Traffic Modeling and Multi-Stage Congestion Mitigation Strategies – Validation Using RC-Car Experiments

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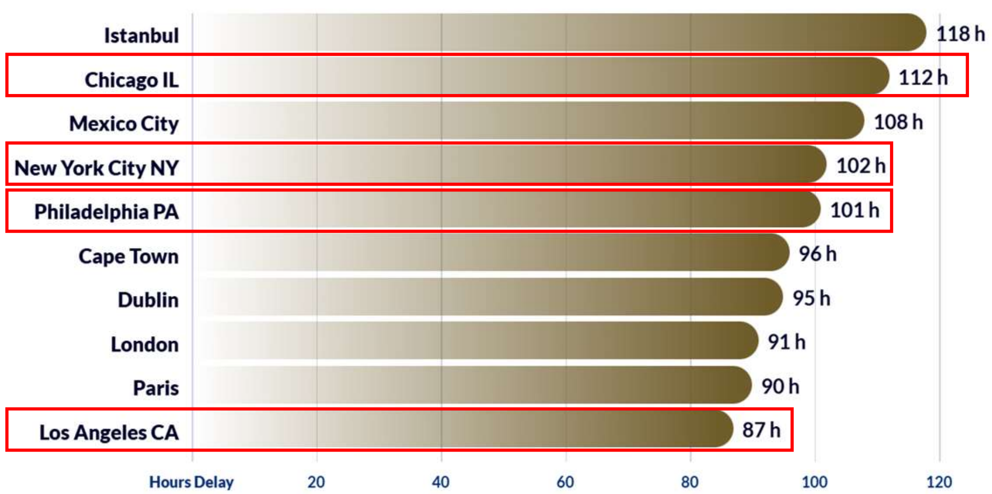
Congestion: Global and U.S. Perspective

Top Global Cities by Annual Delay (Hours Lost per Driver)



(Source: INRIX Global Traffic Scorecard, 2025)

	United States of ...	Milwaukee, WI	Chicago, IL
Average congestion level	27.4%	26.8%	46.1%
Average speed	33.6 mph	28.2 mph	19.6 mph
Average distance driven in 15 min	8.4 mi	7.0 mi	4.9 mi

(Source: TomTom Traffic Index, 2025)

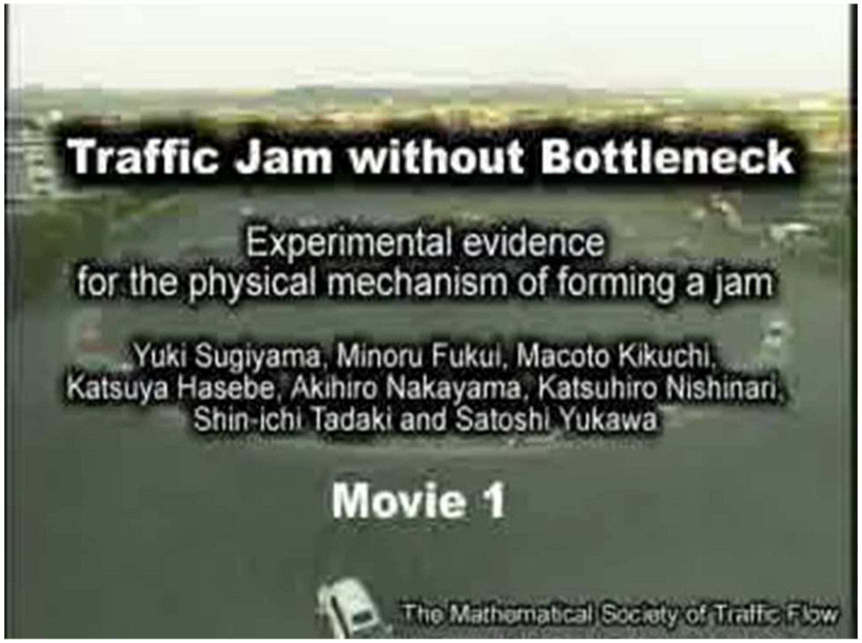
While Milwaukee is performing better than Chicago, metrics like average speeds and distance driven remain below national level.

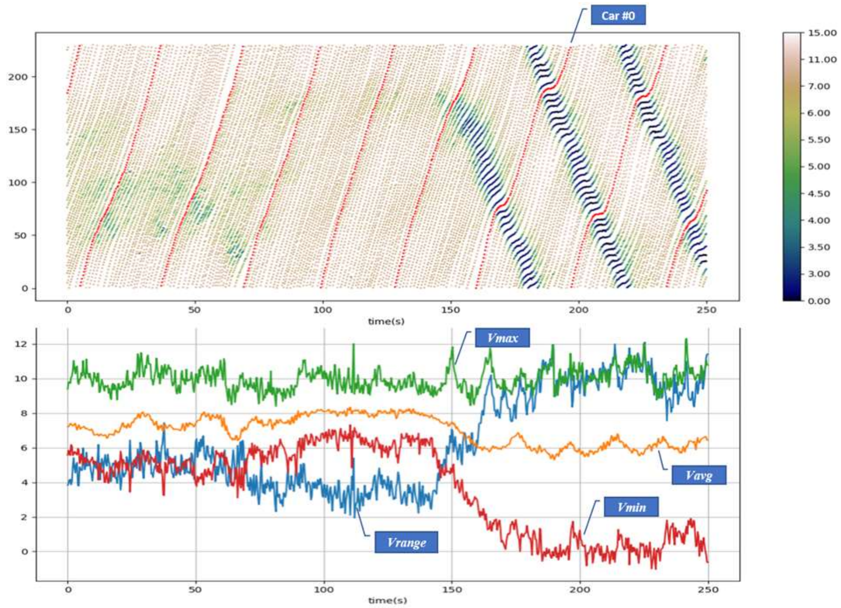
- Average U.S. driver loses **~49 hours/year** in congestion
- Congestion costs **~$900 per driver** annually
- Total U.S. economic cost exceeds **$80B+** per year

Beyond the economic cost, congestion can increase driver stress, rear-end collision risk, & environmental impacts.

Phantom (Stop-and-Go) Traffic Waves

Stop-and-go waves emerge even **without bottlenecks.**





Source: Sugiyama et al. (2008)

Research Questions

- **Q1 (Modeling)**: How can we simulate traffic in a way that reproduces realistic stop-and-go waves and shockwave propagation?
- **Q2 (Control)**: What multi-stage congestion mitigation strategies can effectively dampen these waves and improve flow stability?
- **Q3 (Validation)**: How can we design the strategy so that it can be implemented and validated in RC-car experiments, with the potential for real-world application?

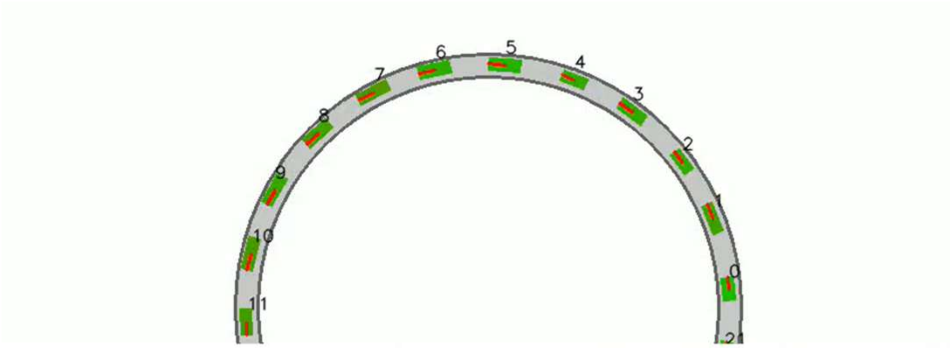
Traffic Flow Modeling

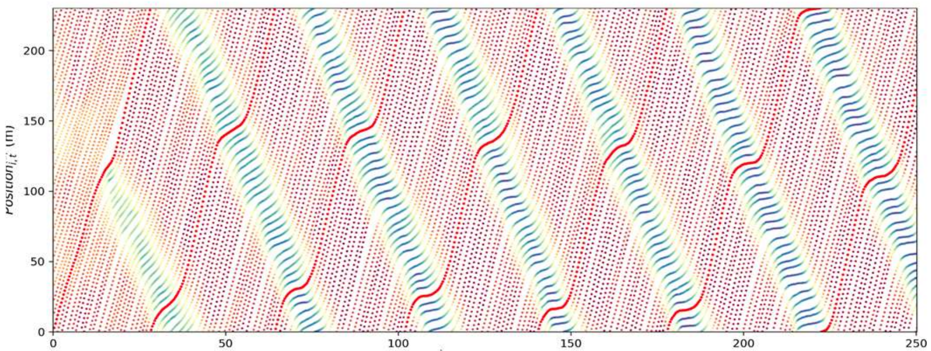
- **Game-theoretic traffic modeling:** Drivers are modeled as strategic decision-makers in an interactive traffic environment.
- **Driver-level utility formulation:** Each driver selects an acceleration action by maximizing a utility function
  - **Speed reward** → maintain ideal speed
  - **Backward penalty** → avoid reversing
  - **Collision penalty** → maintain safe distance
- **Driver heterogeneity:** Different drivers are assigned different preferences, reflecting variation in driving style and behavior.
- **Behavioral interpretation:** Each vehicle balances efficiency, safety, and smoothness when choosing its motion.

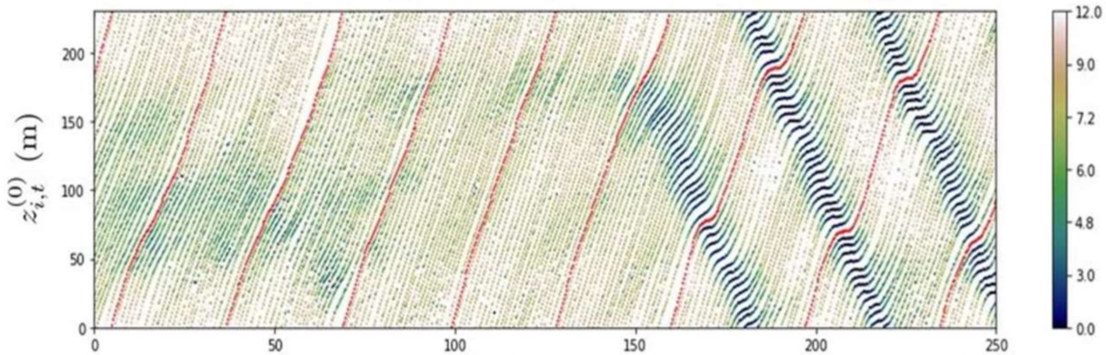
Car ID	σ_v	σ_a	v^*	κ_v	$\mathcal{L}$	
13	0.2140	0.5493	8.9778	0.3324	335.46	cautious
1	0.2311	0.7531	10.3990	0.4837	253.92	
17	0.2657	0.6722	10.1596	0.4373	193.78	
Mean	0.2369	0.6582	9.8455	0.4178	261.05	
21	0.2297	0.4855	12.8659	0.2126	284.96	fast but steady
10	0.2294	0.4265	10.5585	0.3470	337.06	
12	0.2129	0.5780	11.5897	0.4004	340.50	
6	0.2525	0.5929	11.2818	0.2249	205.98	
19	0.2407	0.5446	11.8890	0.2827	259.80	
3	0.2829	0.5888	10.4003	0.2581	149.93	
18	0.2469	0.6107	10.8100	0.3304	237.09	
Mean	0.2421	0.5467	11.3422	0.2937	259.33	
4	0.3200	0.8580	10.1484	0.1225	-21.14	aggressive
9	0.3175	0.5971	9.7172	0.1250	40.17	
20	0.3258	0.6063	9.9275	0.2078	51.48	
2	0.2605	0.7702	10.6746	0.1951	137.62	
5	0.2419	0.9986	10.8618	0.1713	121.88	
8	0.2302	0.6469	9.7444	0.1789	230.43	
7	0.2657	0.5563	10.3870	0.1299	157.12	
11	0.3197	0.5523	10.9688	0.1627	61.52	
Mean	0.2852	0.6982	10.3037	0.1616	97.39	
14	0.3852	0.7810	9.1970	0.3785	-49.91	unsteady
16	0.2501	1.4075	10.1437	0.3062	65.01	
0	0.1988	1.2165	9.8861	0.2759	205.30	
15	0.2542	1.0171	10.1211	0.3203	129.54	
Mean	0.2721	1.1055	9.8370	0.3202	87.48	

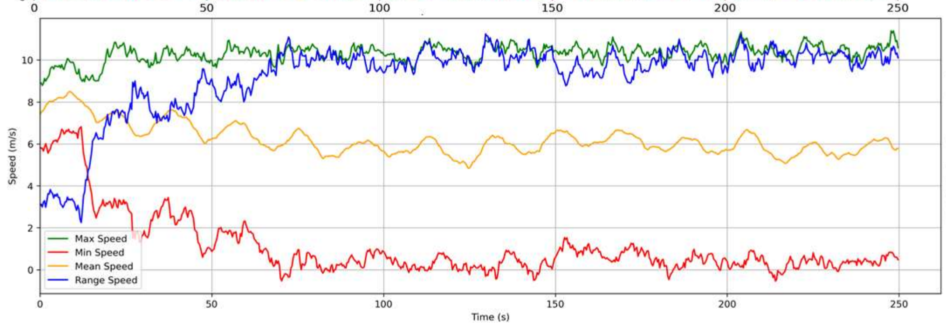
Illustration of heterogeneous driving behaviors

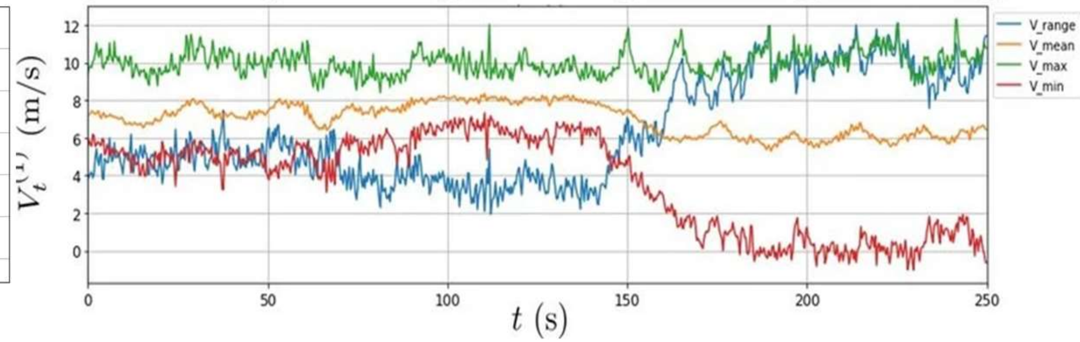
Simulation Result











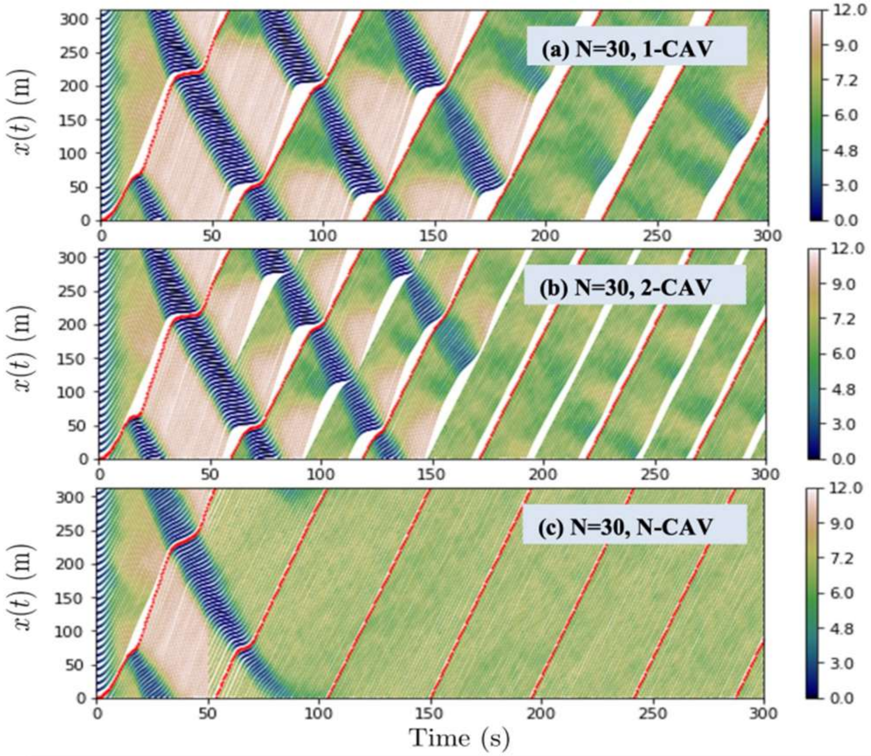
Congestion Mitigation Strategies

Core Idea: Improve overall traffic flow by controlling the motion of one, a few, or all vehicles in the system.

Strategy Levels:

- Control of **one vehicle**,
- Control of **a small group of vehicles**,
- Control of **the full traffic stream**.

Online Learning/Optimal Controls



Multi-Stage Congestion Mitigation Strategies

Stage 1: Infrastructure-Based (Today)

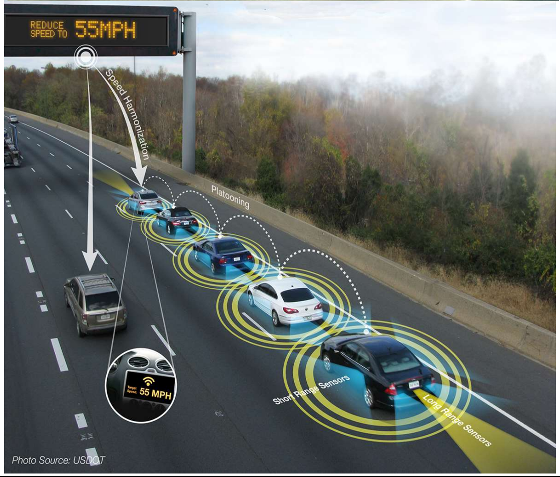
- Variable Speed Limits (VSL)
- **Limitation**: Advisory speeds are not enforceable in Wisconsin
- Connected Vehicles
- **Limitation**: Driver compliance

Stage 2: Partial Automation (Near Future)

- Adaptive Cruise Control (ACC) + Connected Vehicles
- Government owned vehicle act as “wave dampers” in traffic

Stage 3: Full Automation (Future)

- Coordinated vehicle control, providing active wave suppression
- Near elimination of stop-and-go traffic



Robotic Car Test Platform

Hardware: Fleet of RC Cars

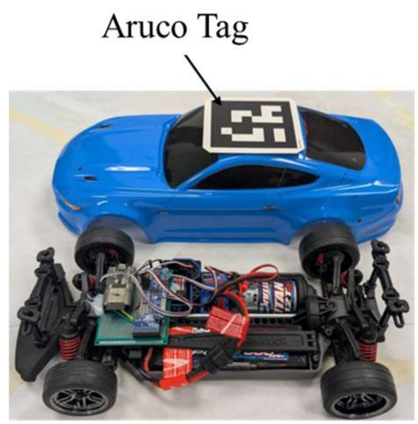
- Retrofitted with ESP32 Microcontroller + Motor Drivers
- Wheel Speed and IMU Sensors

Localization:

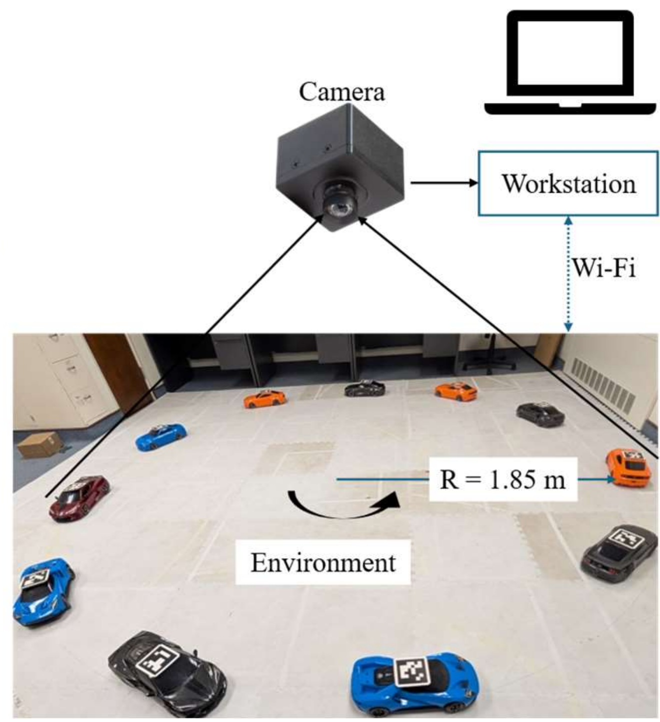
- Camera based
- ArUCo Markers for identification

Why RC?

- Repeatable, flexible, safe
- Captures physical imperfections like “latency”, “noise”



Retrofitted Car



Platform Validation: Control Accuracy

Tracking Accuracy

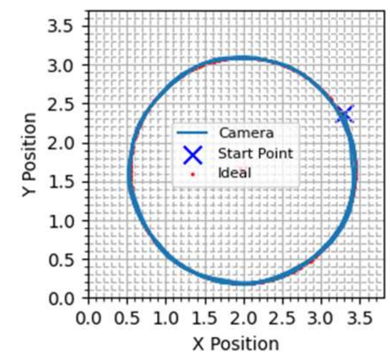
- Speed tracking error < 0.05 m/s
- Trajectory tracking error < 2 cm

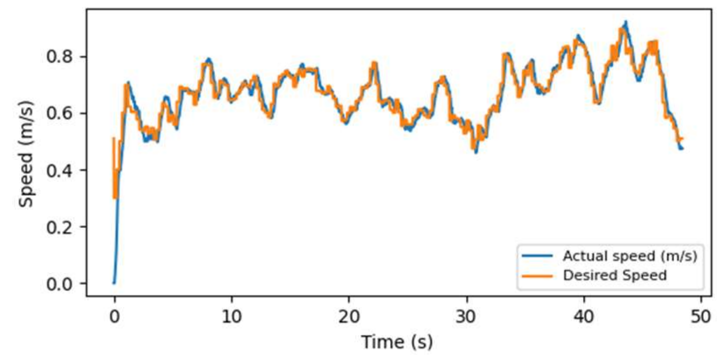
Repeatability

- Consistent trajectories across runs
- Reproducible traffic wave patterns

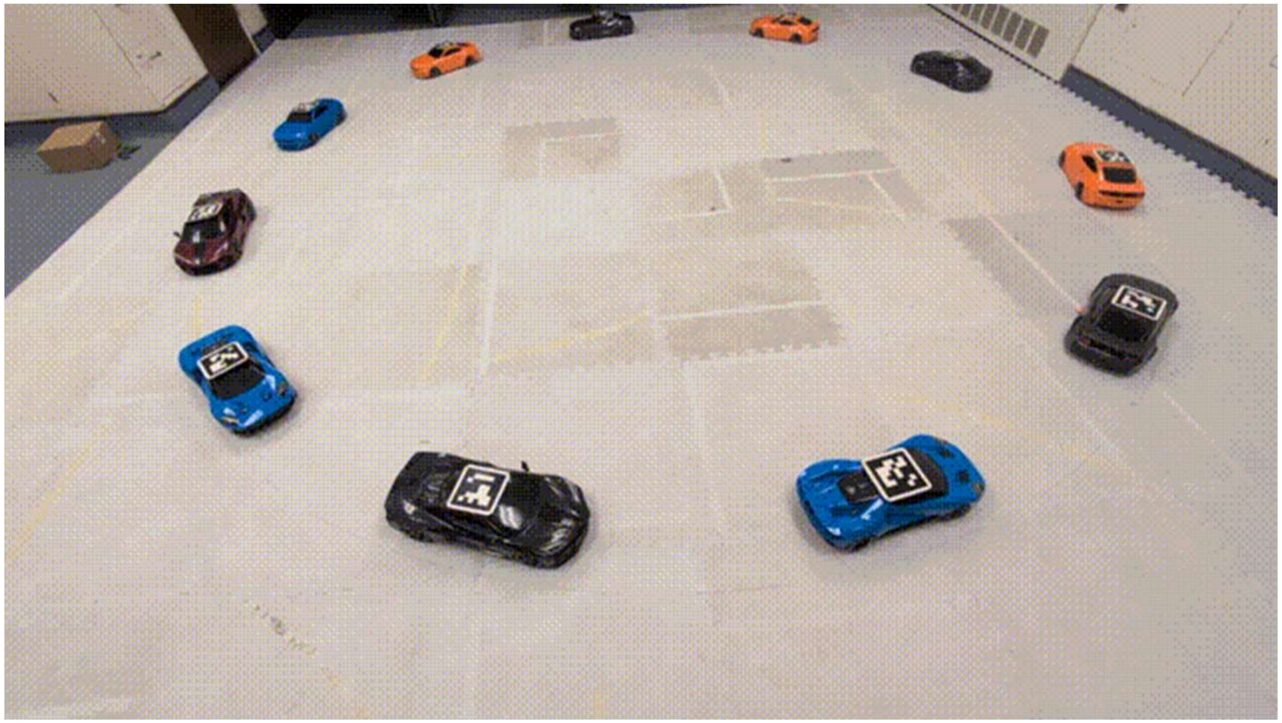
Real-World Fidelity

- Includes **latency, noise, actuation limits**
- Incorporates **feedback control** to correct tracking offsets





Physical Validation: Jam Formation

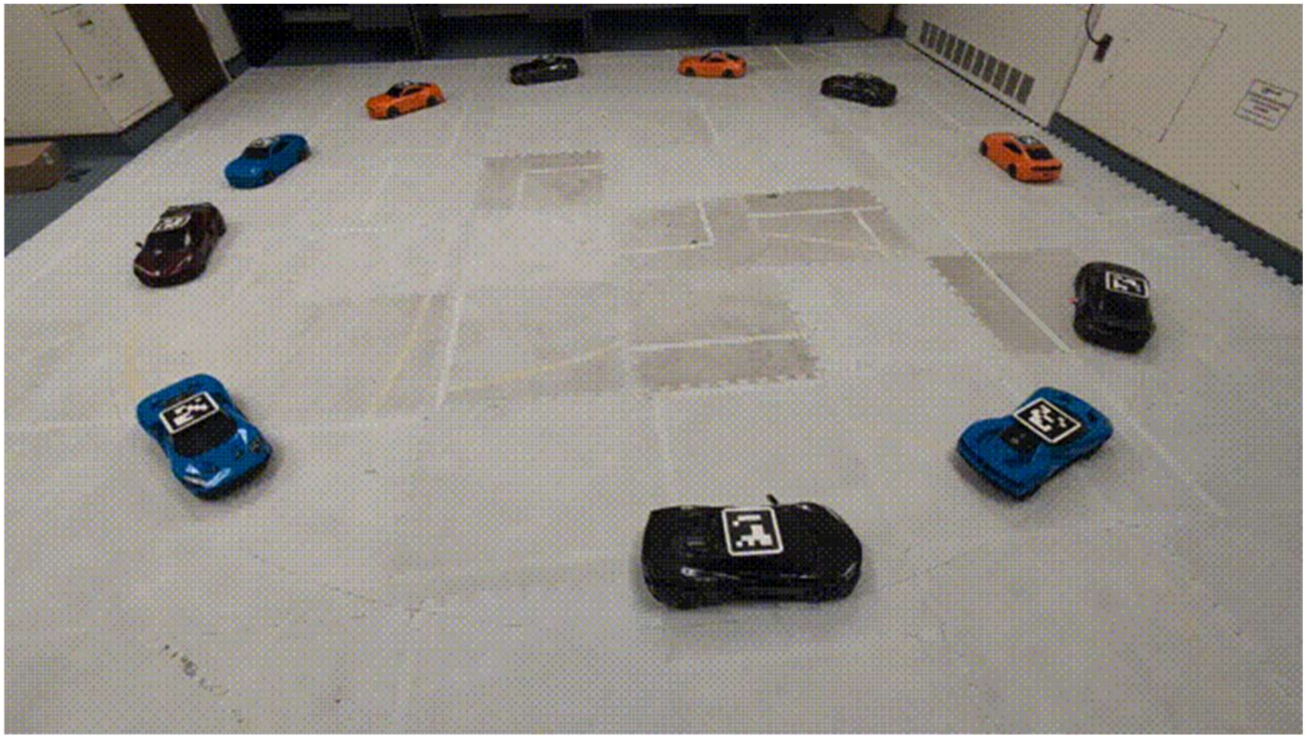


RC-Car Experimental Platform

- Closed-loop circular track
- No lane drops, no incidents
- Human-like driving behavior

“Stop-and-go wave emerges without bottlenecks”

Mitigation: Partial Penetration



Control Strategy

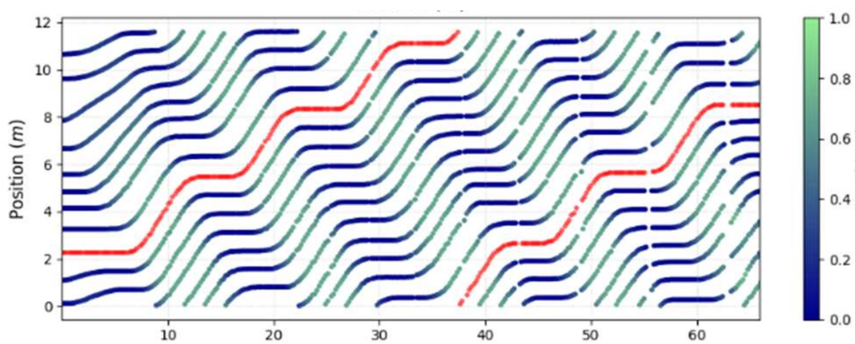
- Maintains steady speed + spacing
- Avoids joining stop-and-go waves

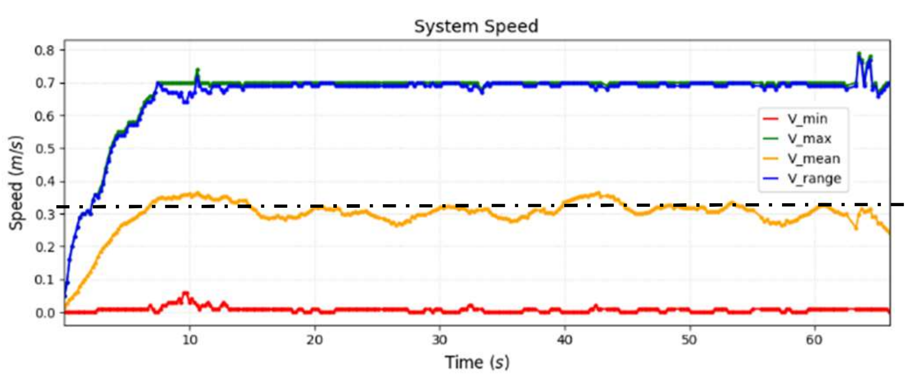
Effect on Traffic

- Dampens shockwaves
- Reduces stop-and-go behavior
- Improves overall flow stability

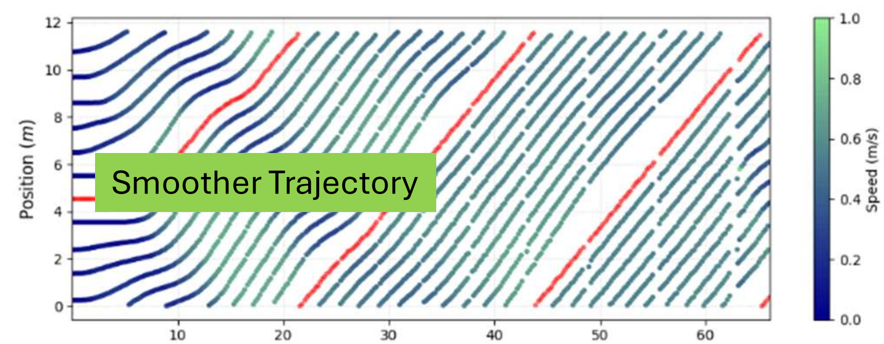
Performance: Baseline vs Controlled

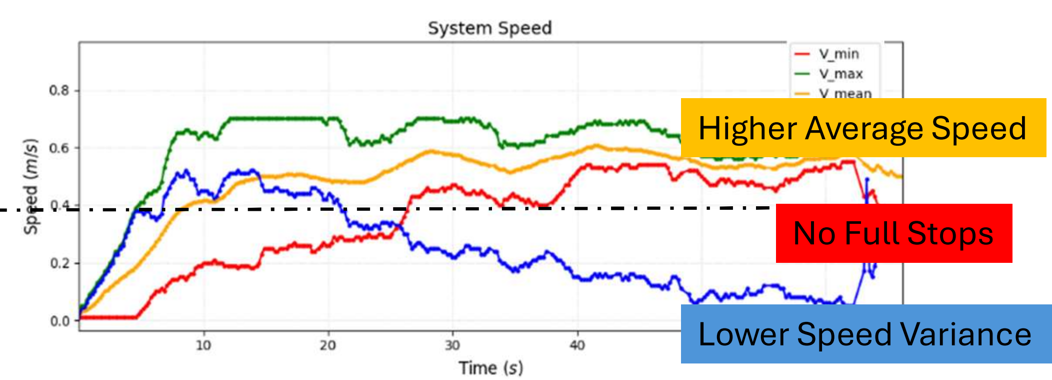
No Control





Controlled





Online Control

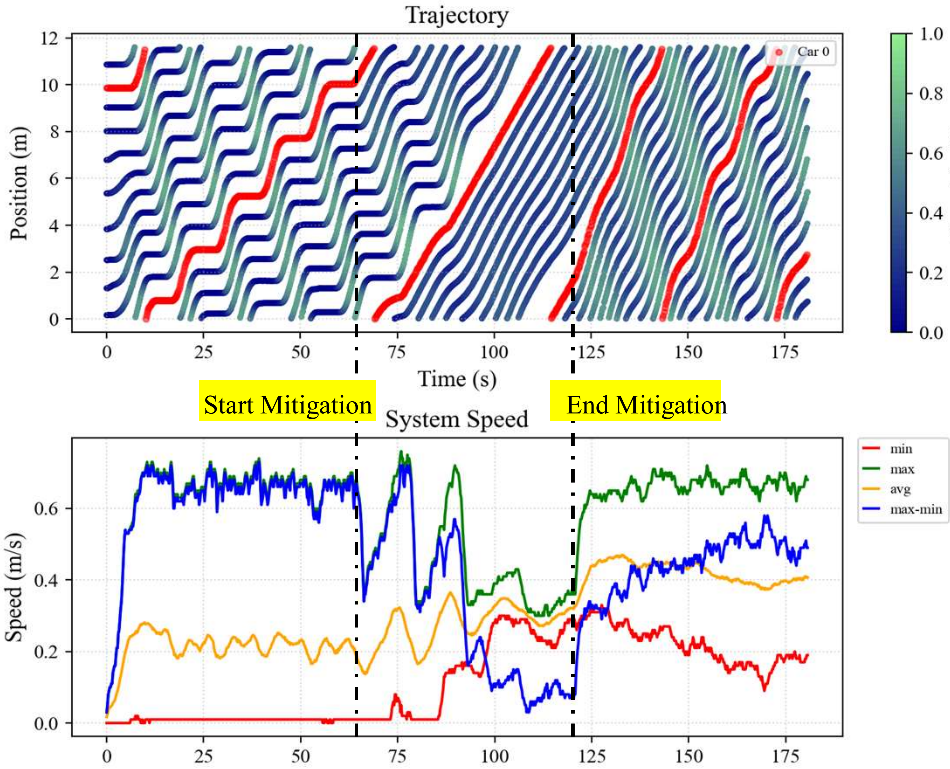
Experiment Setup

State 1: **No control**

State 2: **Mitigation active**

State 3: **Control removed**

- Control reduces oscillations and improves flow stability
- After removing control waves re-emerge



Conclusion & Future Path

Key Takeaways

- Game-theoretic traffic model **reproduces real-world dynamics**
- **Multi-Stage congestion mitigation strategies** which provide immediate benefits
- RC platform provides **physical validation**

Future Works

- Mixed autonomy in **complex road networks**
- **CAV-UAV** (Unmanned Aerial Vehicle) coordination framework
- Real-world deployment strategies

References

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Acknowledgements

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More About Us!

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Thank You!

Questions?