On the Impact of the Clustering Strength of Connected and Autonomous Vehicles in Mixed Traffic

Session: Transport Planning and Operations (1)

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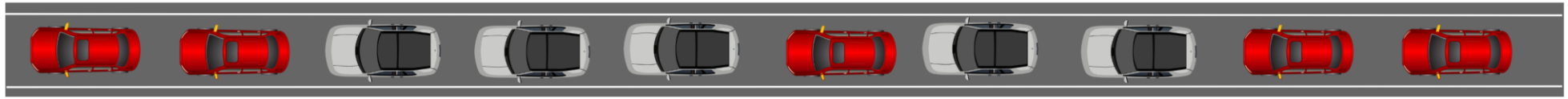
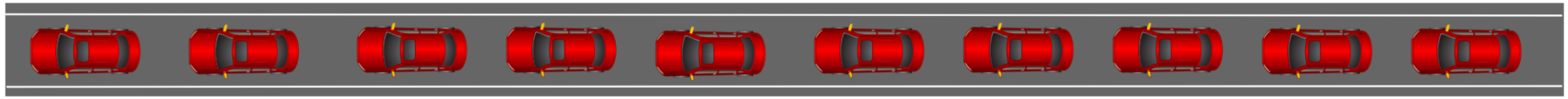
What is the Mixed Traffic?

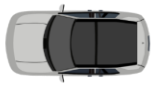
(a) Traditional Traffic



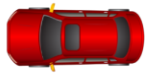
(b) Mixed Traffic



(c) Pure CAV Traffic

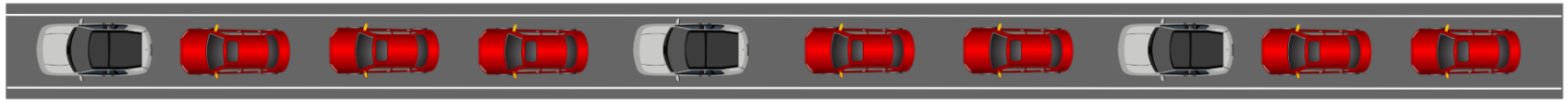


Human-driven Vehicle (HV)

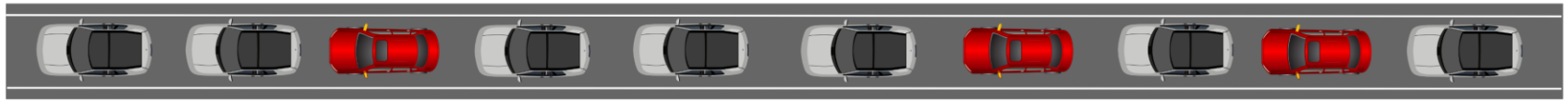


Connected and Autonomous Vehicle (CAV)

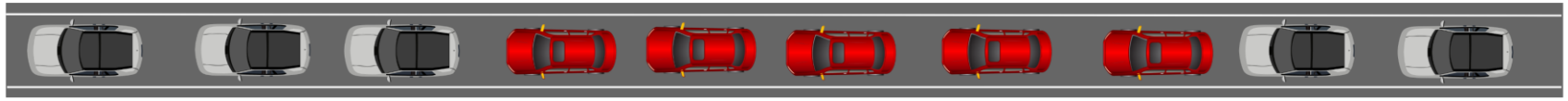
How can we characterize the Mixed Traffic?



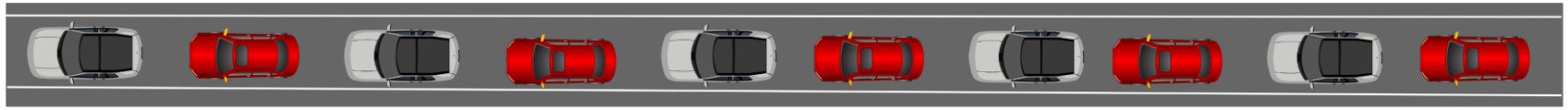
(a) High CAV Penetration Rate



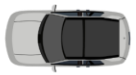
(b) Low CAV Penetration Rate



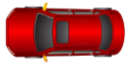
(c) High CAV Clustering Strength



(d) Low CAV Clustering Strength

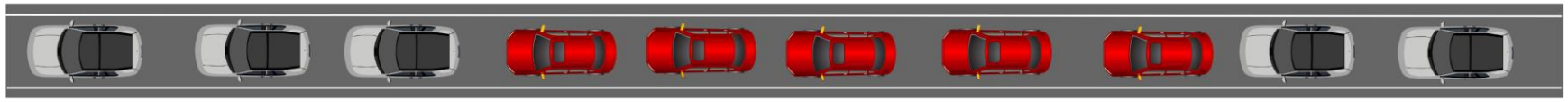


Human-driven Vehicle (HV)

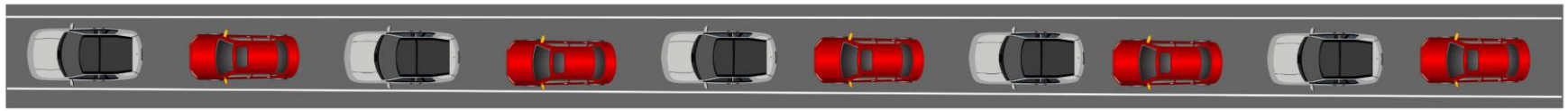


Connected and Autonomous Vehicle (CAV)

CAV Clustering Strength



High CAV Clustering Strength



Low CAV Clustering Strength

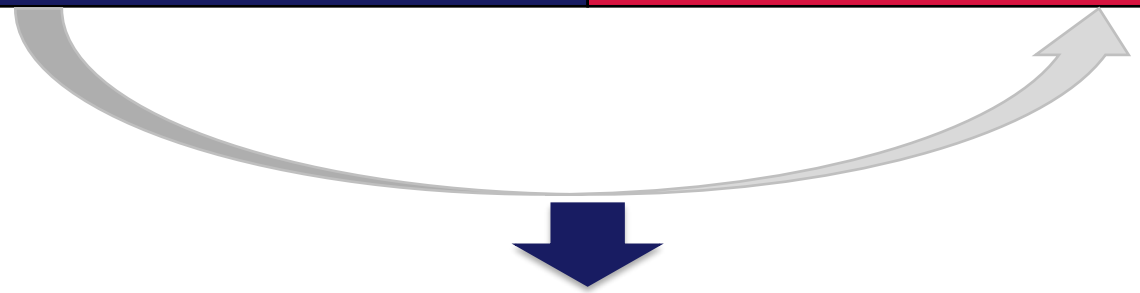
Human-driven Vehicle (HV)

Connected and Autonomous Vehicle (CAV)

- CAV clustering enables vehicles communication and platoon formation.
- Moving as a CAV platoon can increase the traffic efficiency.

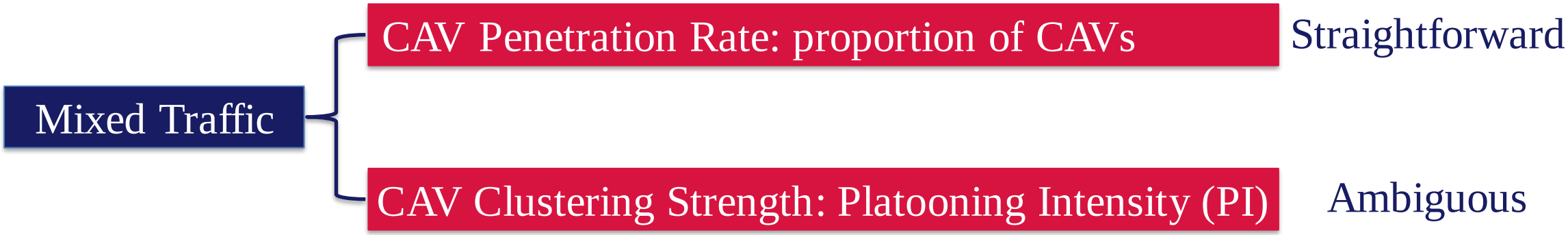
Significance of Mixed Traffic Characteristics

Mixed Traffic Characteristics	Traditional Traffic Characteristics
• CAV Penetration Rate • CAV Clustering Strength • …	• Capacity • Safety • …



Significance
• Mixed Traffic Management • CAV Platoon Control • …

Research Gap



- Platooning Intensity (PI) is proposed to measure CAV clustering strength, but existing definitions of PI exhibit certain limitations.
- Hence, traffic analysis, specifically the impact of CAV clustering strength on traffic capacity, based on these PIs requires further refinement.

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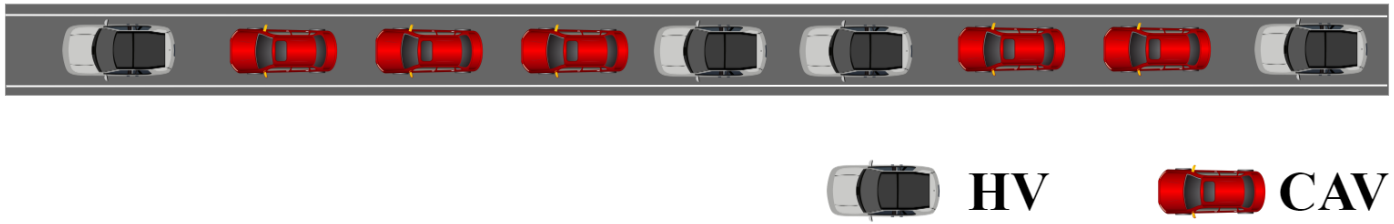
Existing Definitions of Platooning Intensity

Source	Definition	Limitation
[1]	Likelihood of the following vehicle type given a preceding vehicle type for each vehicle pair	Derived from infinite vehicles May be out of bound for finite vehicles
[2]	Average CAV platoon size in mixed traffic	Unlimited range
[3]		
[4]	Proportion of CAVs forming the platoons to all CAVs	Restricted ability capturing CAV spatial distribution when the number of CAVs forming the platoons is fixed but the size of a platoon is random.
[5]	Ratio of the actual number of CAVs in platoons (whose size is larger than 2) to the total number of CAVs	

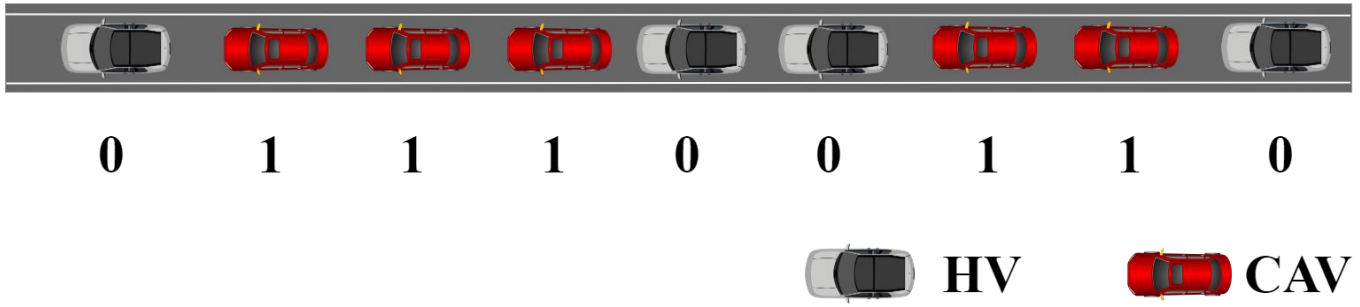
[1] Ghiasi, O. Hussain, Z. S. Qian, X. Li, "A mixed traffic capacity analysis and lane management model for connected automated vehicles: A Markov chain method," Transportation Research Part B: Methodological, vol. 106, pp. 266–292, 2017.
[2] R. W. Whalin, G. Hu et al., "Macroscopic fundamental diagram approach to traffic flow with autonomous/connected vehicles," Southeastern Transportation Research, Innovation, Development and Education, Tech. Rep., 2020.
[3] G. Hu, F. Wang, W. Lu, T. A. Kwembe, R. W. Whalin, "Cooperative bypassing algorithm for connected and autonomous vehicles in mixed traffic," IET Intelligent Transport Systems, vol. 14, no. 8, pp. 915–923, 2020.
[4] S. He, F. Ding, C. Lu, Y. Qi, "Impact of connected and autonomous vehicle dedicated lane on the freeway traffic efficiency," European Transport Research Review, vol. 14, no. 1, p. 12, 2022.
[5] Y. Jiang, F. Zhu, Z. Yao, Q. Gu, B. Ran et al., "Platoon intensity of connected automated vehicles: Definition, formulas, examples, and applications," Journal of Advanced Transportation, vol. 2023, 2023.

Model Assumptions



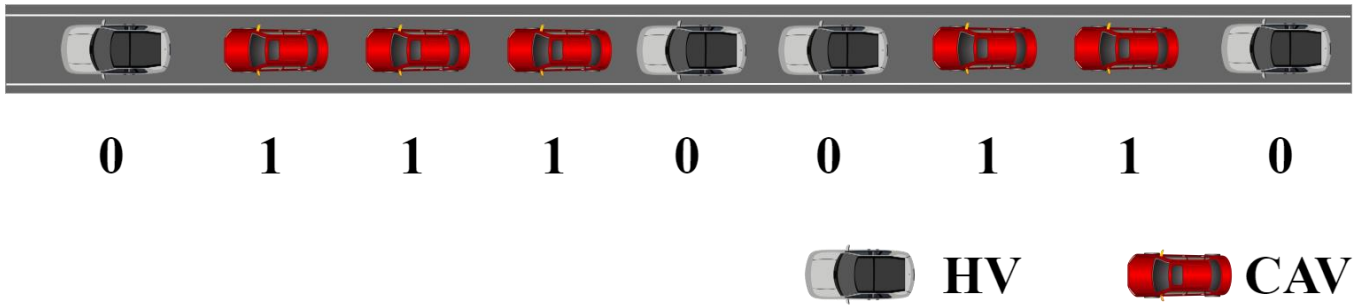
1. The research focuses on the longitudinal behaviour of vehicles on the single-lane road. Therefore, the lateral vehicle actions, e.g., lane-changing and merging, are not considered.
2. The study concentrates on mixed traffic, which only includes connected and autonomous vehicles (CAVs) and human-driven vehicles (HVs). Pure CAVs or HVs on the road could be considered as special cases.

Modeling the Mixed Traffic



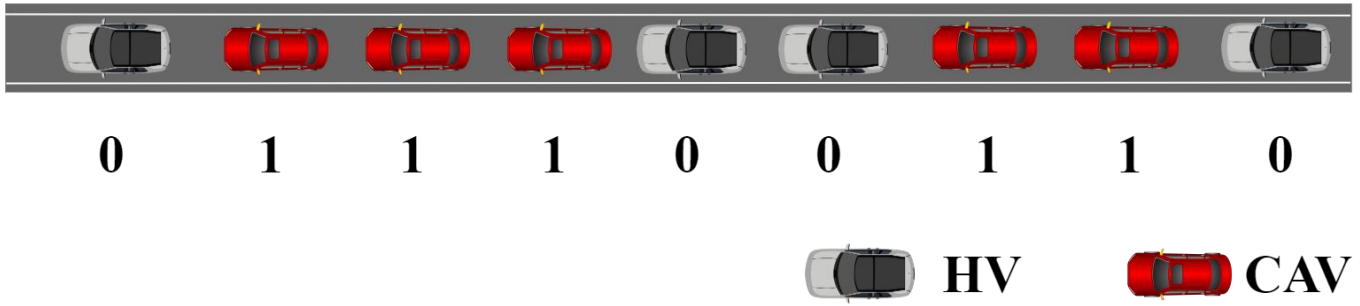
Item	Representation
HV	0
CAV	1
HV penetration rate	P_0
CAV penetration rate	P_1
Number of vehicles in this vehicle sequence	N
Number of vehicle pairs in this vehicle sequence	$N_{sr}, sr \in \{00,01,10,11\}$

Autocorrelation-based Platooning Intensity (API)



Definition	Similarity in vehicle types between two consecutive vehicles within a vehicle sequence.
Calculation	Sequence Autocorrelation Function (ACF), ranging between -1 and 1, measures the relationship between a variable's present value and its lagged values. Applied in mixed Traffic, it can also reflect the relationship between 2 consecutive vehicles.

Autocorrelation-based Platooning Intensity (API)



Consider a stream of N vehicles on a single-lane road, indexed by $\{1, 2, \ldots, N\}$. Let $x_i \in \{0, 1\}$ represents the type of the i^{th} vehicle in the sequence, where 1 denotes a CAV and 0 signifies an HV.

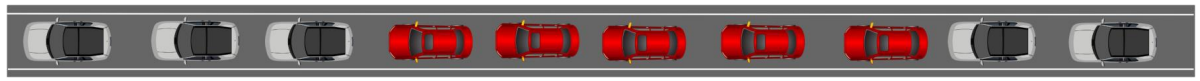
$$\rho = \frac{\frac{1}{N-1}\sum_{i=1}^{N-1}(x_i - \bar{x})(x_{i+1} - \bar{x})}{\frac{1}{N}\sum_{i=1}^{N}(x_i - \bar{x})^2}$$

API can effectively quantify the degree of CAV platoon clustering

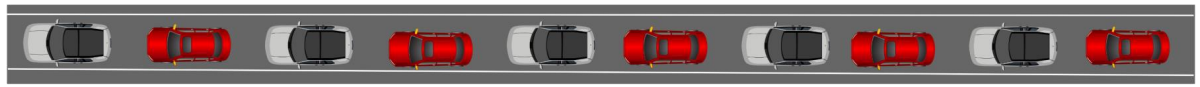
$$\rho = \frac{P_0}{(N-1)P_1} \cdot N_{11} + \frac{P_1}{(N-1)P_0} \cdot N_{00} - \frac{N_{01} + N_{10}}{N-1}$$

- ρ is an increasing function of N_{11} and N_{00}.
- ρ is a decreasing function of N_{01} and N_{10}.
- If the probability of consecutive 2 vehicles of the same type is larger, the value of ρ would also be higher.
- Increase in CAV-CAV pairs indicates that CAVs becomes more clustering.

Features of API



High CAV Clustering Strength



Low CAV Clustering Strength

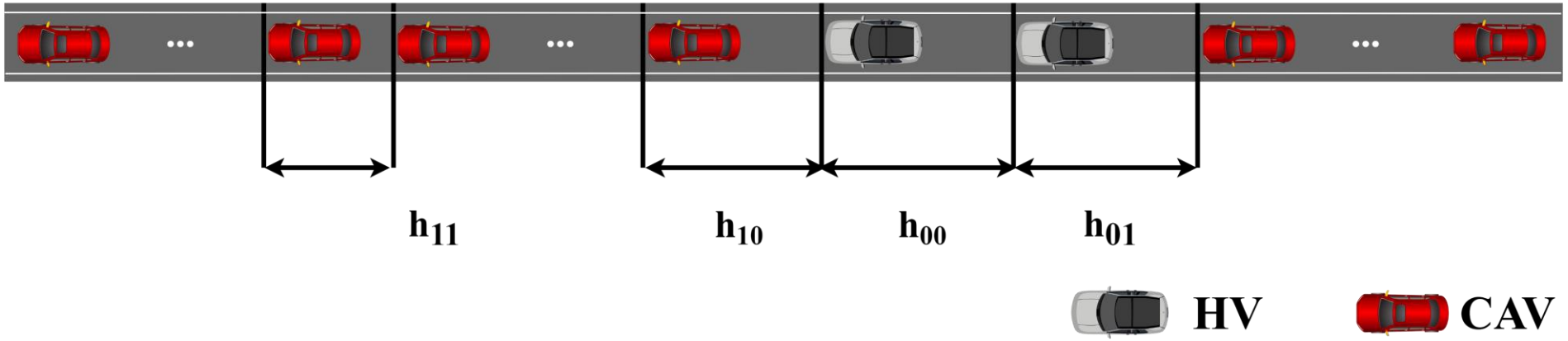
Human-driven Vehicle (HV)

Connected and Autonomous Vehicle (CAV)

Existing PIs	API
Derived from infinite vehicles	Suitable for any number of vehicles
May be out of bound for finite vehicles	Based on ACF, API is strictly ranging from -1 to 1
Unlimited range	
Restricted ability capturing CAV spatial distribution when the number of CAVs forming the platoons is fixed but the size of a platoon is random.	Rather than focusing on platoons, API is based on vehicle pairs which can effectively quantify the clustering strength as demonstrated before.

Modelling Traffic Capacity

- Traffic Flow Calculation
  - Reciprocal of Average headway (This Study)
  - Relationship among flow, density and speed, i.e., fundamental Diagram



Modeling Traffic Capacity

$$\hat{q} = \frac{1}{\bar{h}} = \frac{1}{(1-P_1)(\rho P_1 + 1 - P_1)h_{00} + P_1(1-P_1)(1-\rho)(h_{01}+h_{10}) + P_1[\rho(1-P_1)+P_1]h_{11}}$$

- $\bar{h}$: Average headway.
- h_{sr}: Headway between vehicle pairs.
- P_1: CAV Penetration rate.
- ρ: Proposed API to quantify the CAV clustering strength.

Impact of CAV Clustering Strength on Traffic Capacity

$$\hat{q} = \frac{1}{\bar{h}} = \frac{1}{(1-P_1)(\rho P_1 + 1 - P_1)h_{00} + P_1(1-P_1)(1-\rho)(h_{01}+h_{10}) + P_1[\rho(1-P_1)+P_1]h_{11}}$$

- $\bar{h}$: Average headway.
- h_{sr}: Headway between vehicle pairs.
- P_1: CAV Penetration rate.
- ρ: Proposed API to quantify the CAV clustering strength.

$$\frac{\partial \hat{q}}{\partial \rho} = \frac{P_1(1-P_1)(h_{01}+h_{10}-h_{00}-h_{11})}{\bar{h}^2}$$

1. Capacity is an increasing function of platooning intensity when $h_{01} + h_{10} > h_{00} + h_{11}$
2. Capacity is a decreasing function of platooning intensity when $h_{01} + h_{10} < h_{00} + h_{11}$

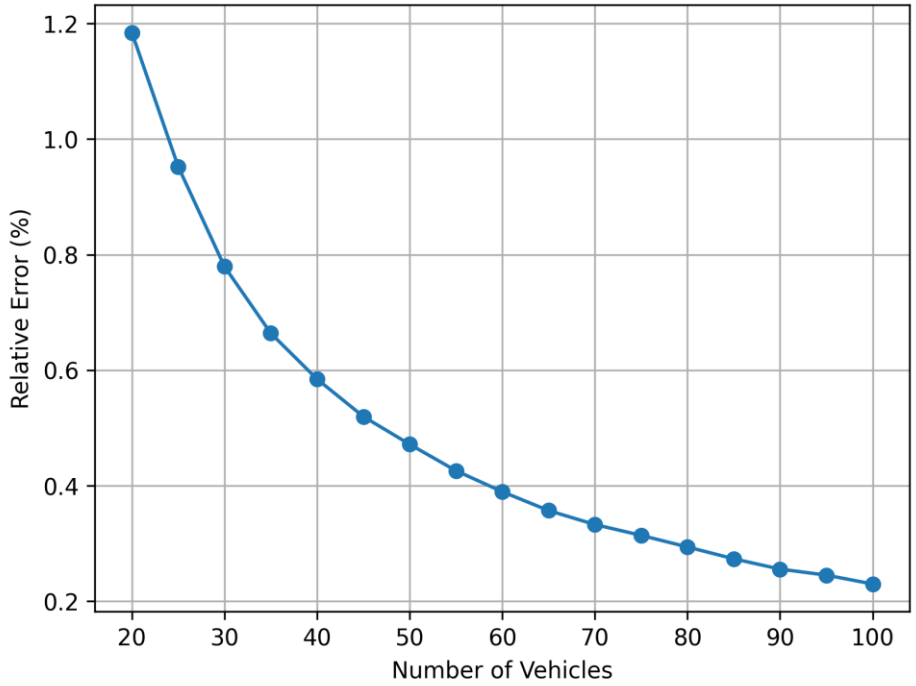
Accuracy of Capacity Approximation

Estimated Capacity: $\hat{q} = \frac{1}{\bar{h}} = \frac{1}{(1-P_1)(\rho P_1+1-P_1)h_{00}+P_1(1-P_1)(1-\rho)(h_{01}+h_{10})+P_1[\rho(1-P_1)+P_1]h_{11}}$

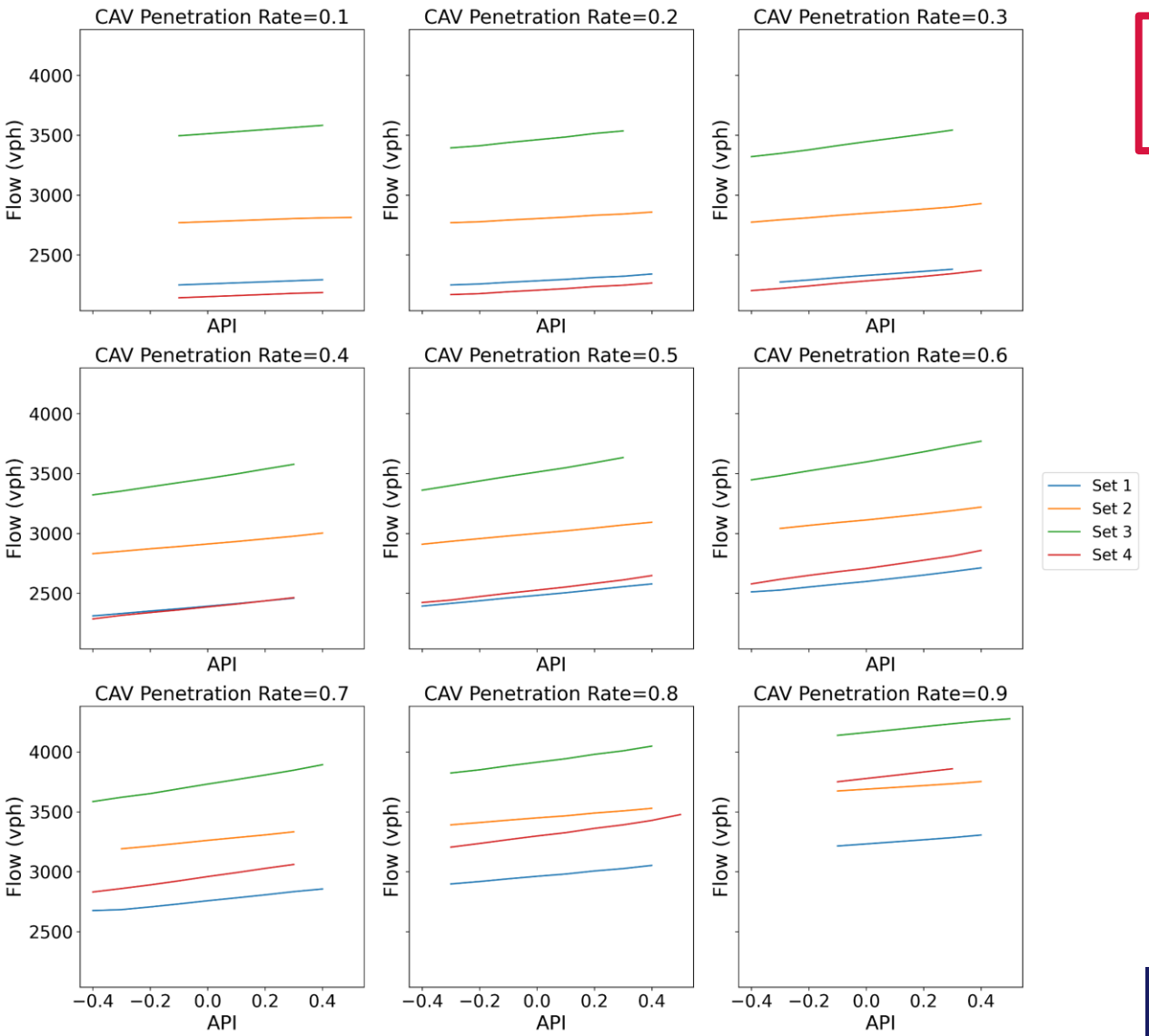
Theoretical Capacity : $q = \frac{1}{\bar{h}} = \frac{N-1}{N_{00}h_{00}+N_{01}h_{01}+N_{10}h_{10}+N_{11}h_{11}}$

Relative Error: $\varepsilon = \frac{|q-\hat{q}|}{q}$

Headways	Values
h_{00}	Uniform (0.8, 2.2)
h_{10}	Uniform (0.8, 2.2)
h_{01}	Uniform (0.7, 1.5)
h_{11}	Uniform (0.6, 1.1)



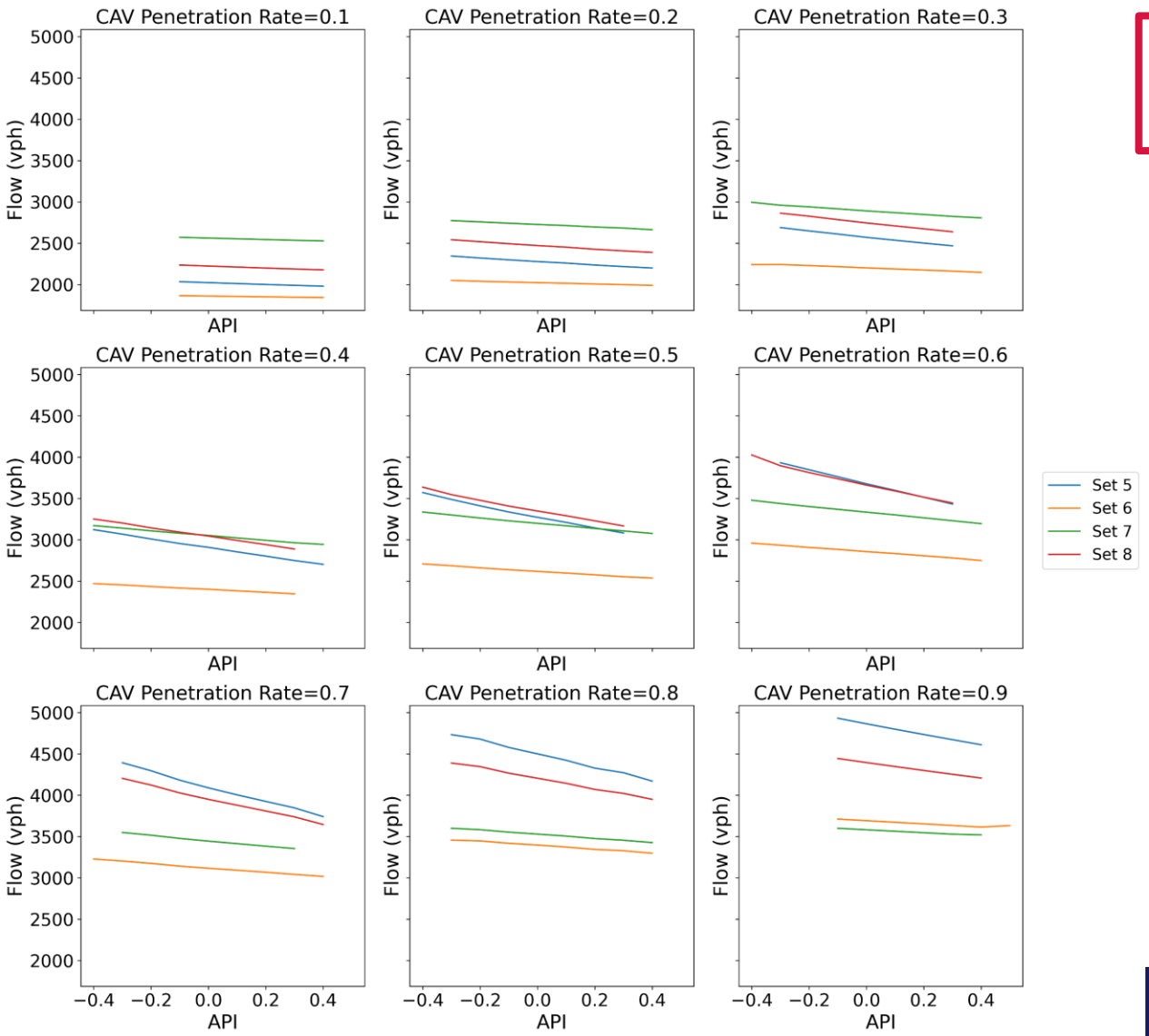
Verification of Proposition 1



Capacity is an increasing function of platooning intensity when $h_{01} + h_{10} > h_{00} + h_{11}$

Set	h_{00}	h_{10}	h_{01}	h_{11}
1	1.6	1.5	1.7	1.0
2	1.3	1.3	1.3	1.0
3	1.0	1.2	1.1	0.8
4	1.7	1.4	1.8	0.8

Verification of Proposition 2



Capacity is a decreasing function of platooning intensity when $h_{01} + h_{10} < h_{00} + h_{11}$

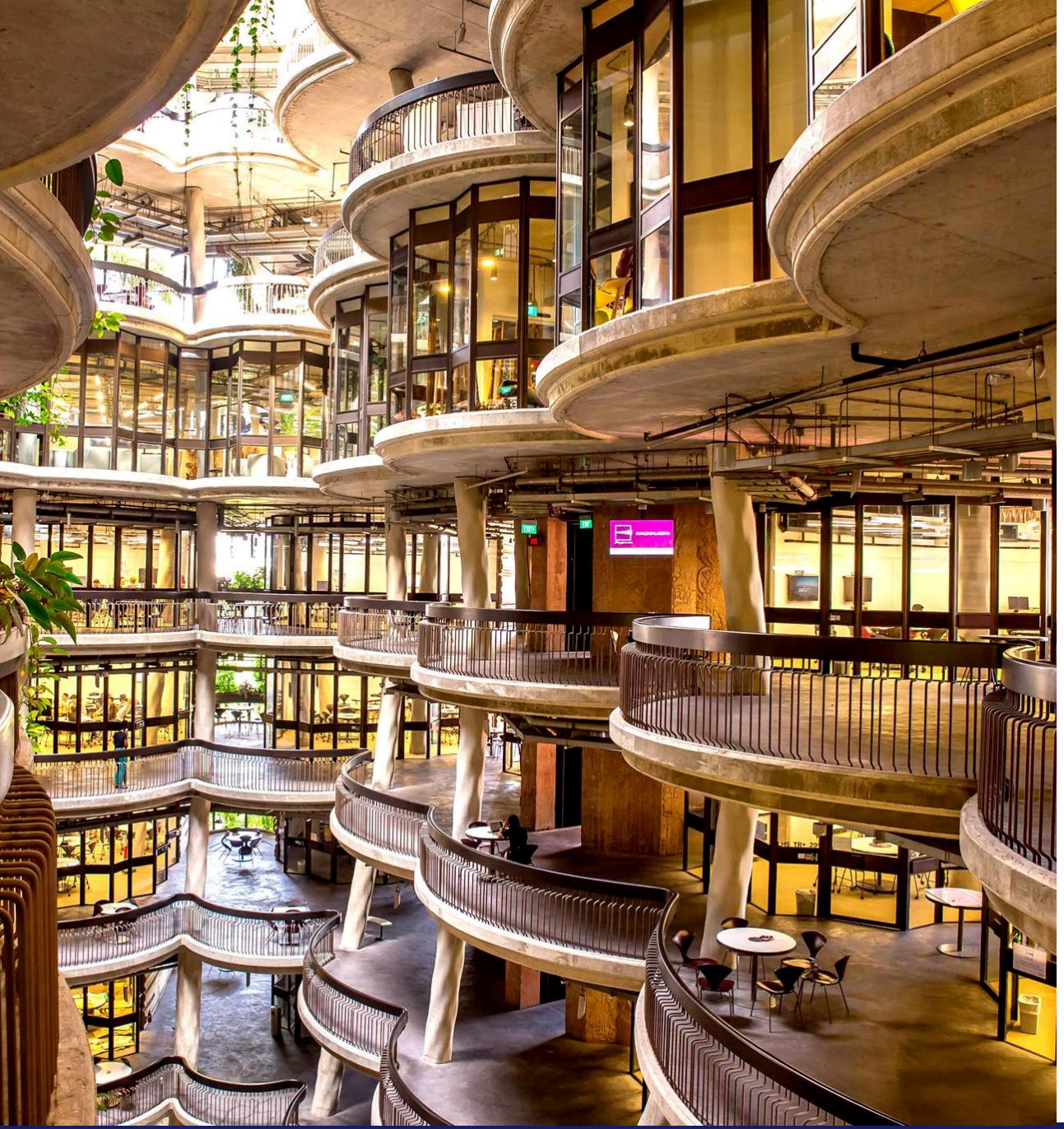
Set	h_{00}	h_{10}	h_{01}	h_{11}
5	2.0	0.8	0.9	0.7
6	2.1	1.1	1.4	0.9
7	1.5	1.1	0.9	1.0
8	1.8	0.7	1.0	0.8

Conclusions

1. The employment of auto-correlation function in mixed traffic, as the platooning intensity, can effectively quantify the degree of CAV clustering.
2. A framework is formulated to estimate the traffic capacity considering CAV penetration rate, platooning intensity, and headway, which has a small error with theoretical traffic capacity.
3. Marginal analysis shows that the mixed traffic capacity does not consistently exhibit an increasing or decreasing trend with respect to platooning intensity under the influence of headway stochasticity, which can be used as a supplement to the existing research.

Contributions

- Theoretical contributions:
  - A novel and superior definition of platooning intensity to quantify the clustering strength.
  - A framework to evaluate mixed traffic capacity is formulated.
- Application contributions:
  - Under the influence of headway, it is revealed that clustering more CAVs together may not necessarily enhance traffic capacity.
  - To improve traffic capacity, the sum of heterogeneous headways should be larger than the homogeneous headways.
  - This insight provides valuable guidance for mixed traffic management and headway design.



Thank you

Welcome the feedback to make us work better.

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