The Capacity Paradox of Mixed Traffic with CAVs

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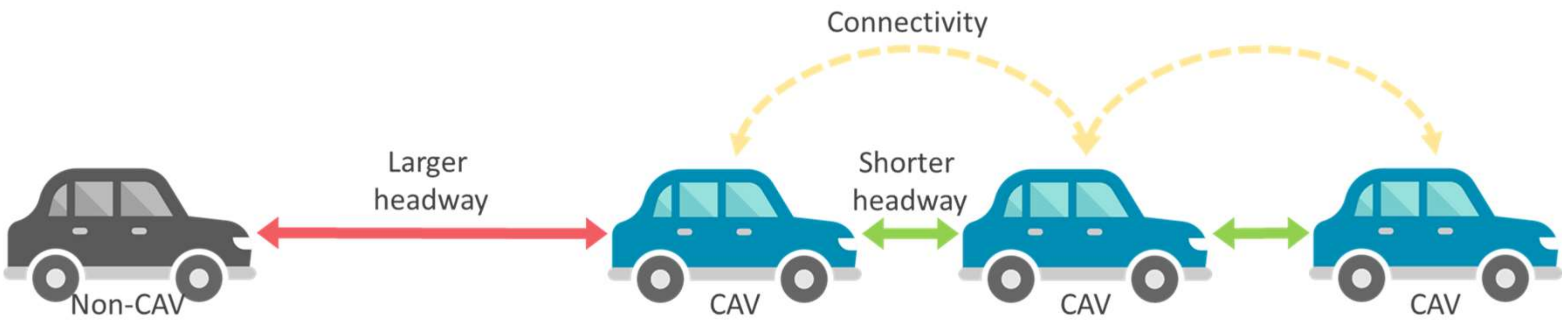
Introduction

Connected Automated Vehicles (CAVs)

- CAVs bring promise of roadway capacity improvement without investing in the road infrastructure
  - 2000 vph/lane to 3900 vph/lane at full market penetration*
- Cooperative Adaptive Cruise Control (CACC) is currently available to automate the car-following task by
  - Monitoring the relative speed and gap to the leading vehicle
  - Sharing with other CAVs, such as the acceleration and speed

*H. Liu, X. (David) Kan, S. E. Shladover, X. Y. Lu, and R. E. Ferlis, “Modeling impacts of Cooperative Adaptive Cruise Control on mixed traffic flow in multi-lane freeway facilities,” Transp. Res. Part C Emerg. Technol., vol. 95, no. December 2017, pp. 261–279, 2018.

Roadway Capacity Improvement with CAVs



- Vehicle-to-Vehicle (V2V) communication in real-time and in high frequency
- Reduction of the cumulative delay in reaction and the perception error
- Safe with shorter headways in a tight platoon
  - Increased roadway capacity (veh/hr)
- The present research will assume a **freeway setting**

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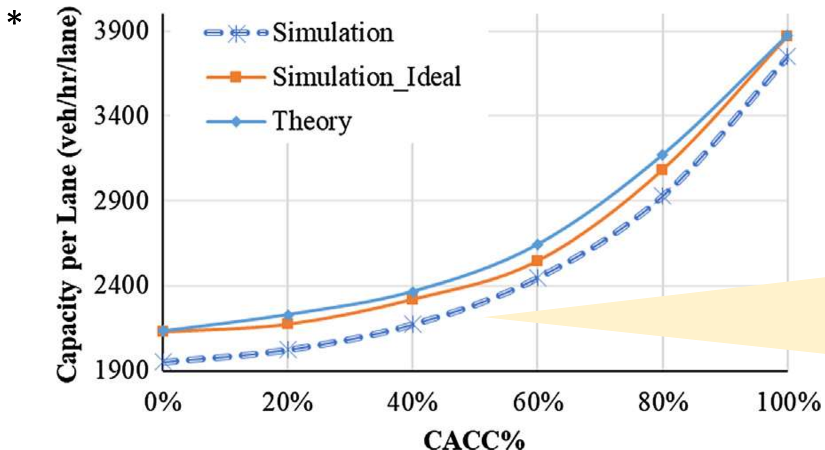
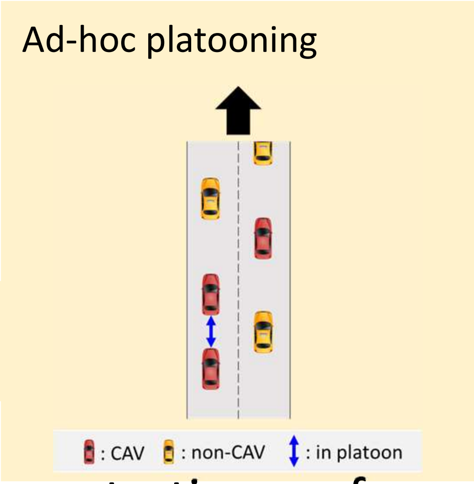
Capacity depends on CAV Penetration





- Minimal improvement of capacity at low CAV penetration on freeway
- A low probability of forming a long platoon and reducing the average headway

*H. Liu, X. (David) Kan, S. E. Shladover, X. Y. Lu, and R. E. Ferlis, "Modeling impacts of Cooperative Adaptive Cruise Control on mixed traffic flow in multi-lane freeway facilities," Transp. Res. Part C Emerg. Technol., vol. 95, no. December 2017, pp. 261–279, 2018.

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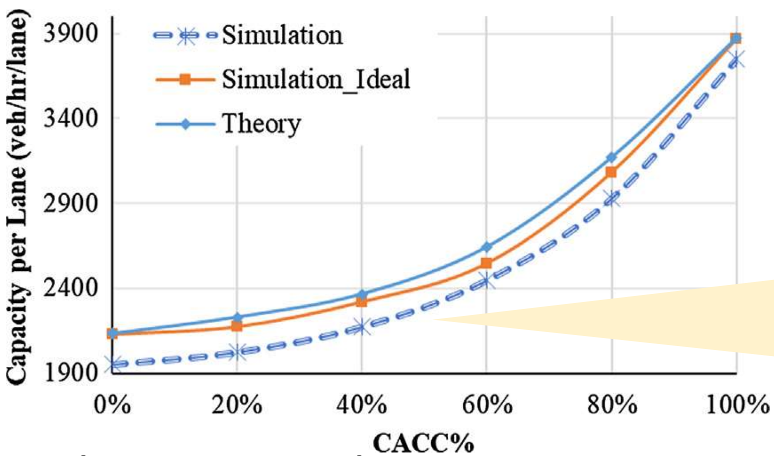

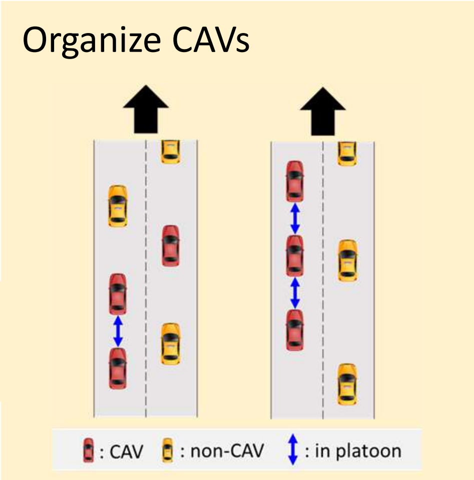

- Researchers argue that capacity can increase if the CAVs organize themselves to form a longer platoon, reducing headways further*

*D. Chen, S. Ahn, M. Chitturi, and D. A. Noyce, "Towards vehicle automation: Roadway capacity formulation for traffic mixed with regular and automated vehicles," *Transp. Res. Part B Methodol.*, vol. 100, pp. 196–221, 2017.
*L. Xiao, M. Wang, W. Schakel, and B. van Arem, "Unravelling effects of cooperative adaptive cruise control deactivation on traffic flow characteristics at merging bottlenecks," *Transp. Res. Part C Emerg. Technol.*, vol. 96, no. October, pp. 380–397, 2018.
*T. S. Dao, C. M. Clark, and J. P. Huissoon, "Distributed platoon assignment and lane selection for traffic flow optimization," *IEEE Intell. Veh. Symp. Proc.*, pp. 739–744, 2008.

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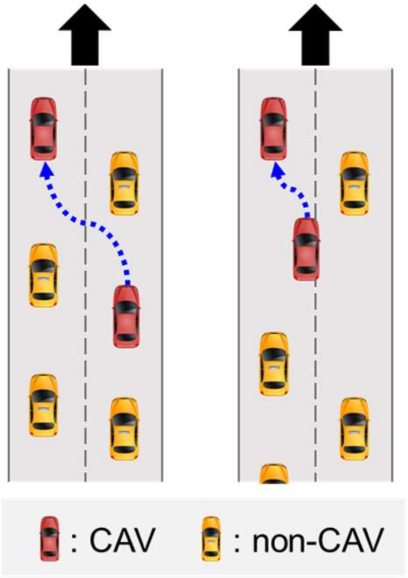
Platoon Organization Strategy

A strategy to organize CAVs and form longer platoons on the road

- CAVs maneuver to change their relative positions
- Researchers expect this as a potential solution to increase capacity further at low penetration
- May require lane changes



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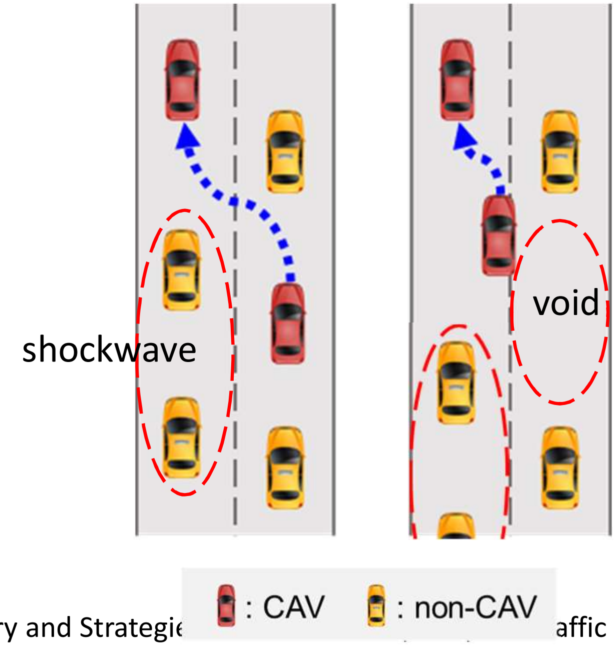
Platoon Organization Strategy

Lane changes may disrupt the traffic flow*

- Propagate a shockwave upstream
- Create a void
- Result a capacity drop

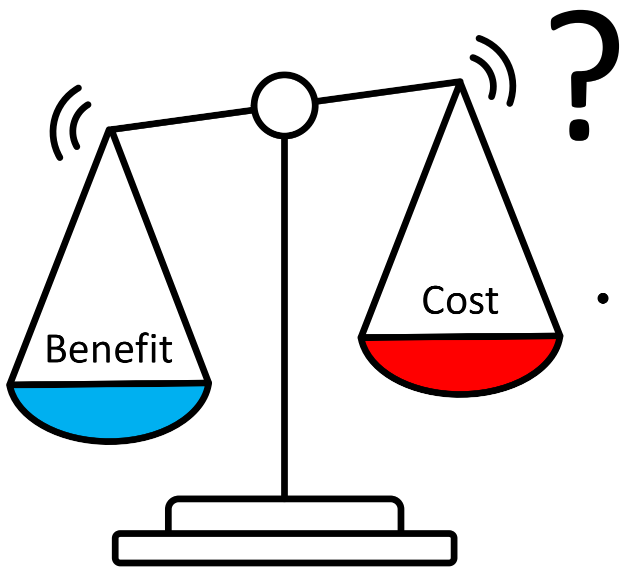


*J. Laval, M. Cassidy, and C. Daganzo, “Impacts of Lane Changes at Merge Bottlenecks: A Theory and Strategie … affic and Granular Flow’05, 2007.

Platoon Organization Strategy

Two opposing forces in improving the capacity

- Longer platoons
- Shorter headways



- Lane changes that disrupt the traffic flow

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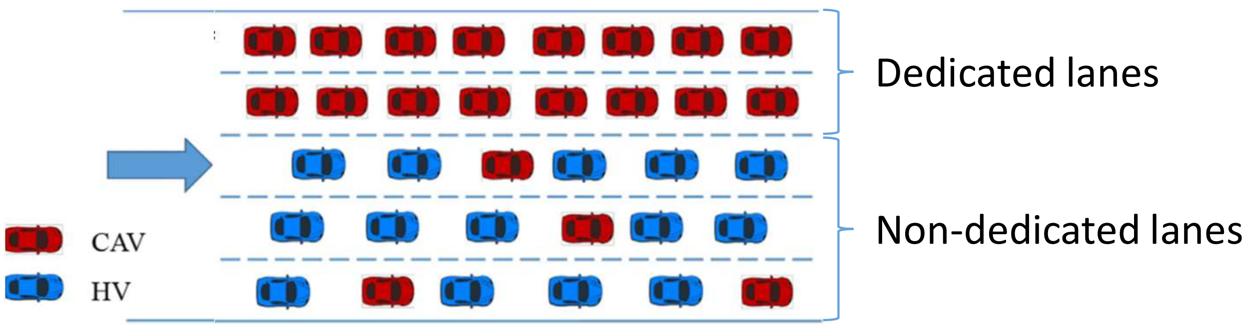
Motivation

Can the CAVs maneuver to form longer platoons and improve the capacity further?

Current Literature

Unrealistic analysis without lane changes

- No lane changes to form platoons
- Possible overestimation of the capacity



A. Ghiasi, O. Hussain, Z. (Sean) Qian, and X. Li, "A mixed traffic capacity analysis and lane management model for connected automated vehicles: A Markov chain method," *Transp. Res. Part B Methodol.*, vol. 106, pp. 266–292, 2017.

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Current Literature

Realistic analysis with lane changes*

- Dedicated lanes for CAVs – underutilized b
- Total delay *increases* at low CAV penetratic
- Cannot isolate the impact of unsaturated c capacity analysis

	CACC					
	0%	10%	20%	30%	40%	50%
Total TT (h)	10961	15546	14337	10997	7586	7065
mean TTD (s/veh)	255	536	446	324	86	79
std TTD (s/veh)	381	861	723	555	110	89

Note: TT is travel time; TTD is travel time delay and std is the standard deviation.

*L. Xiao, M. Wang and B. van Arem, "Traffic Flow Impacts of Converting an HOV Lane Into a Dedicated CACC Lane on a Freeway Corridor," in IEEE Intelligent Transportation Systems Magazine, vol. 12, no. 1, pp. 60-73, Spring 2020, doi: 10.1109/MITS.2019.2953477.

Research Hypothesis

H_0: CAVs cannot improve the capacity further with platoon organization on the road.

- From queuing theory, $q_{out} <= q_{in}$, regardless of what CAVs do to form longer platoons.
- The only way to improve q_{out} with longer platoons is to have q_{in} with longer platoons. (Chicken and egg problem)
- In other words, platoon organization *on the road* will not increase capacity.

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Research Objectives

1. To test the hypothesis that the roadway capacity cannot increase further with organizing CAVs into longer platoons on the road
2. To recommend the operation strategies of CAVs to ensure maximal traffic flow when improving the platooning performance of CAVs

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Research Considerations

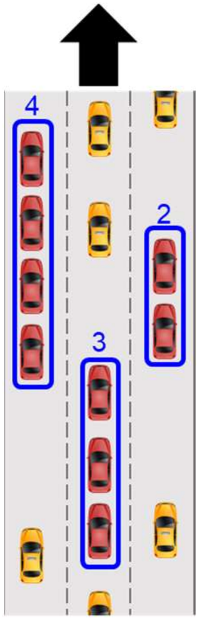
Microscopic traffic model

Sample strategies for platoon organization

Microscopic Traffic Model for Platoon Organization

The PATH model* will be used

- Description of mixed traffic of CAVs and non-CAVs
- A microscopic model
- Detailed lane change algorithm
- Calibration with experiments



*X. Lu, X. D. Kan, S. E. Shladover, D. Wei, and R. Ferlis, "An Enhanced Microscopic Traffic Simulation Model for Application to Connected Automated Vehicles," 96th Annu. Meet. Transp. Res. Board, no. January, p. 20p, 2017.

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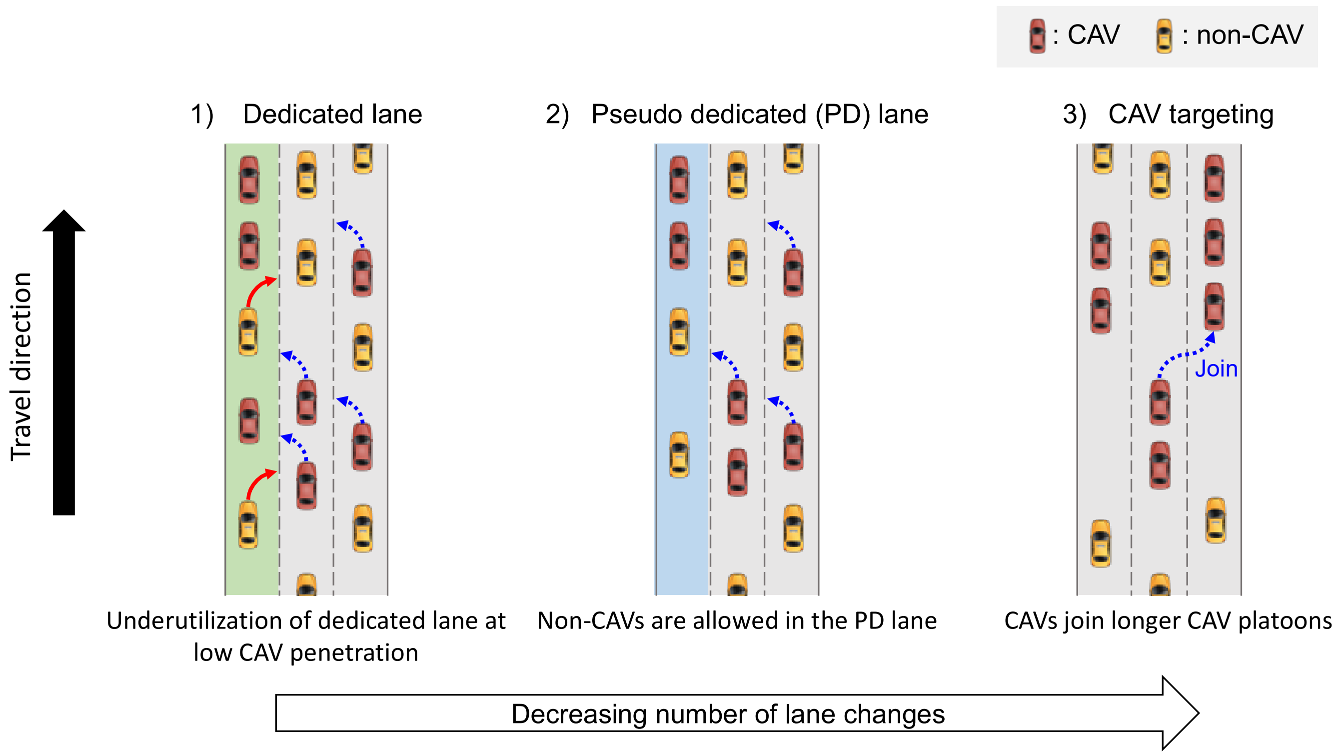
Sample Strategies for Platoon Organization



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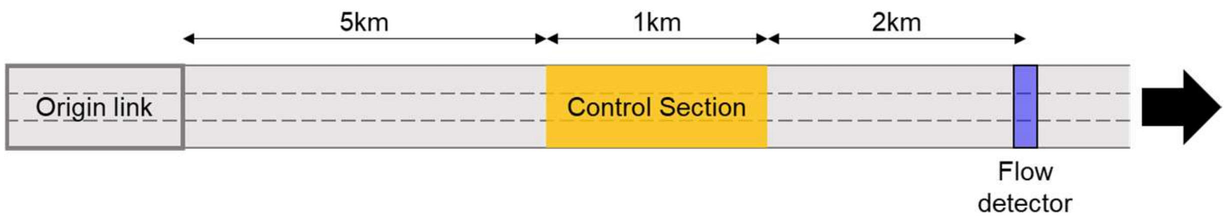
Experiment 1

1. To test the hypothesis that the roadway capacity cannot increase further with organizing CAVs into longer platoons on the road

Experiment Set-up

Compare the bottleneck capacity in a simple road geometry

- CAV penetration: 0, 25, 50, 75, and 100%
- Ad-hoc platooning



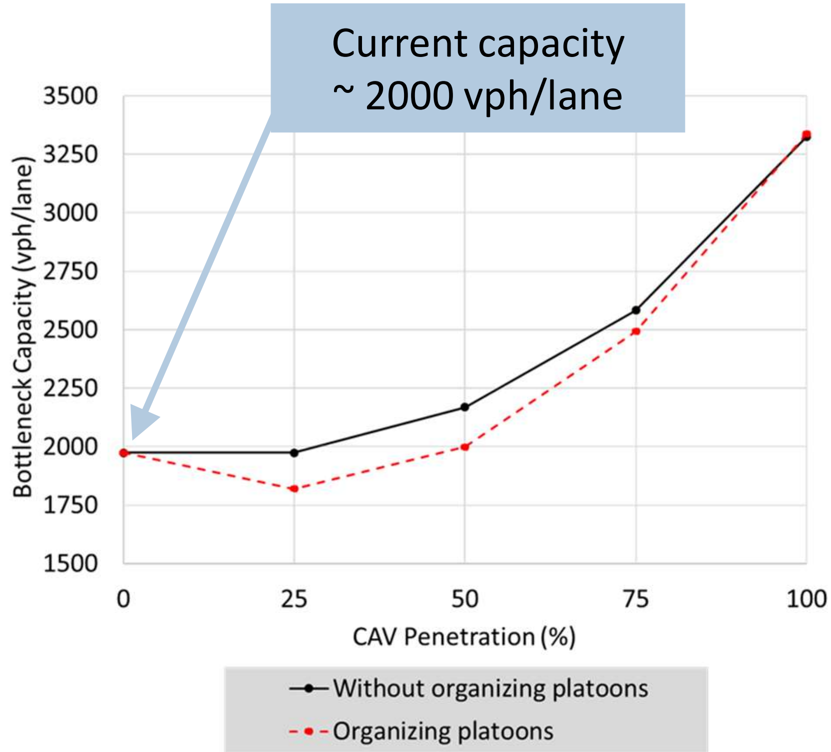
- Baseline
  - No platoon organization
  - 60 minutes
  - Bottleneck in the origin link
- Platoon Organization case
  - Warm-up with 20 minutes with no platoon organization
  - 40 minutes with PD lane strategy
  - Bottleneck in the control section

Results

Capacity drops with platoon organization

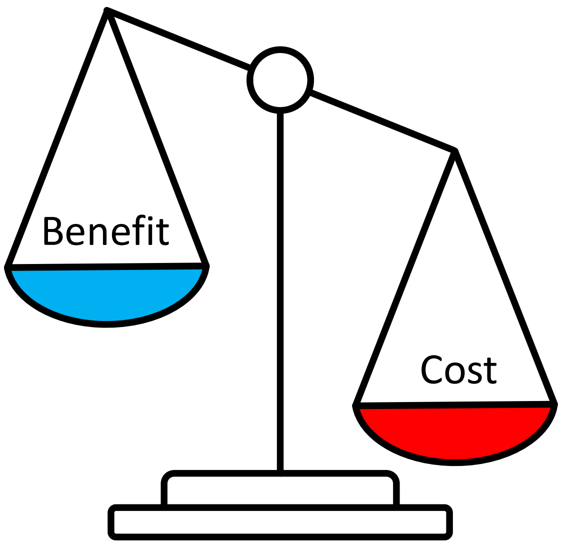
The hypothesis was correct.

- The PD lane strategy reduces the capacity from the baseline.
- At 25%, the PD lane produces capacity of 1800 vph/lane.
- The platoons are longer with PD lane strategy.
  - At 50% CAVs, the average platoon length increases from 3.3 to 5.5 CAVs/platoon.



The Paradox of Increasing Capacity with CAVs

- At low penetration, CAVs that enter the road randomly do not improve capacity significantly.
- CAVs can change lanes to form longer platoons with smaller headways within the platoons. However, the lane changes disrupt the flow and negate the benefit of reducing those headways.
- <u>The capacity decreases overall!</u>



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The Paradox of Increasing Capacity with CAVs

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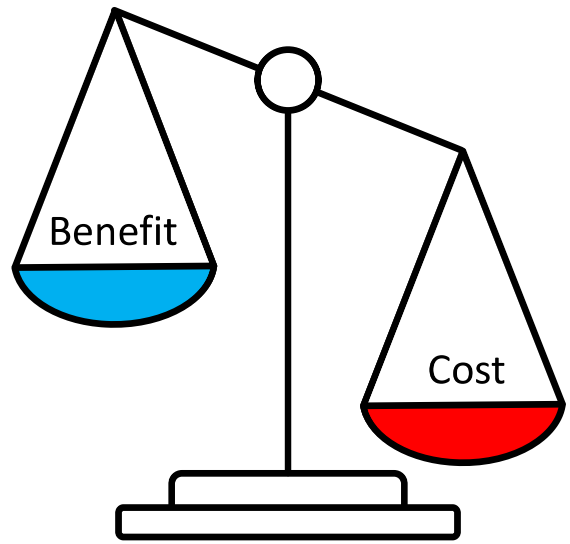
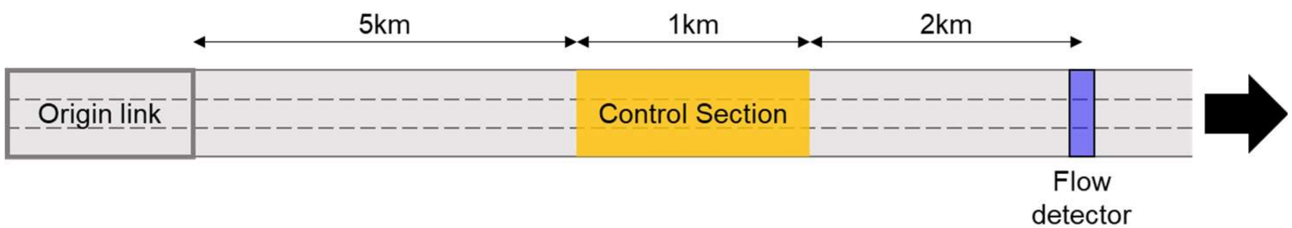
CAVs should not organize platoons at high flow. What about at low flow?



Experiment 2

2. To recommend the operation strategies of CAVs to ensure maximal traffic flow when improving the platooning performance of CAVs

Experiment Set-up



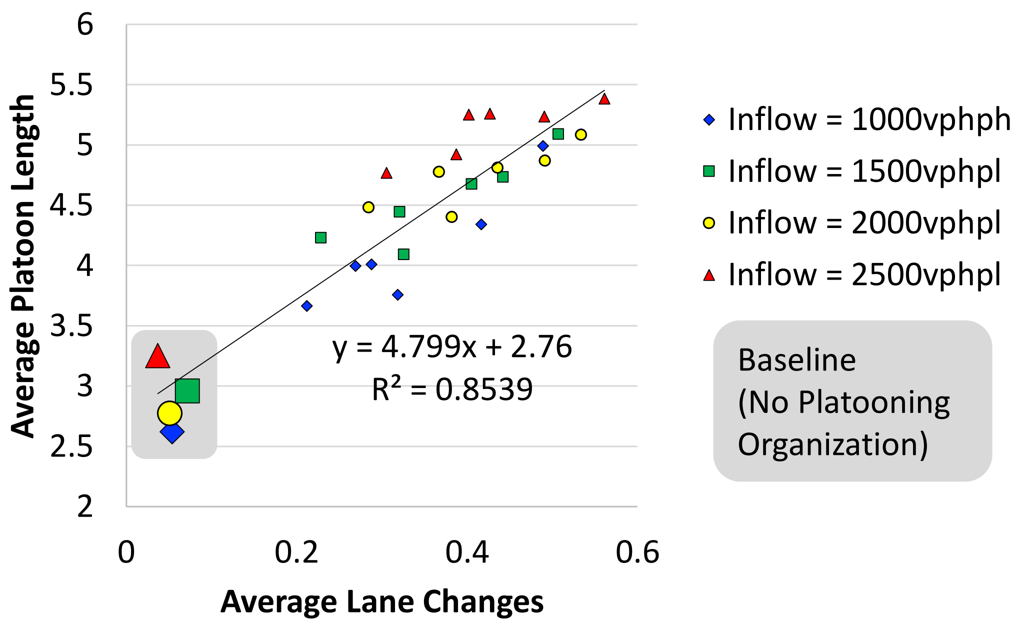
Test various levels of input flow

- Input flows: 1500, 2000, and 2500vph/lane
- Fixed CAV penetration at 50%
- Baseline vs. platoon organization with PD lane and CAV targeting (with various parameters)
- CAV platooning performance metric
  - Average platoon length = E(Platoon length | CAV)
  - Platooning probability = P(In CAV Platoon| CAV)
- Various platooning organization results in different disruption to the flow, measured with:
  - Average lane changes = number of lane changes / number of vehicles

Results

More aggressive strategy increases the average platoon length further.

- As CAVs change lanes to form longer platoons, the average length of CAV platoon increases. This is true for *all input flows – low or high.*
- As the platooning strategy becomes more aggressive with more lane changes, the average platoon length increases.



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Results

At low flow, CAVs can organize platoons without reducing the discharge flow.

- The average platoon length increases regardless of input flow.
- But at low input flow, platoon organization does not reduce the discharge flow.

Input flow (vph/lane)	Average Platoon Length			Discharge Flow (vph/lane)		
	Baseline		Platoon organization, max	Baseline, Q_B	Platoon Organization, Q_{PO}	$Q_{PO} - Q_B$
1000	2.6	→	5.0	1006.3	1006.74	0.04%
1500	3.0	→	5.1	1483.4	1478.3	-0.34%
2000	2.8	→	5.1	1961.7	1924.6	-1.89%
2500	3.3	→	5.4	2260.6	2045.0	-9.54%

*Only showing the results of strategies with the most lane changes

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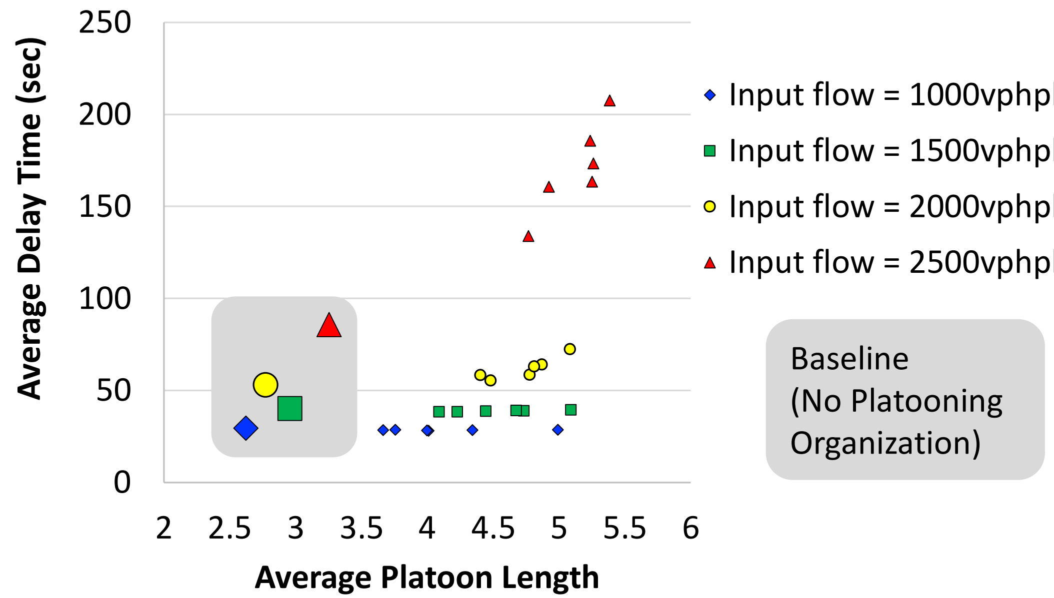
Results

As flow increases, forming long platoons increases the delay time.

- With a higher input flow, the cost of enhancing platooning is more expensive, i.e. more delay time.
- Need to beware, the CAVs may be still motivated to organize platoons despite the increase of delay time!



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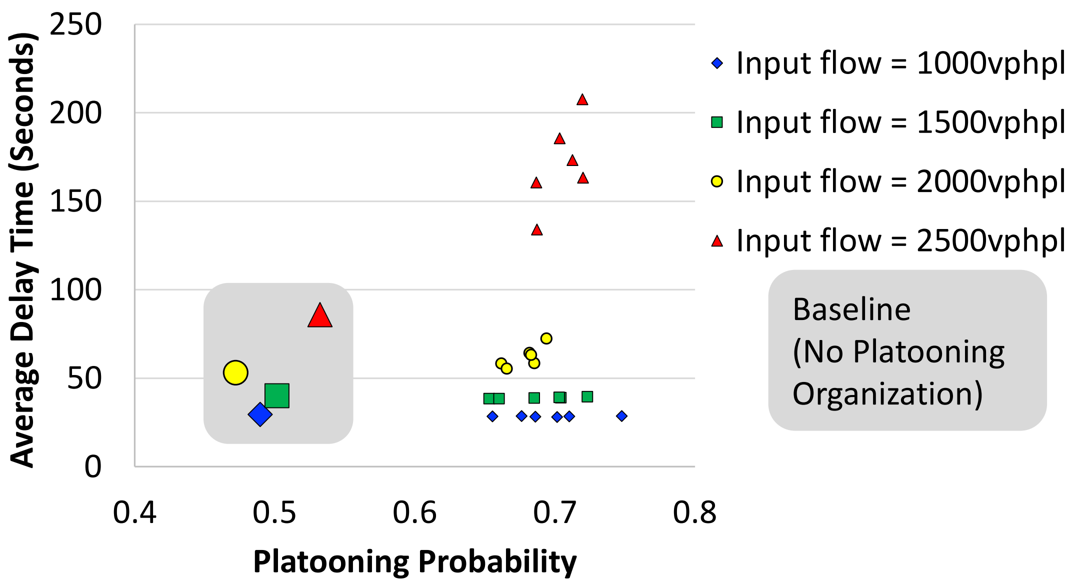

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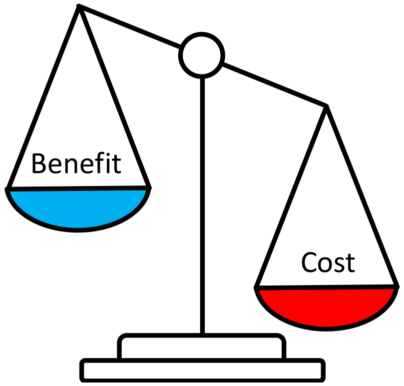
Conclusion

Main take-away 1

- CAVs can change lanes to find other CAVs on the road and form platoons. This increases the average length of CAV platoon and the probability of a CAV being in a platoon, at all levels of traffic flow.

Main take-away 2

- The capacity will be REDUCED if the CAVs organize into longer platoons at high flow
  - The capacity paradox with CAVs!
- This is because the platoon organization induces vehicles to change lanes that disrupt the flow.
- At a high flow, the CAVs should not maneuver to form longer platoons.



Main take-away 3

- At low flow, the CAVs maneuvering to form platoons will not reduce the flow because the capacity has not been reached yet.
- The CAVs can maneuver to form longer platoons (and enjoy platooning benefits) without disrupting the flow.

Future Work

Future work

- Can we devise platoon organization strategies so that the platooning length increases more efficiently with a given increase of lane changes?
- How does capacity improve if the CAVs form platoons *off the road*? (Logistics application)

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