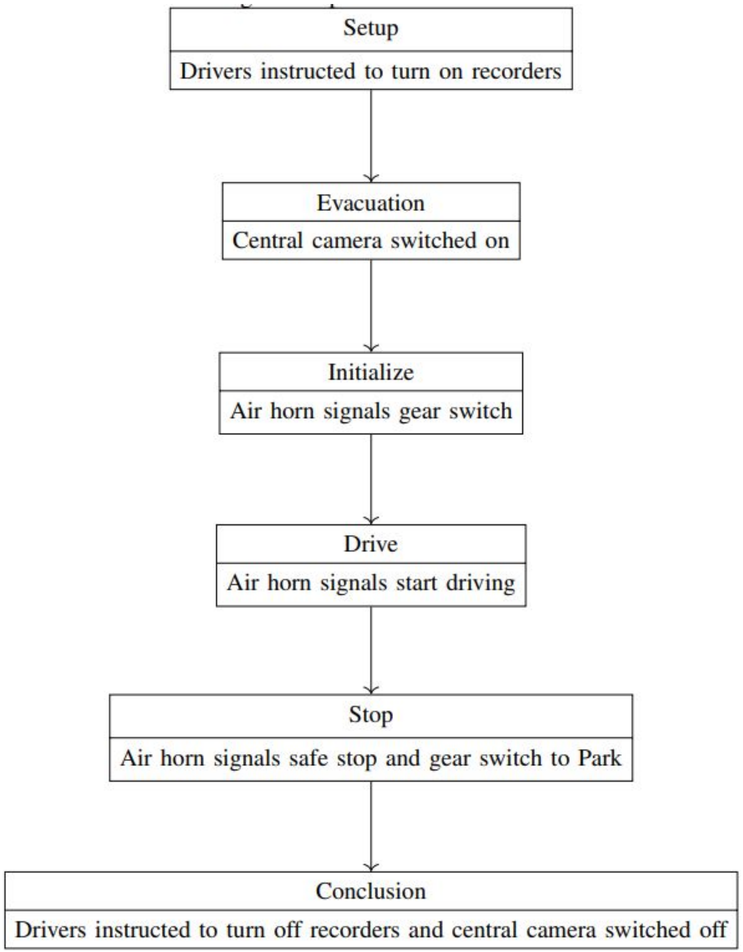
Experiment Setup

Instructions:

- Drive as if you were in rush hour traffic.
- Do not pass the car ahead.
- Do not hit the car ahead.
- Drive safely at all times.
- Do not tailgate.

Experiment: 22 vechiles

- A: Follower Stopper Control
- B: Human Driver Control
- C: PI Saturation Control



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Experiment Setup

(a) Alignment of vehicles at start of Experiment A.

(b) Alignment of vehicles 93 seconds into Experiment A when wave is present in back right.

(c) Alignment of vehicles 327 seconds into Experiment A when the CAT Vehicle is actively dampening the wave.

TABLE I
EXPERIMENT A EVENTS

Time (seconds)	Event Description
79	First traffic wave observed
126	FollowerStopper wave-dampening controller activated
126	Desired velocity set to 6.50
222	Desired velocity changed to 7.00
292	Desired velocity changed to 7.50
347	Desired velocity changed to 8.00
415	Desired velocity reduced to 7.50
463	Human driver resumes control
567	Experiment ended

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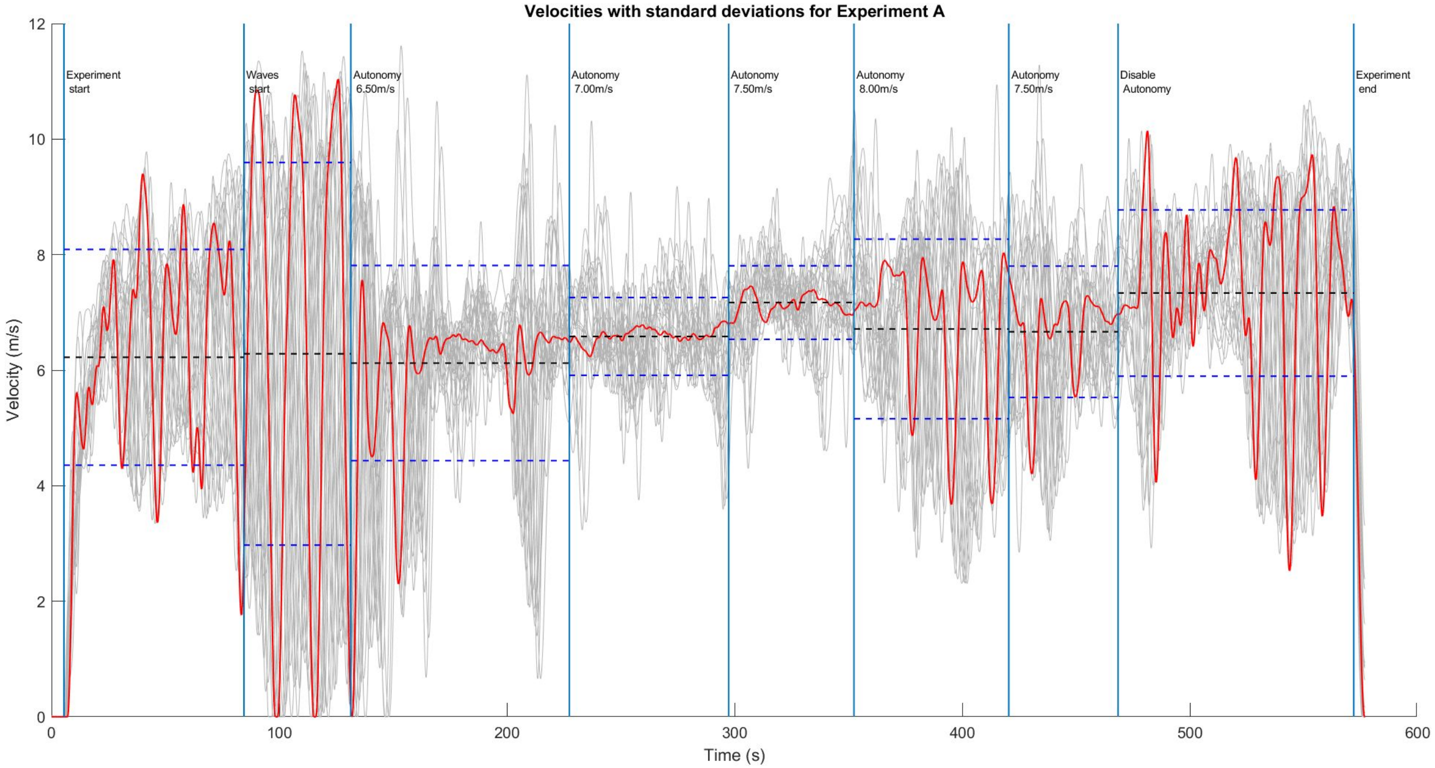
Results: Publication Dataset



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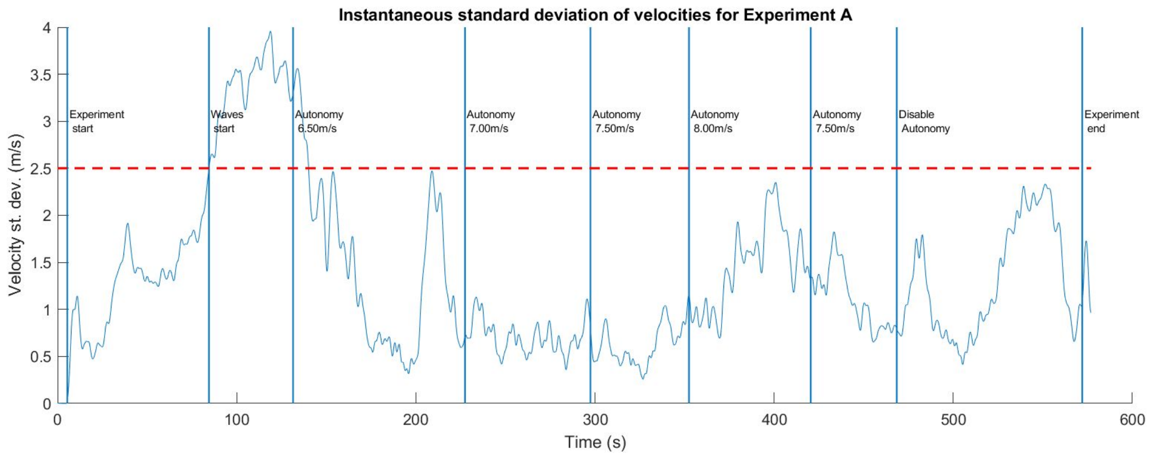
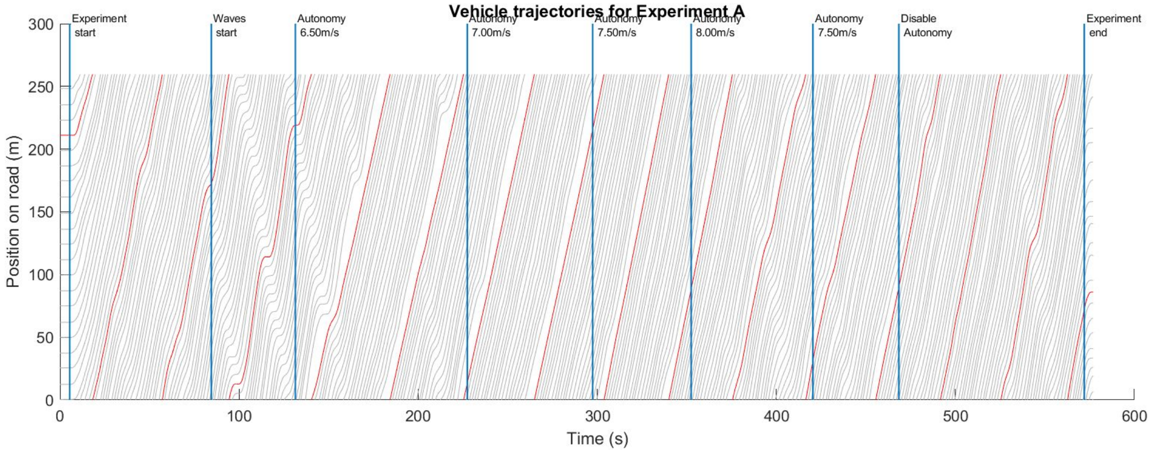
Results: Publication Dataset





Results: Paper

Exp.	Velocity st. dev. (m/s)			Fuel consumption (ℓ/100km)			Braking (events/veh/km)			Throughput (veh/hr)		
	WS	CA	%	WS	CA	%	WS	CA	%	WS	CA	%
A	3.31	0.64	-80.8	24.6	14.1	-42.5	8.58	0.12	-98.6	1827	2085	+14.1
B	2.36	1.19	-49.5	21.8	17.0	-22.1	9.50	2.27	-76.2	1828	2008	+9.8
C	3.85	1.74	-54.7	29.0	20.9	-28.1	9.66	2.47	-74.4	1755	1711	-2.5

WS: wave starts without control

CA: control is active

Throughput: # of vehicles passing a section

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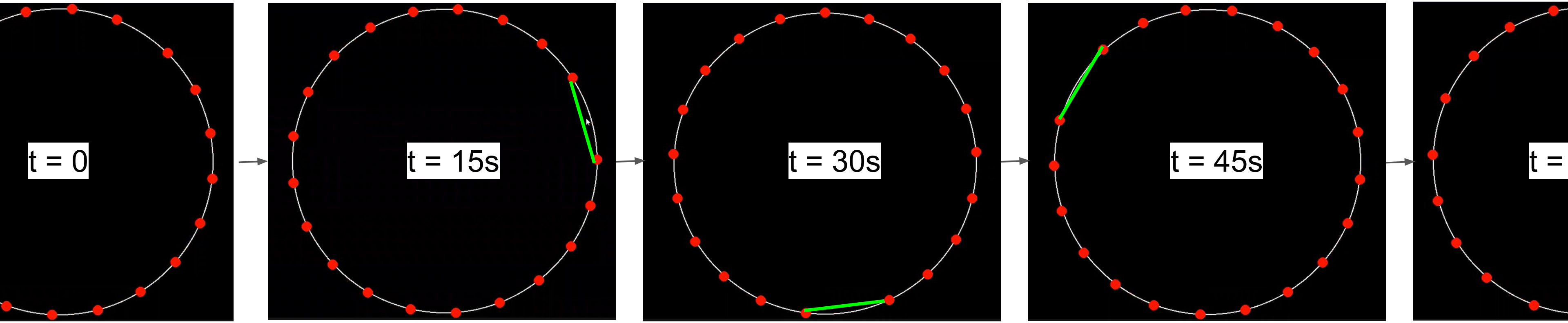
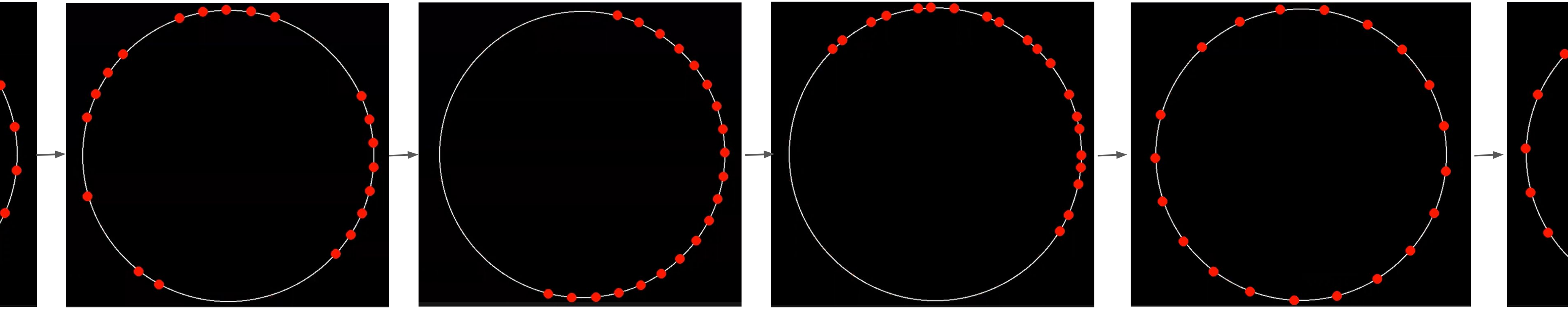
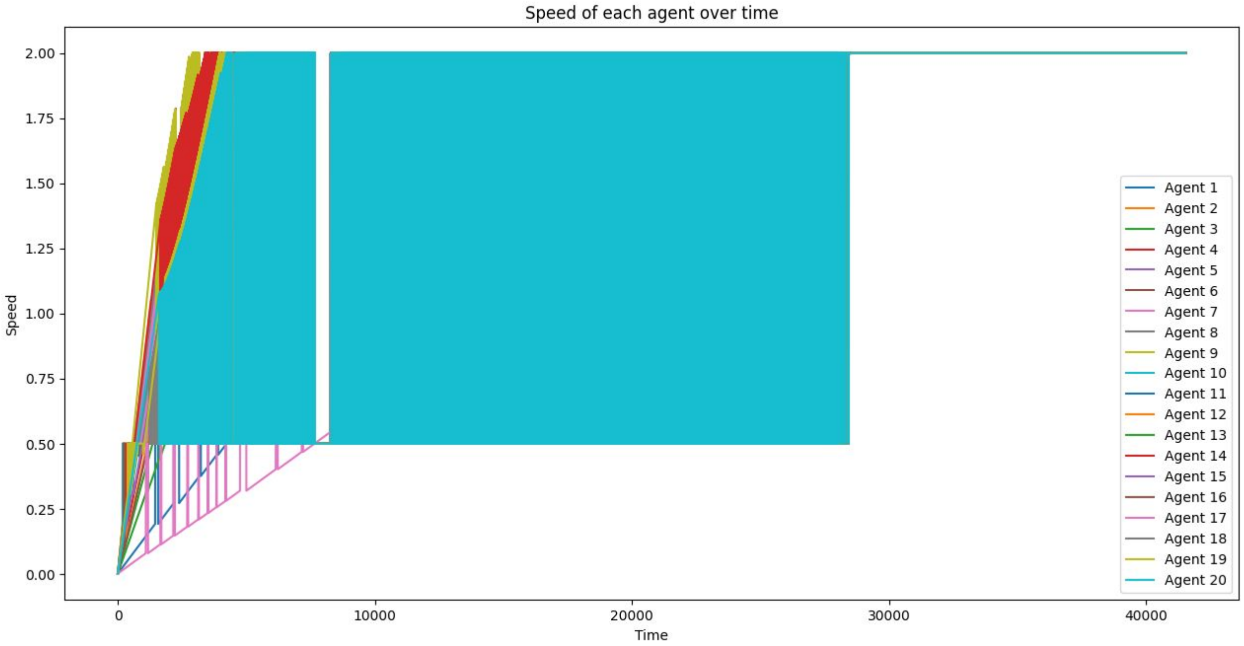
Simulations (Follower Stopper Control)





Result: Stopping distance: 80, Max speed: 2, Stopping speed: 0.5



Simulation files:
https://github.com/Prathamesh-Saraf/Autonomous-Vehicle-Traffic-Dampening

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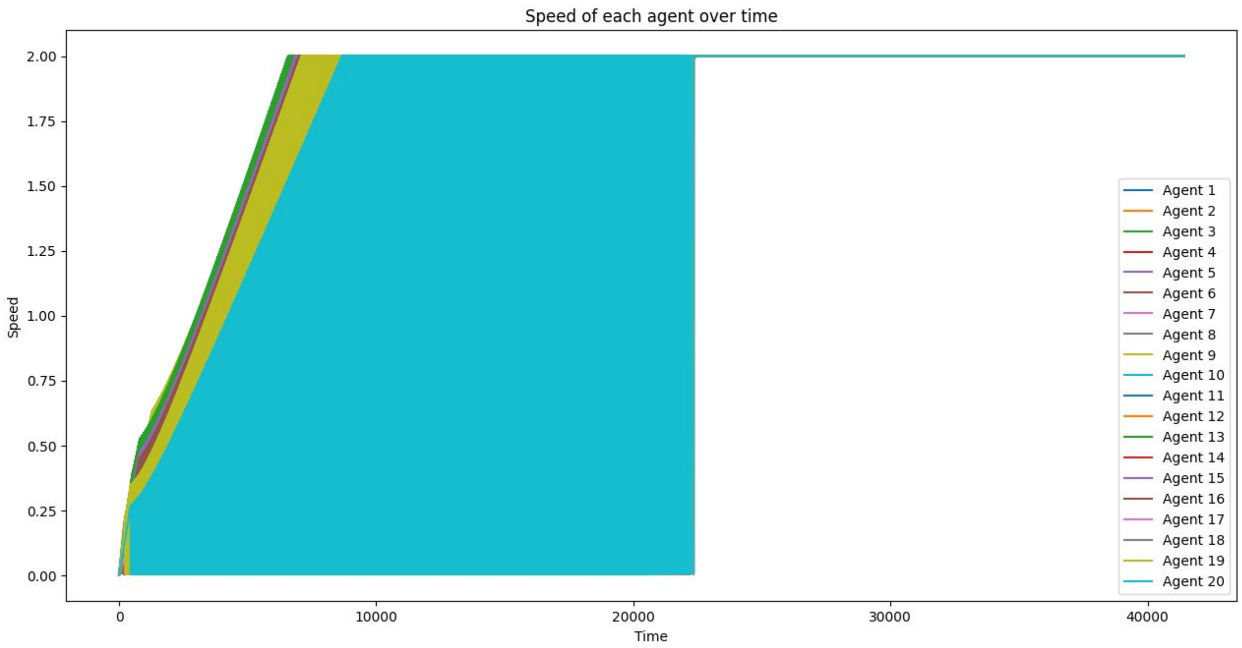
Results: Stopping distance: 80, Max speed: 2, Stopping speed: 0



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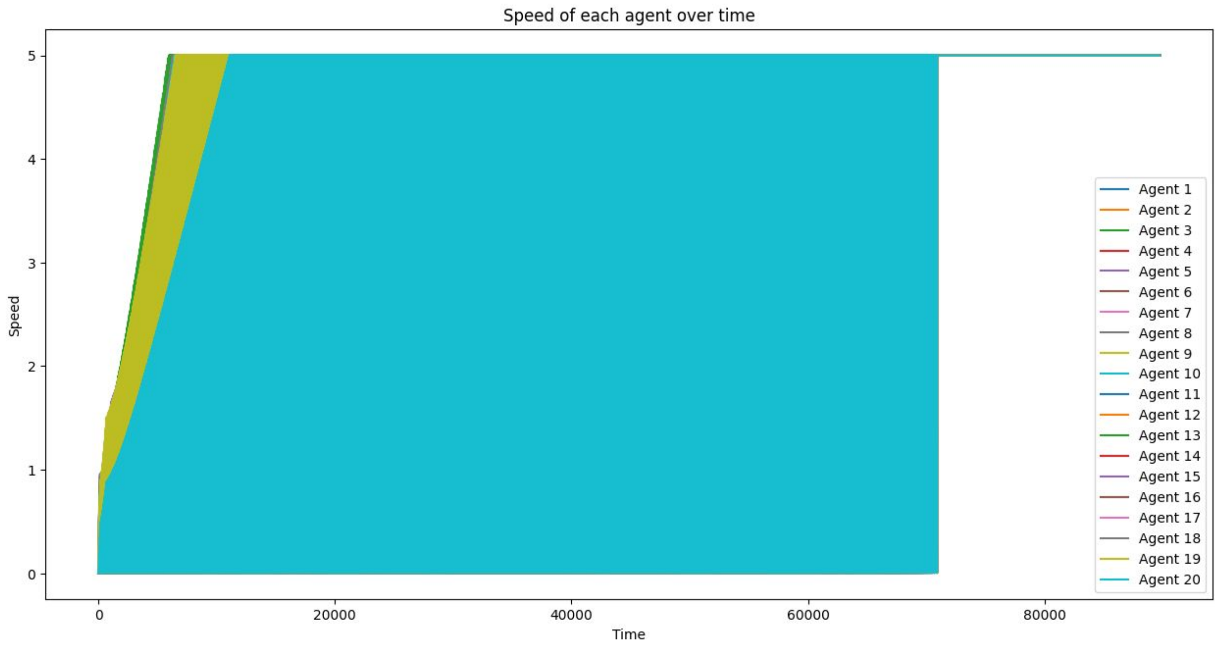
Results: Stopping distance: 50, Max speed: 5, Stopping speed: 0



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Conclusion

- AV's can:
  - Solve the traffic problem
  - Lead to congestion if poorly designed
- The system is stabilizable, not controllable
- Uncontrollable mode: stable spacing due to the ring structure
- A small amount (3-5%) of AV's are enough to regulate the traffic
- Effective controllers for the ring road experiment
- Follower Stopper control shows best throughput compared to:
  - Ramp metering
  - Variable speed limit
  - PI Saturation control

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Future Work and Unanswered Questions

- Lane changes can
  - Trigger stop-and-go waves.
  - Create gaps which can
    - Lead to more lane changes (INEFFECTIVE)
- Experiments on urban freeways
- Regular roads and intersections

Thank you!

Questions?

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