CAV Trajectory Optimization & Capacity Analysis - Modeling Methods and Field Experiments

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6/25/2018

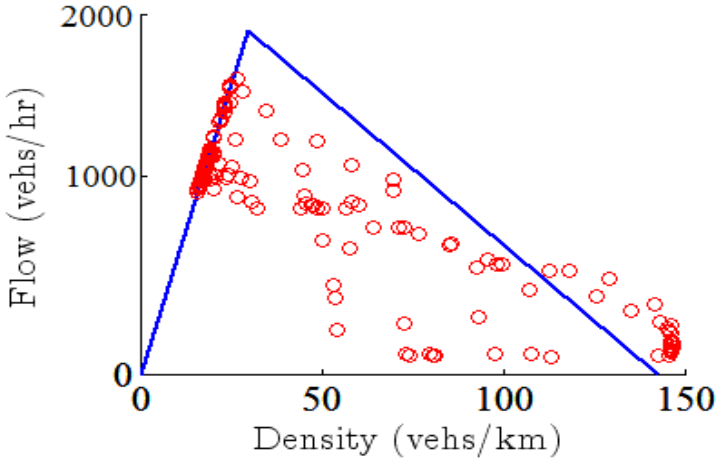
Session 2B: Are We Ready for the AV Future?
7th Innovations in Travel Modeling Conference

USF UNIVERSITY OF SOUTH FLORIDA

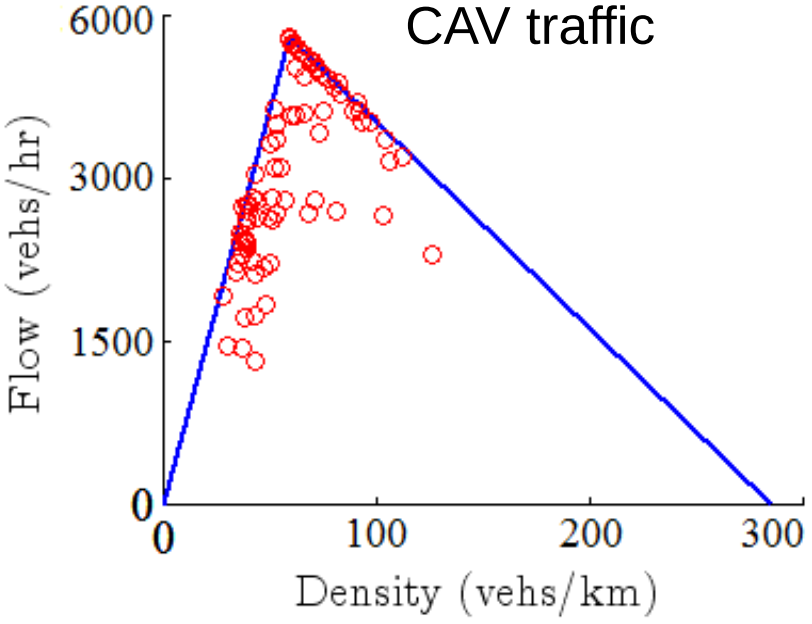
Hope for CAV: Capacity Booster

- People expect connected automated vehicles can significantly increase (or even multiple) high way capacity
- How to realize this potential?

Human-driven traffic



CAV traffic

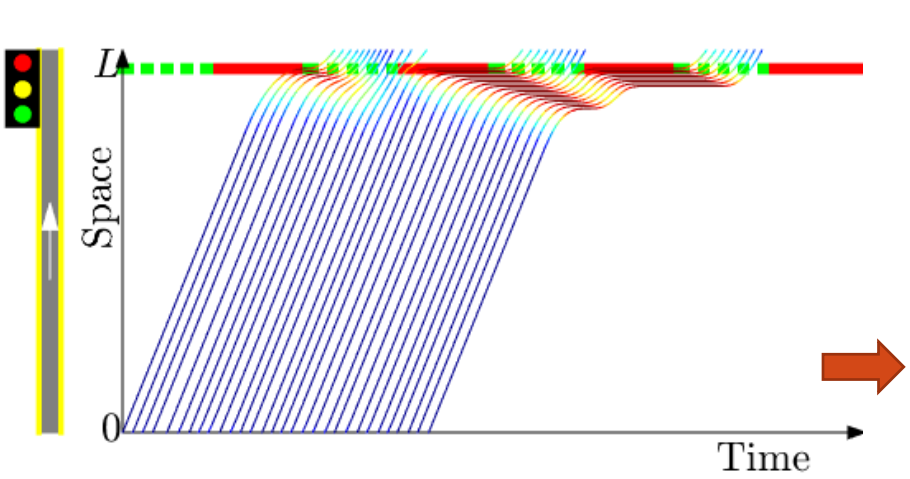


Steps to Improve CAV Capacity

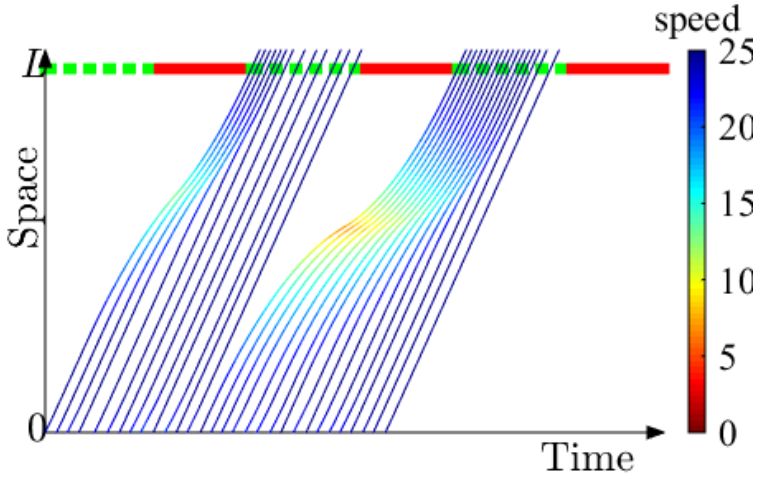
- Microscopic trajectory control
  - Reduce headway
  - Improve traffic smoothness
- Macroscopic capacity analysis
  - Understand the relationship between cav traffic characteristics (e.g., CAV penetration ratio) and macroscopic measures (e.g., traffic throughput)
- Validation
  - Field experiments
  - Data analysis

CAV Trajectory Optimization

- Signalized Intersections
  - Coordinate signal timing with vehicle trajectory control



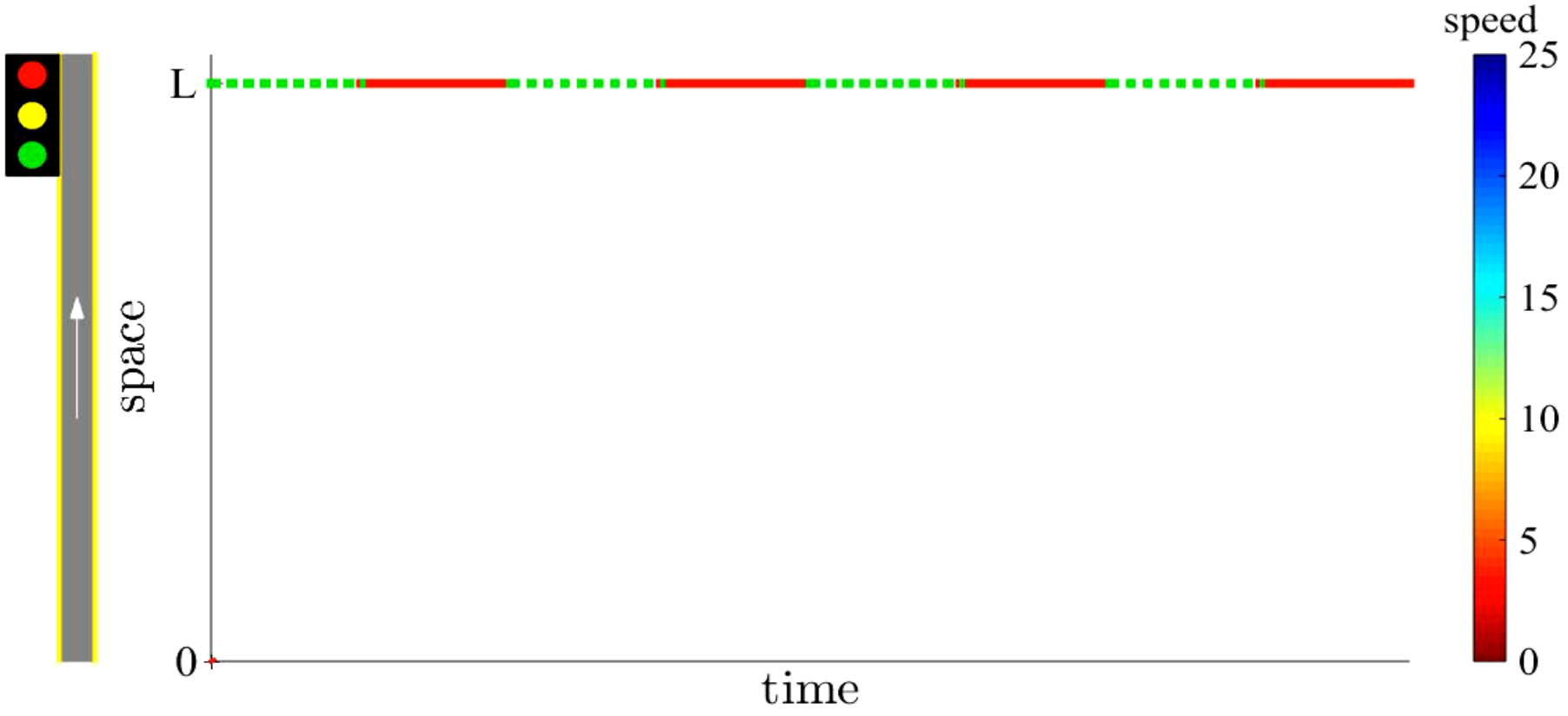
Human-driven traffic



CAV traffic

Parsimonious Algorithms

- Shooting heuristic (SH)
  - A *small* number of *analytical* sections



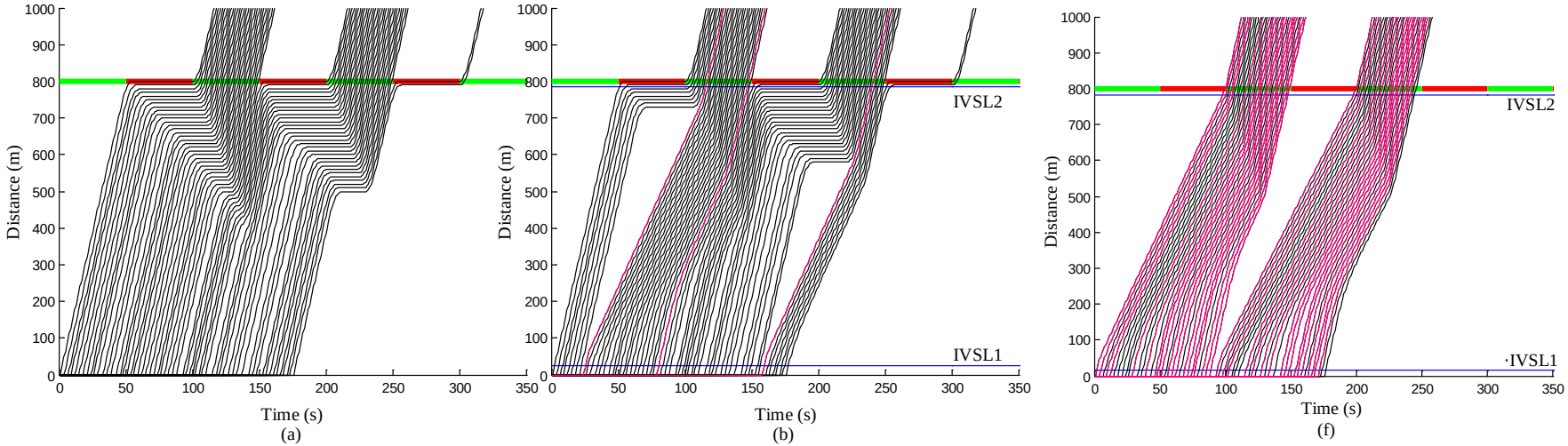
Benchmark vs. SH

C(s)	L(m)	f^s	ΔT	ΔE	ΔS	ΔM	Solution Time
60	1500	0.9	35.22%	32.78%	66.36%	41.23%	12.14
60	1500	1.5	34.23%	33.86%	66.43%	40.00%	9.44
60	2500	0.9	41.86%	46.96%	77.79%	50.78%	9.63
60	2500	1.5	41.72%	48.07%	80.21%	51.01%	13.05
80	1500	0.9	40.11%	32.06%	62.94%	43.07%	9.16
80	1500	1.5	38.73%	40.10%	62.26%	44.28%	12.26
80	2500	0.9	32.29%	45.91%	74.00%	43.22%	8.89
80	2500	1.5	29.59%	37.96%	46.49%	34.20%	7.29
Average			36.72%	39.71%	67.06%	43.47%	10.2

Reference
*Ma, J., Li, X., Zhou, F., Hu, J. and Park, B. 2017. “Parsimonious shooting heuristic for trajectory design of connected automated traffic part II: Computational issues and optimization” Transportation Research Part B, 95, 421-441.
*Zhou, F., Li, X. and Ma, J. 2017. “Parsimonious shooting heuristic for trajectory design of connected automated traffic part I: Theoretical analysis with generalized time geography.” Transportation Research Part B, 95, 394-420.

CAV Trajectory Optimization

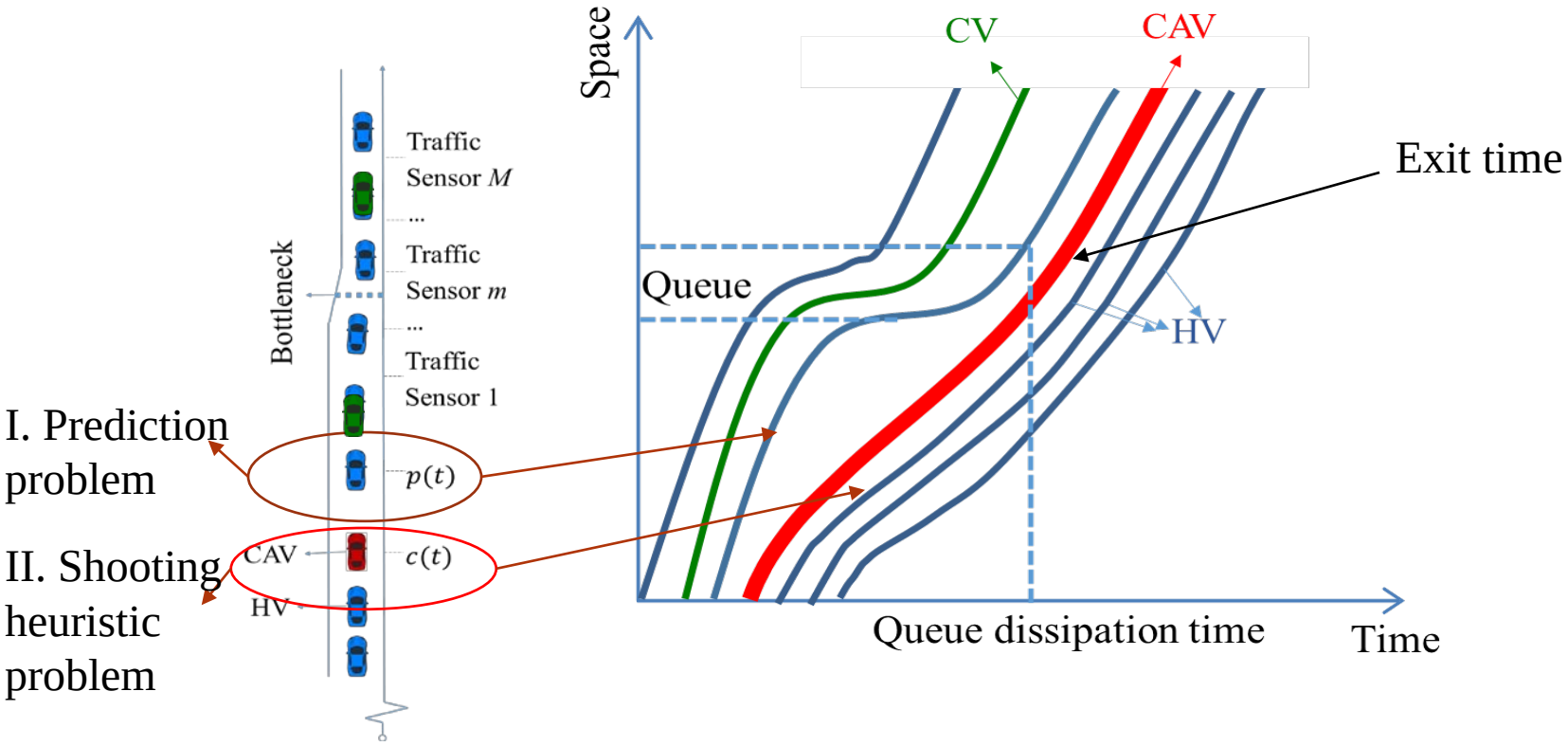
- Signalized Intersections
  - Mixed Traffic (CAVs + Human-driven vehicles (HVS))



Reference
*Yao, H., Cui, J., Li, X., Wang, Y. and An, S., 2018, “A Trajectory Smoothing Method at Signalized Intersection based on Individualized Variable Speed Limits with Location Optimization”, Transportation Research Part D, 62, pp. 456-473

CAV Trajectory Optimization

- Freeway Speed Harmonization

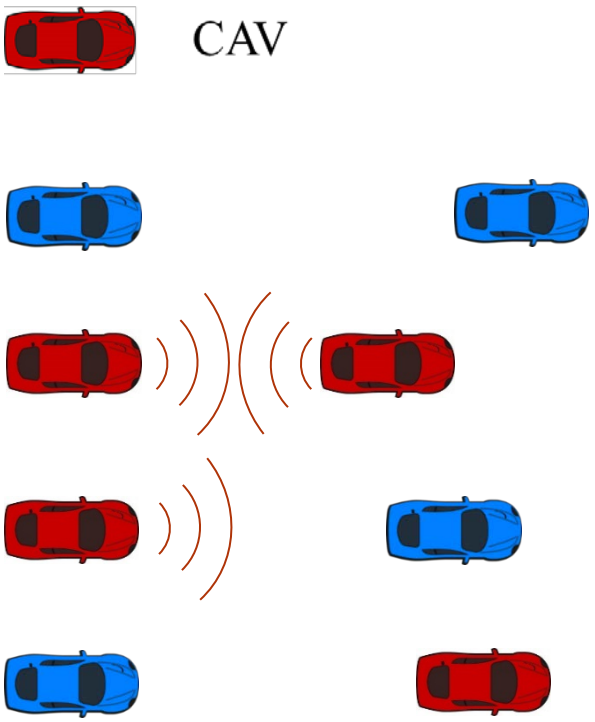


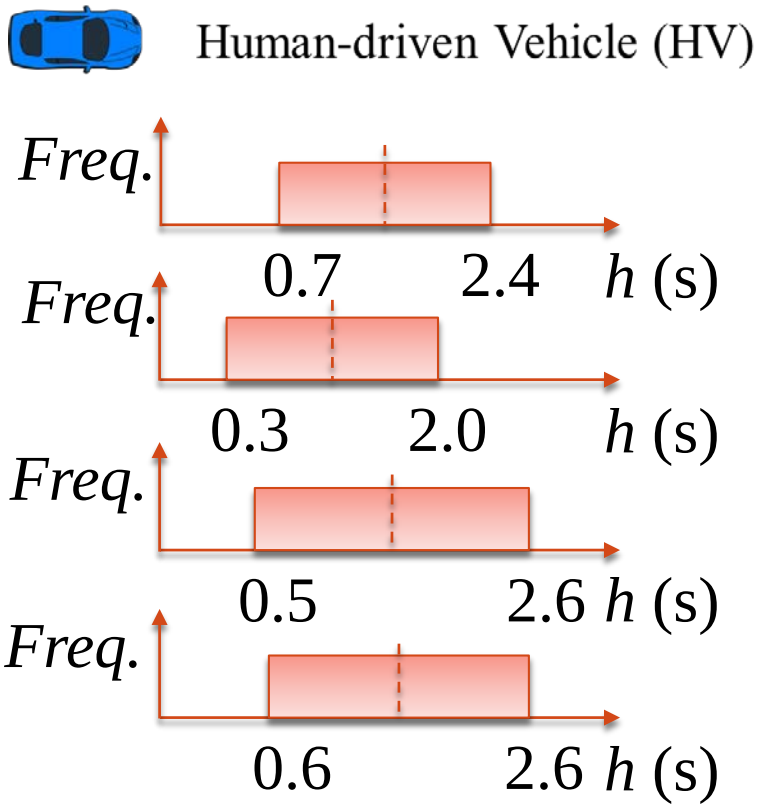
Reference:

* Ghiasi, A., Li, X., Ma, J. and Qu, X. 2018. “A Mixed Traffic Speed Harmonization Model with Connected Automated Vehicles”, Transportation Research Part C. Under Revision

Trajectory Control → Capacity Analysis

- CAV control → Heterogeneous headways in mixed traffic





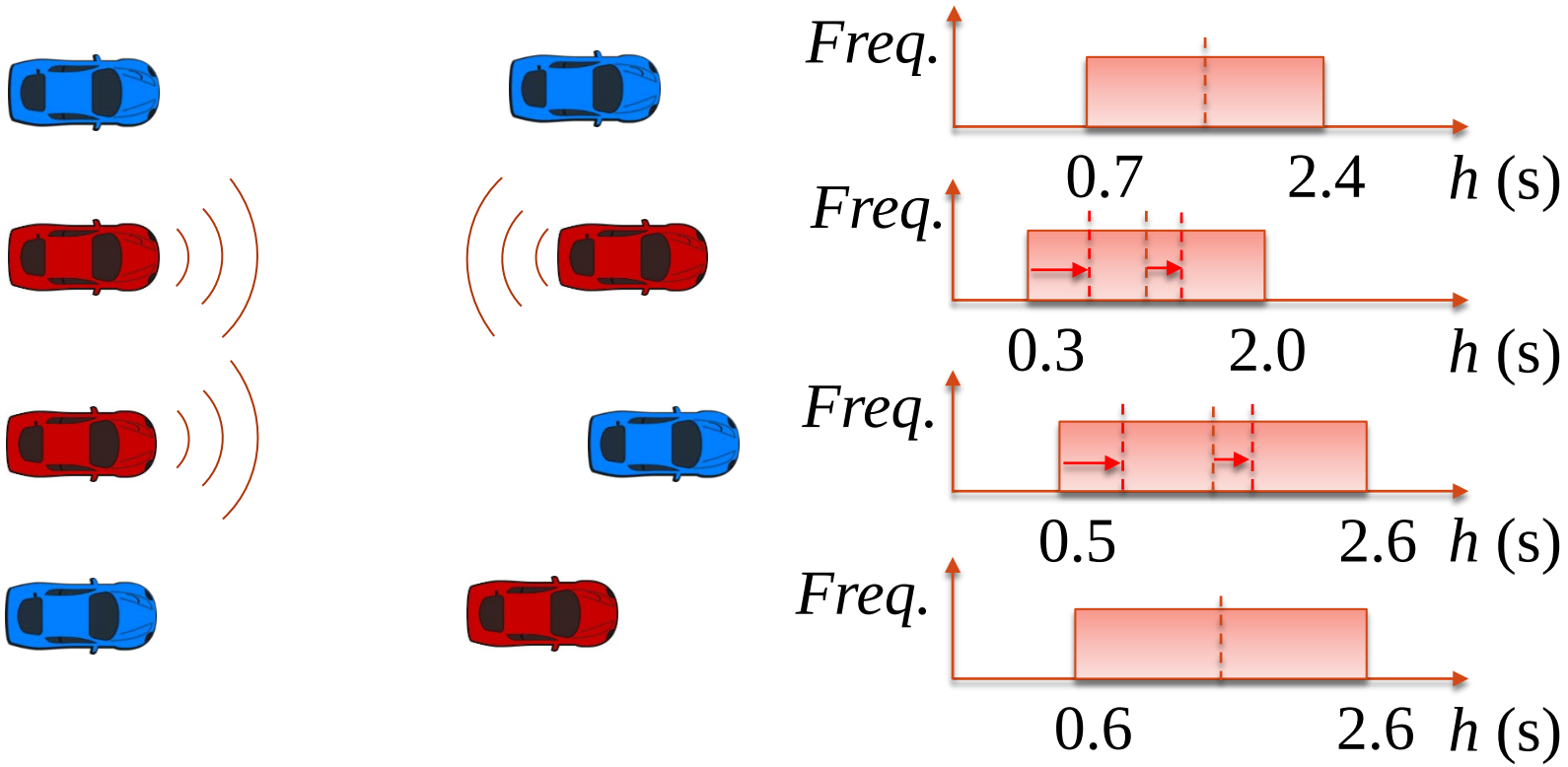
Capacity Analysis

- CAV technology uncertainties
  - Will CAV reduce headways?

Google car pulled over for being too slow
http://www.bbc.com/news/technology-34808105

Capacity Analysis

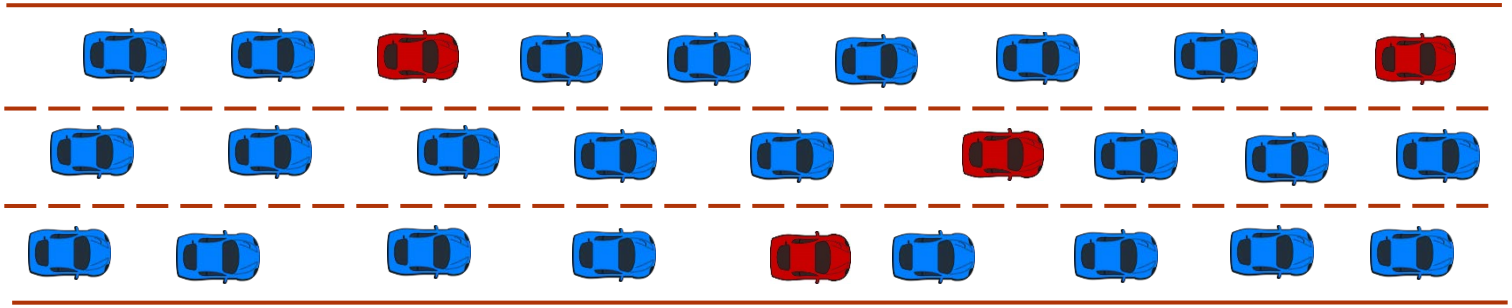
- Different technology scenarios



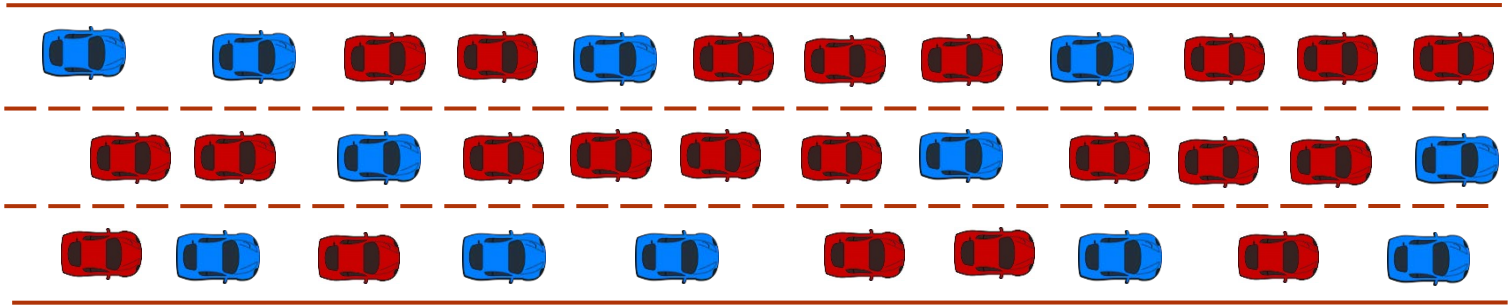
Capacity Analysis

- CAV market penetration rate

Low CAV market penetration rate



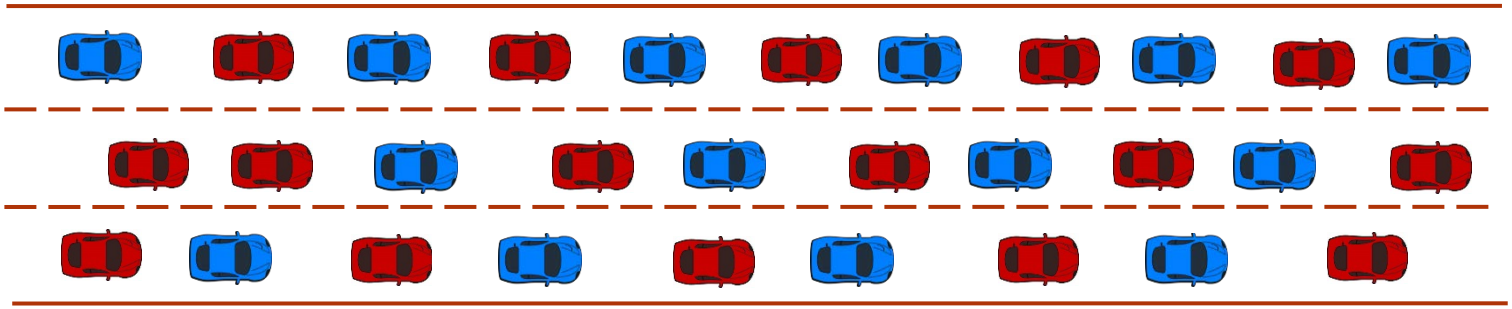
High CAV market penetration rate



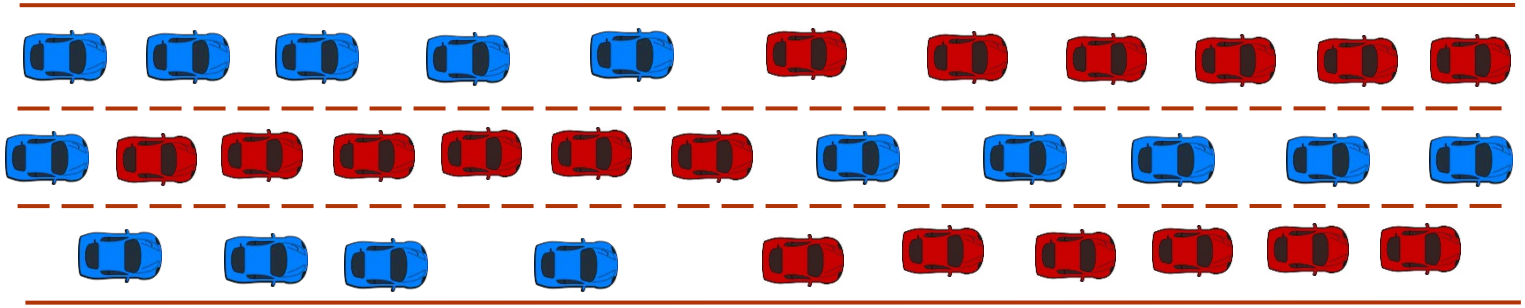
Capacity Analysis

- CAV platooning intensity

Low CAV platooning intensity

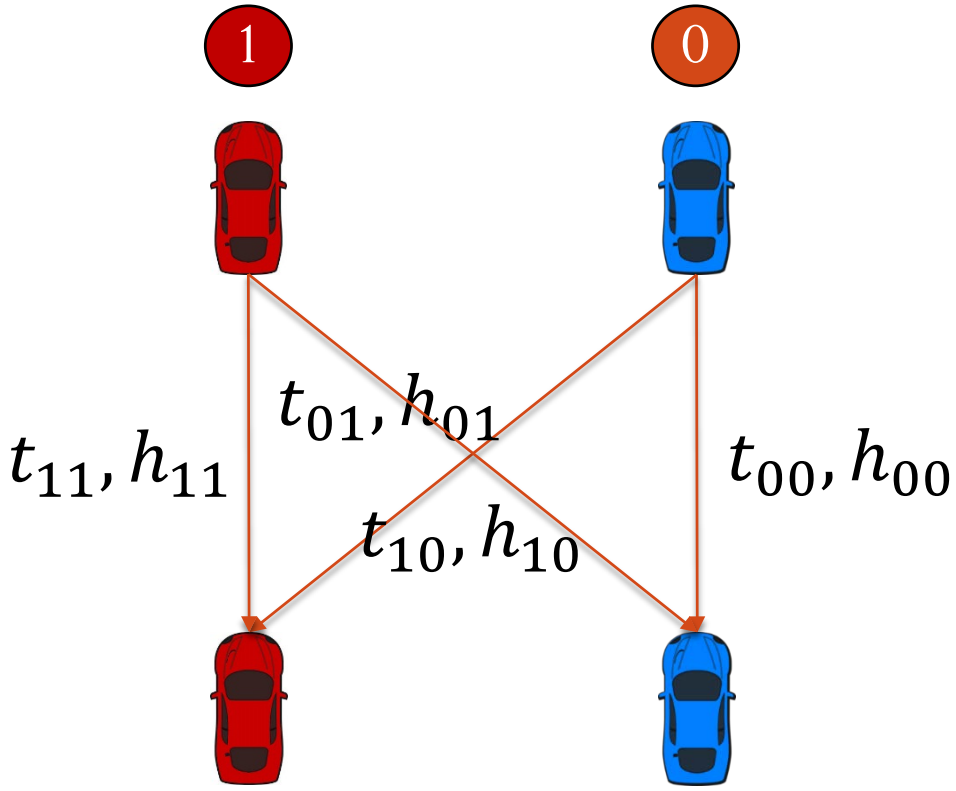


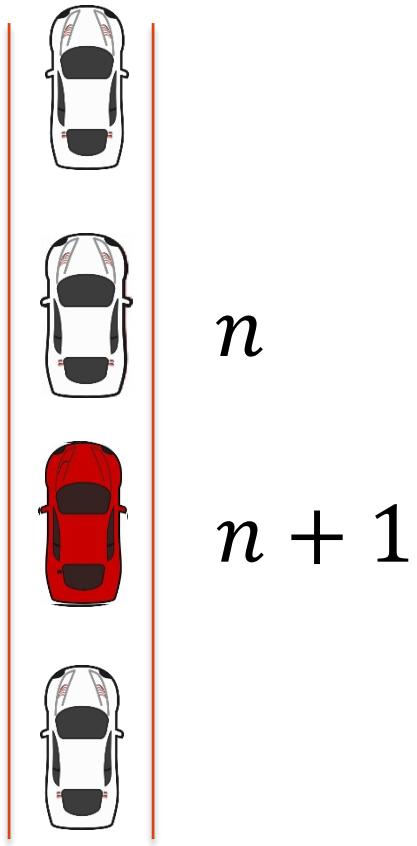
High CAV platooning intensity



Analytical Capacity Formulation

- Markov chain model





Analytical Capacity Formulation

- Markov chain model
  - $P_1 \in [0,1]$: CAV market penetration rate
  - $O \in [-1,1]$: CAV platooning intensity
  - $T := \begin{bmatrix} t_{11} & t_{10} \\ t_{01} & t_{00} \end{bmatrix}$

$$t_{10}(P_1, O) := \begin{cases} P_0(1-O), & O \geq 0; \\ P_0 + O\left(P_0 - \min\left\{1, \frac{P_0}{P_1}\right\}\right), & O < 0, \end{cases}$$

$$t_{11}(P_1, O) := 1 - t_{10}(P_1, O),$$

$$t_{01}(P_1, O) := \begin{cases} P_1(1-O), & O \geq 0; \\ P_1 + O\left(P_1 - \min\left\{1, \frac{P_1}{P_0}\right\}\right), & O < 0, \end{cases}$$

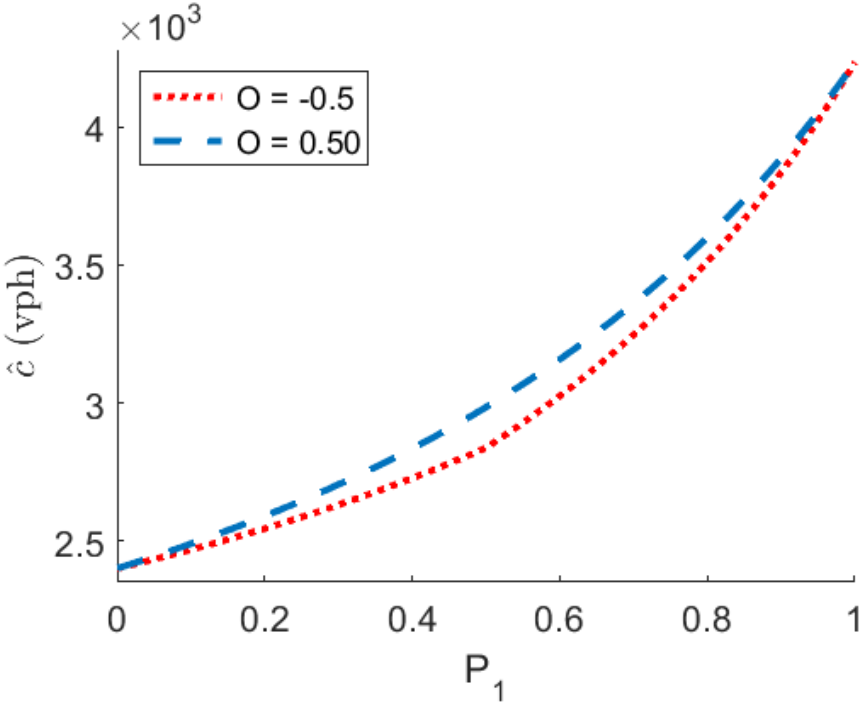
$$t_{00}(P_1, O) := 1 - t_{01}(P_1, O).$$

Analytical Capacity Formulation

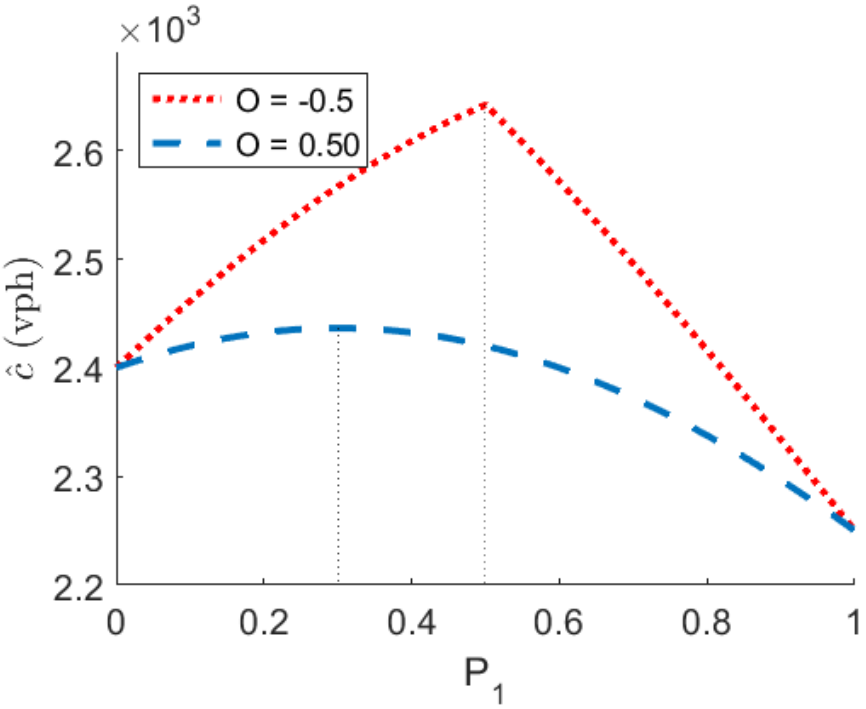
- Approximate capacity
  - $\hat{c} := \frac{N-1}{\sum_{n=1}^{N-1} \mathbb{E}(h_n)} = \frac{N-1}{\sum_{n=1}^{N-1} \bar{h}_{A_n A_{n+1}}} = \frac{1}{\sum_{s\in S, r\in S} P_s t_{sr} \bar{h}_{sr}}$
  - **Theorem 1:** *$\hat{c} \leq \bar{c}$ for any finite N*
  - **Theorem 2:** *When $0 < 1$,* $\mathbf{Pr}(\hat{c} \to \bar{c} \ as \ N \to \infty)$

Capacity analysis

- Numerical analysis



Optimistic Headway

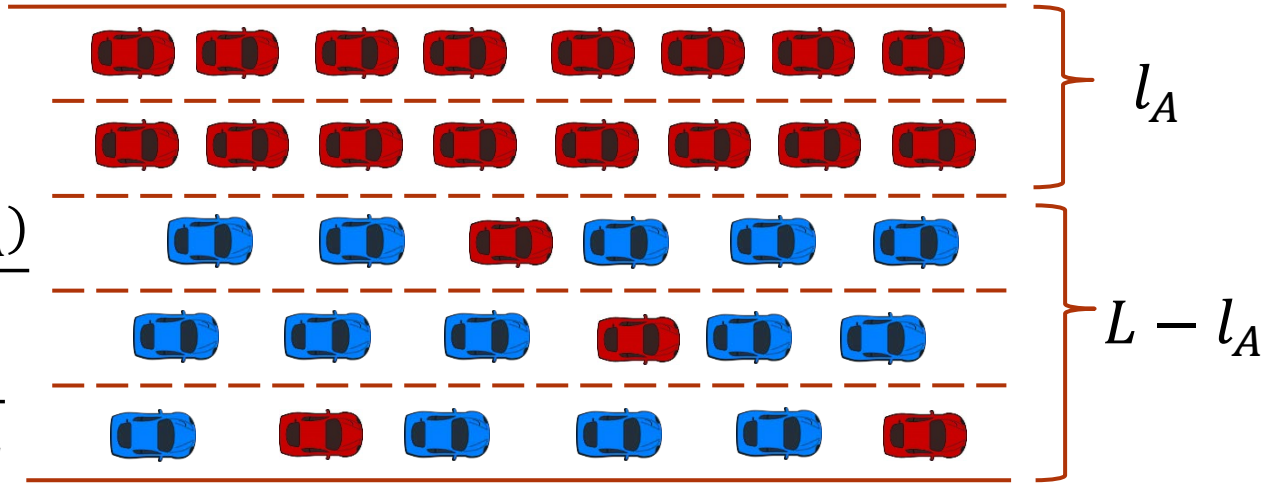


Conservative Headway

Application – Lane Management

- Determine the optimal number of CAV lanes

$$\hat{c}_{\mathrm{A}} := 1/\hat{h}_{11}$$
$$q_A := min(P_1 D, l_A \hat{c}_{\mathrm{A}})$$
$$p_1 := \frac{max(0, P_1 D - l_A \hat{c}_{\mathrm{A}})}{max(1, D - q_A)}$$
$$\hat{c}_{\mathrm{mix}} := \frac{1}{\sum_{s \in S, r \in S} p_s t_{sr} \bar{h}_{sr}}$$



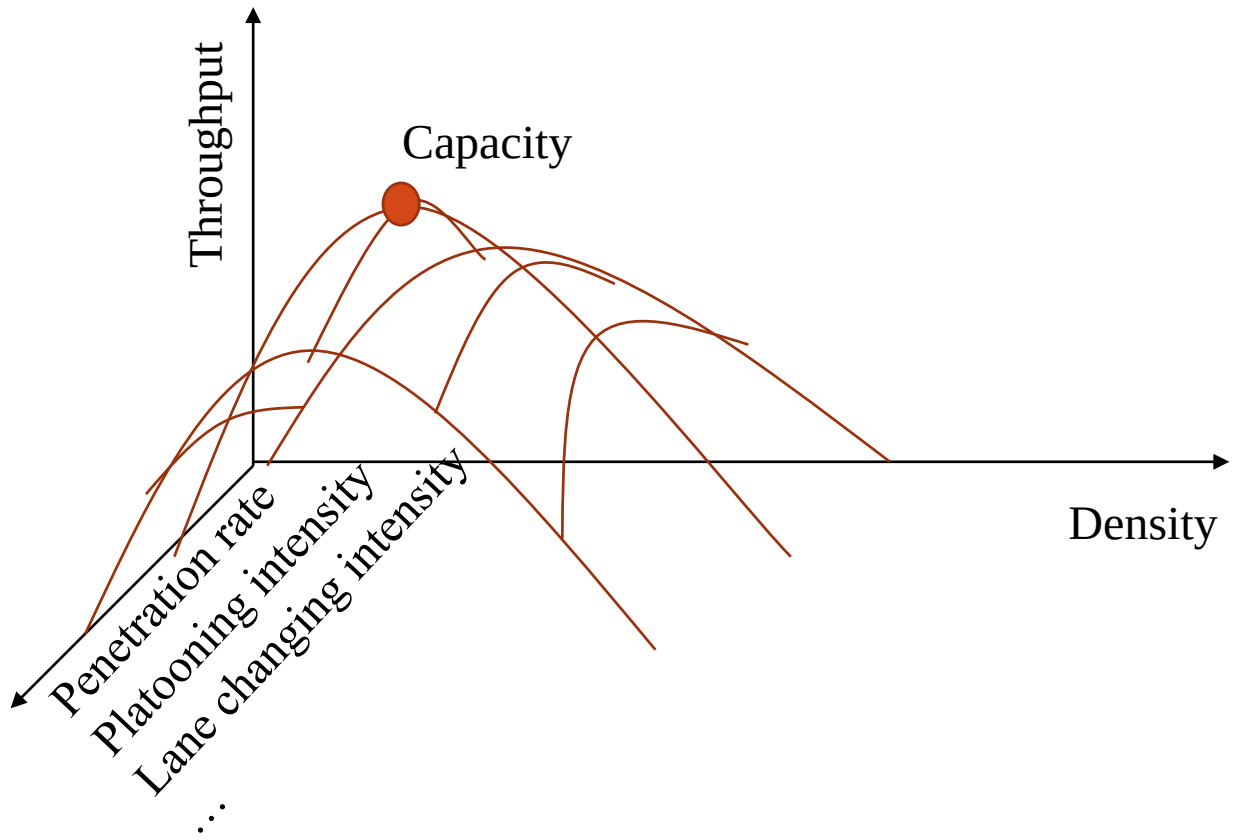
$$Q := q_A + \min(D - q_A, (L - l_A)\hat{c}_{\mathrm{mix}})$$

$$\text{ML}: \quad Q^* := \max_{l_A} Q(l_A, P_1, D, \alpha)$$
$$\text{subject to} \quad l_A \in [0, 1, \ldots, L]$$

Reference:
* Ghiasi, A., Hussein, O., Qian, S.Z. and Li, X., 2017. “A mixed traffic capacity analysis and lane management model for connected automated vehicles: a Markov chain method”, Transportation Research Part B, 106, pp. 266-292.

CAV Fundamental Diagrams

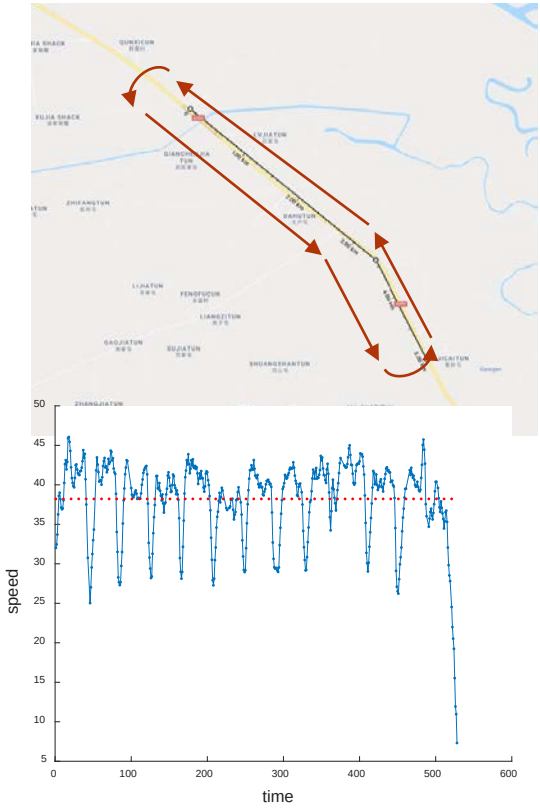
- Ongoing Research



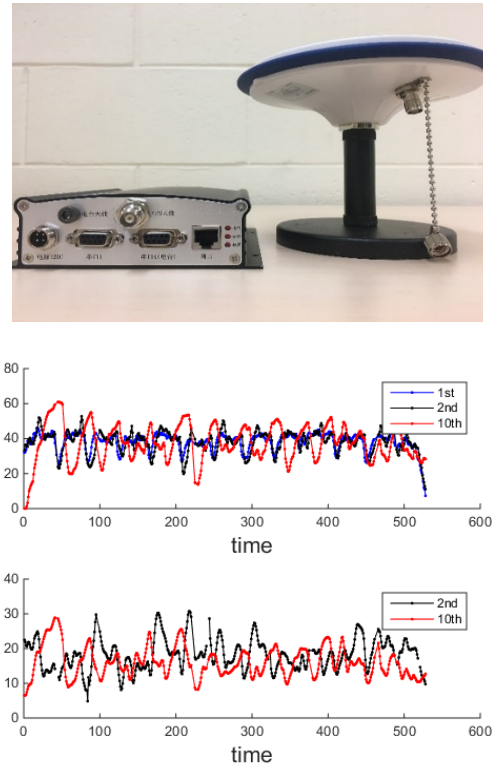
Reference: Qian, Z.S., Li, J., Li, X., Zhang, M. and Wang, H., 2017. “Modeling heterogeneous traffic flow: A pragmatic approach”. Transportation Research Part B, 99, pp.183-204.

Field Experiments

- 10 HVs following tests in Harbin, China (collaborating with Harbin Institute of Technology)



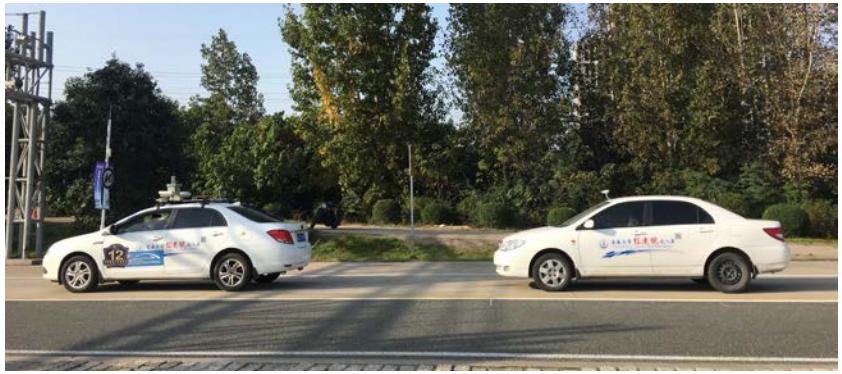
Lead vehicle



Following vehicles

Field Experiments

- HV following CAV/HV at the 2.4 km test track at Chang'an University, China
- Test different drivers, different CAV speed

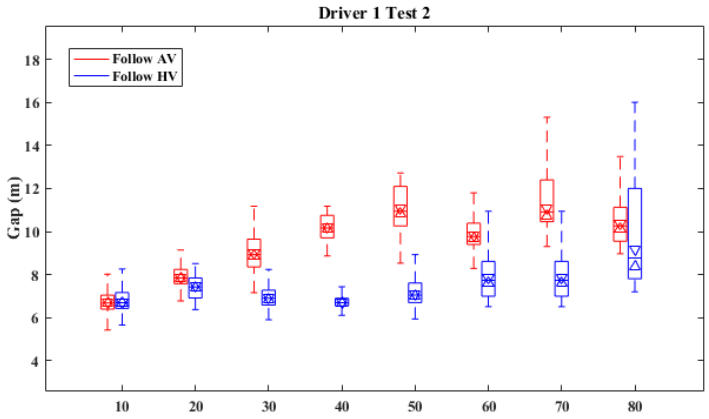


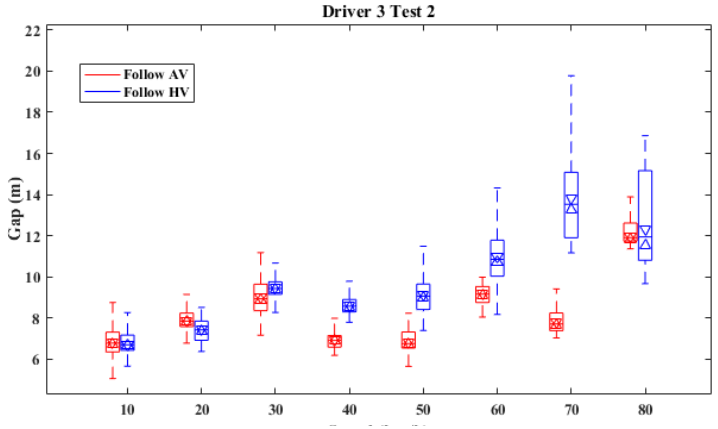
Field Experiments

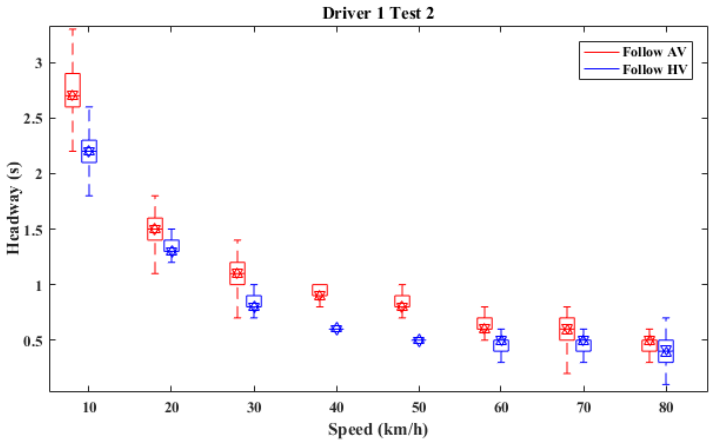
- HV following CAV/HV at the 2.4 km test track at Chang'an University, China
- Test different drivers, different CAV speed

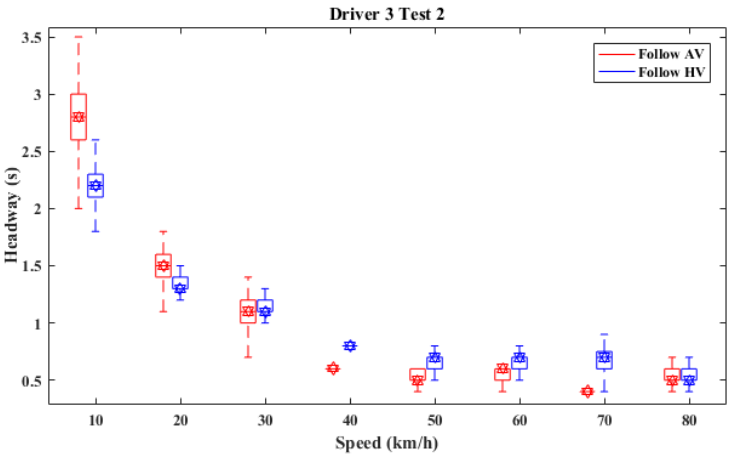
Field Experiments

- Difference between HV-following-CAV and HV-following-AV









Acknowledgements

- Students
  - Fang Zhou (Li's student)
  - Amir Ghiasi (Li's student)
  - Omar Hussain (Li's student)
  - Handong Yao (Harbin Institute of Technologies)
  - Zhen Wang (Chang'an University)
- Collaborators
  - Jiaqi Ma (University of Cincinnati)
  - Zhigang Xu (Chang'an University)
  - Jianxun Cui (Harbin Institute of Technologies)
  - Sean Qian (CMU)
- Funding agencies

Thank you!
Q & A?

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