Platoon-Centric Framework for Mixed Traffic Capacity Modeling

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Transitioning into the Mixed Traffic Era

(a) Traditional traffic: Full HVs

- Human drivers
- No Driving Automation

Autonomous | *Driving*

(b) Mixed Traffic: HVs + AVs (Current)

- Intelligent driving system
- Automated driving capabilities

Cooperative | *Driving*

(c) Mixed Traffic: HVs + AVs + CAVs (Future)

- Vehicle-to-vehicle (V2V) communication
- **Platoon formation**

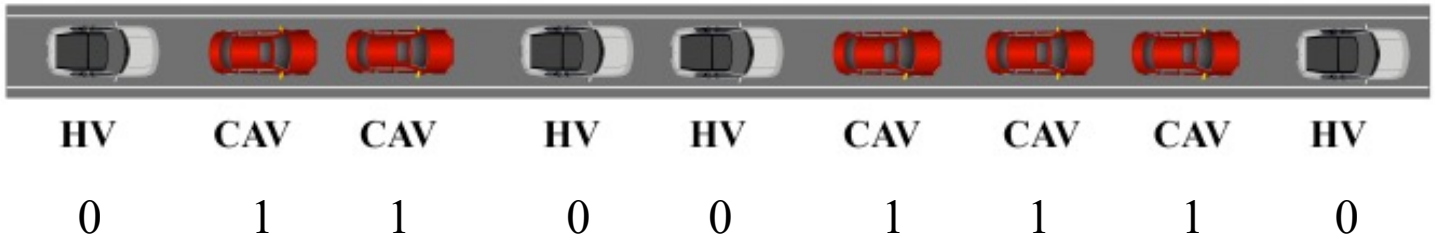
 Human-driven Vehicle (HV)

 Autonomous Vehicle (AV)

 Connected and Autonomous Vehicle (CAV)

Platoon-centric Framework

Vehicle-centric framework

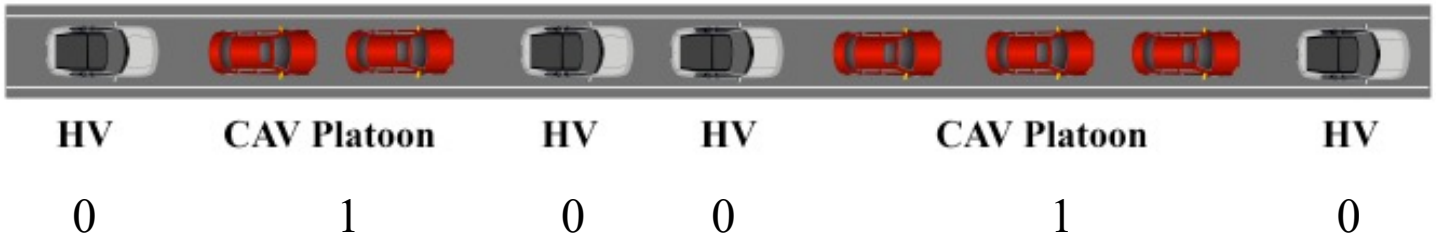


CAV characteristics:
- CAV penetration rate
- Clustering strength
- …

→

Traffic flow characteristics:
- Capacity
- Fundamental diagram
- …

Platoon-centric framework



Platoon characteristics:
- Maximum Platoon Size
- Platoon management
- …

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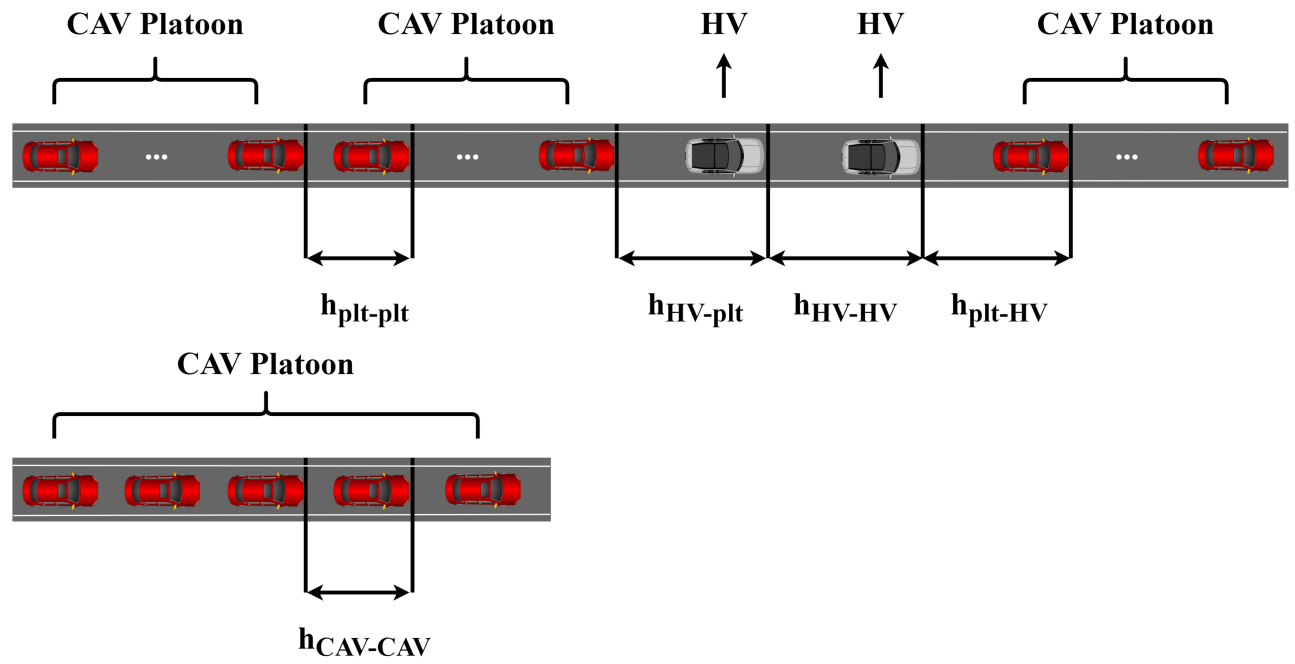
Traffic flow characteristics:
- Capacity
- Fundamental diagram
- …

Platoon-centric Capacity Modeling



Assumptions:

1. Only CAVs and HVs
2. Adjacent CAVs form platoons via V2V communication
3. HVs lack V2V communication and cannot form platoons.

- To compute the traffic capacity, these headways stand for the minimum headway on the road.

$$C_{mixed} = \frac{1}{\bar{h}}$$

$$\bar{h} = \sum_{pair \in \{plt-plt, HV-plt, \dots\}} (P_{pair} \cdot h_{pair})$$

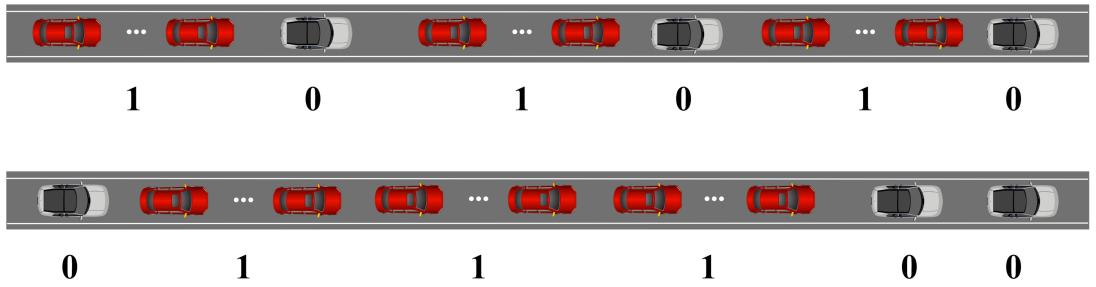
Average Inter-platoon Headway

1st order Autocorrelation Function (ACF) for a binary sequence – Spatial distribution of platoons and HVs

- **Calculation:** for a platoon sequence $M: \{\mathbb{x}_1, \mathbb{x}_2, \dots, \mathbb{x}_M\}$,

$$\gamma = \frac{\frac{1}{M-1}\sum_{i=1}^{M-1}(\mathbb{x}_i - \bar{\mathbb{x}})(\mathbb{x}_{i+1} - \bar{\mathbb{x}})}{\frac{1}{M}\sum_{i=1}^{M}(\mathbb{x}_i - \bar{\mathbb{x}})^2}$$

- **Demonstration:** clustered or scattered



MPS ⇒ 1

Platoon Sequence ⇒ Vehicle Sequence

Clustering strength of CAVs

- **Average Inter-platoon Headway:**

$$\bar{h}_{inter} = \mathbb{P}_0\left[\gamma(1-\mathbb{P}_0)+\mathbb{P}_0\right]h_{HV-HV} + \mathbb{P}_0(1-\mathbb{P}_0)(1-\gamma)h_{HV-plt}$$

$$+ (1-\mathbb{P}_0)\mathbb{P}_0(1-\gamma)h_{plt-HV} + (1-\mathbb{P}_0)(\gamma\mathbb{P}_0+1-\mathbb{P}_0)h_{plt-plt}$$

Average Headway

Number of inter-platoon headways

Number of inner-platoon headways

$$\bar{\mathbb{h}} = \frac{(M-1)\bar{h}_{inter} + (N-M)h_{CAV-CAV}}{N-1} \xrightarrow{N \to \infty} \bar{\mathbb{h}} \approx \frac{M}{N} \cdot \bar{h}_{inter} + \left(1 - \frac{M}{N}\right) \cdot h_{CAV-CAV}$$

Total number of headways

Mixed Traffic Capacity Formulation

- Mixed Traffic Capacity:

$$\hat{\mathbb{C}} \approx \frac{1}{\bar{\mathbb{h}}} = \frac{1}{\alpha h_{HV-HV} + \beta h_{plt-HV} + \beta h_{HV-plt} + \mu h_{plt-plt} + \delta h_{CAV-CAV}}$$

$$\alpha = (1 - P_{CAV})\left[\gamma(1 - \mathbb{P}_0) + \mathbb{P}_0\right]$$

$$\beta = (1 - P_{CAV})(1 - \mathbb{P}_0)(1 - \gamma)$$

$$\mu = \frac{1 - P_{CAV}}{\mathbb{P}_0}(1 - \mathbb{P}_0)(\gamma\mathbb{P}_0 + 1 - \mathbb{P}_0)$$

$$\delta = 1 - \frac{1 - P_{CAV}}{\mathbb{P}_0}$$

- P_{CAV}: CAV penetration rate
- L: Maximum Platoon Size (MPS)
- P_0: Probability of size-0 CAV Platoon

$$P_0 = \frac{P_{CAV}^L}{1 - P_{CAV}^L + P_{CAV}}$$

NGTS-4:

- Combination Theory
- Assumptions:
  - HVs and CAVs Randomly distributed on the lane
  - When the size of a platoon exceeds the MPS, the next CAV in line will serve as the leader of a new platoon.

Model Accuracy

Experiment:

- 10,000 random sequences for each N
- Vehicle sequence → Platoon sequence (MPS∈ [1,10])
- Compute P_{CAV} and ACF
- Theoretical capacity (benchmark):

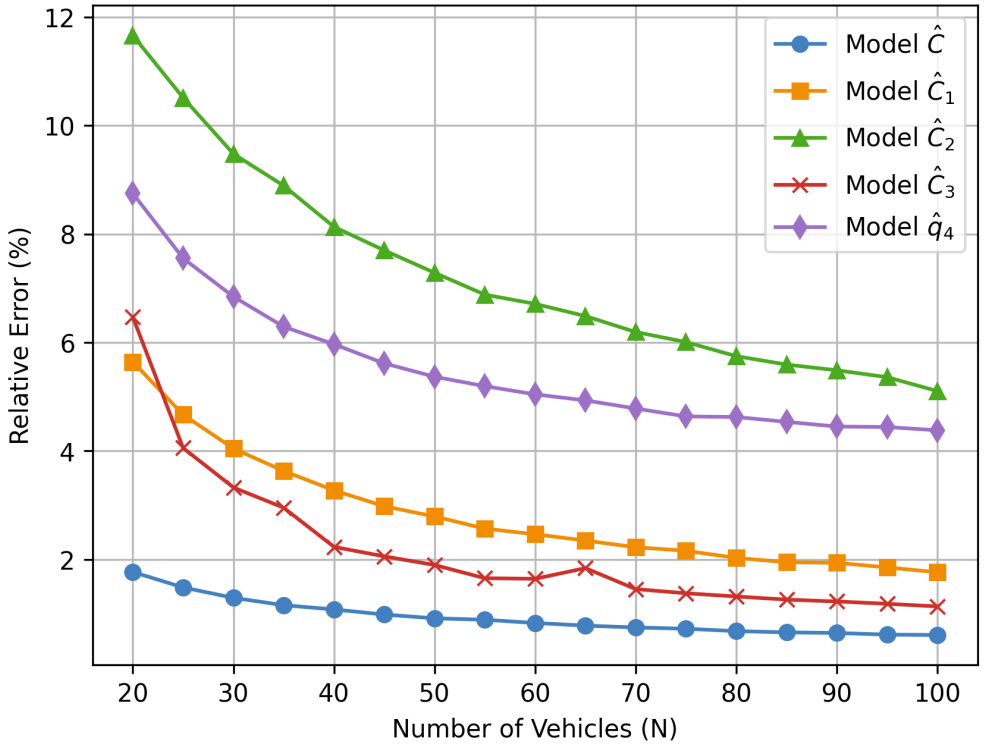
$$\bar{\mathbb{h}} = \frac{1}{N-1}(N_{HV-HV}h_{HV-HV} + N_{plt-HV}h_{plt-HV} + N_{HV-plt}h_{HV-plt} + N_{plt-plt}h_{plt-plt} + N_{CAV-CAV}h_{CAV-CAV})$$

$$\mathbb{C} = \frac{1}{\bar{\mathbb{h}}}$$

Headway	Values
h_{HV-HV}	Uniform (0.8, 2.2)
$h_{\text{plt}-HV}$	Uniform (0.8, 2.2)
h_{HV-plt}	Uniform (0.7, 1.5)
$h_{\text{plt}-plt}$	Uniform (0.7, 1.5)
$h_{CAV-CAV}$	Uniform (0.6, 1.1)

Findings:

- Average relative error between estimated and theoretical capacity $< 2\%$, when $N > 20$, lower than existing capacity models.



Marginal Analysis: Higher MPS → larger Capacity?

Higher MPS → higher capacity $\frac{\partial C}{\partial L} > 0$

Case 1: common sense

- $h_{HV-HV} + h_{plt-plt} \leq h_{plt-HV} + h_{HV-plt}$
- $h_{CAV-CAV} \leq h_{plt-plt}$

Case 2:

- $h_{HV-HV} + h_{plt-plt} > h_{plt-HV} + h_{HV-plt}$
- $h_{CAV-CAV} < h_{plt-plt}$
- $(1-\gamma)(h_{HV-HV} - h_{plt-HV} - h_{HV-plt} + h_{plt-plt}) \leq (1+P_{CAV})^2(h_{plt-plt} - h_{CAV-CAV})$

Higher MPS → lower capacity $\frac{\partial C}{\partial L} < 0$

Case 3:

- $h_{HV-HV} + h_{plt-plt} > h_{plt-HV} + h_{HV-plt}$
- $h_{CAV-CAV} > h_{plt-plt}$

Case 4:

- $h_{HV-HV} + h_{plt-plt} < h_{plt-HV} + h_{HV-plt}$
- $h_{CAV-CAV} > h_{plt-plt}$
- $(1-\gamma)(h_{HV-HV} - h_{plt-HV} - h_{HV-plt} + h_{plt-plt}) \geq (1+P_{CAV})^2(h_{plt-plt} - h_{CAV-CAV})$

Critical MPS: $L_{crit} = log_{P_{CAV}}(1 + \frac{P_{CAV}}{1-\sqrt{\frac{\zeta}{\eta}}})$ $\frac{\partial C}{\partial L} = 0$

Case 5: Capacity attains the maximum at L_{crit}:

- $h_{HV-HV} + h_{plt-plt} > h_{plt-HV} + h_{HV-plt}$
- $h_{CAV-CAV} < h_{plt-plt}$
- $(1-\gamma)\left(h_{HV-HV} - h_{plt-HV} - h_{HV-plt} + h_{plt-plt}\right) > (1+P_{CAV})^2(h_{plt-plt} - h_{CAV-CAV})$

Case 6: Capacity attains the minimum at L_{crit}

- $h_{HV-HV} + h_{plt-plt} < h_{plt-HV} + h_{HV-plt}$
- $h_{CAV-CAV} > h_{plt-plt}$
- $(1-\gamma)\left(h_{HV-HV} - h_{plt-HV} - h_{HV-plt} + h_{plt-plt}\right) < (1+P_{CAV})^2(h_{plt-plt} - h_{CAV-CAV})$

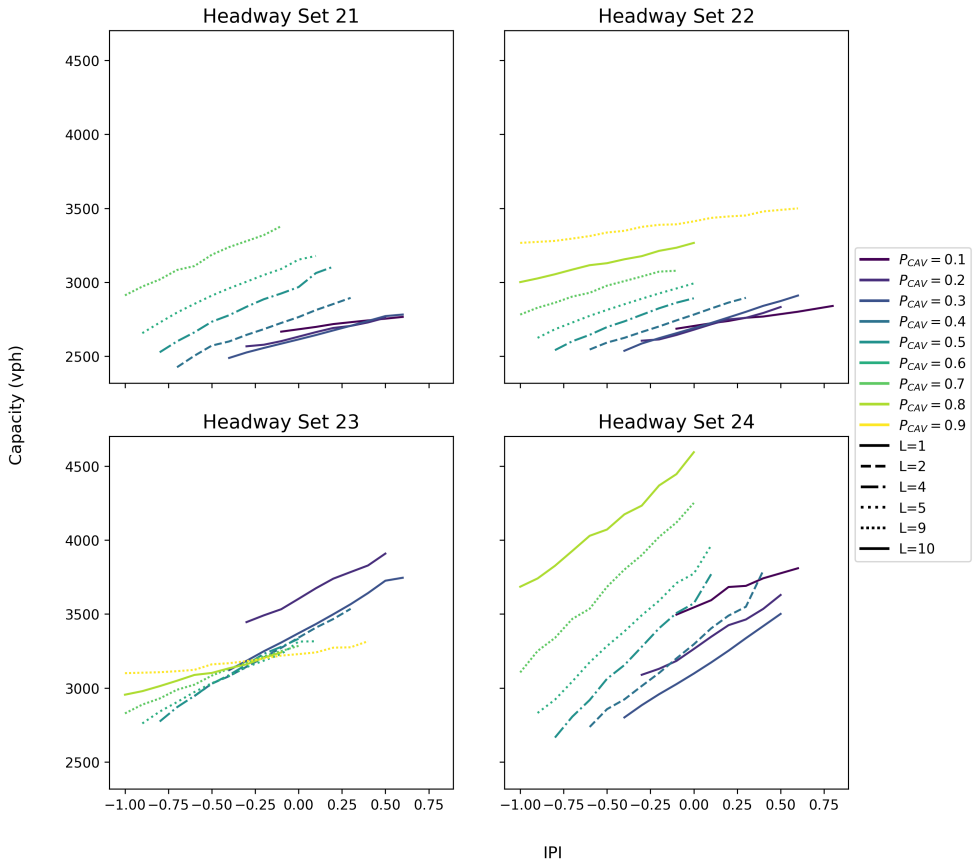
Marginal Analysis: Clustering more CAV→ larger Capacity?

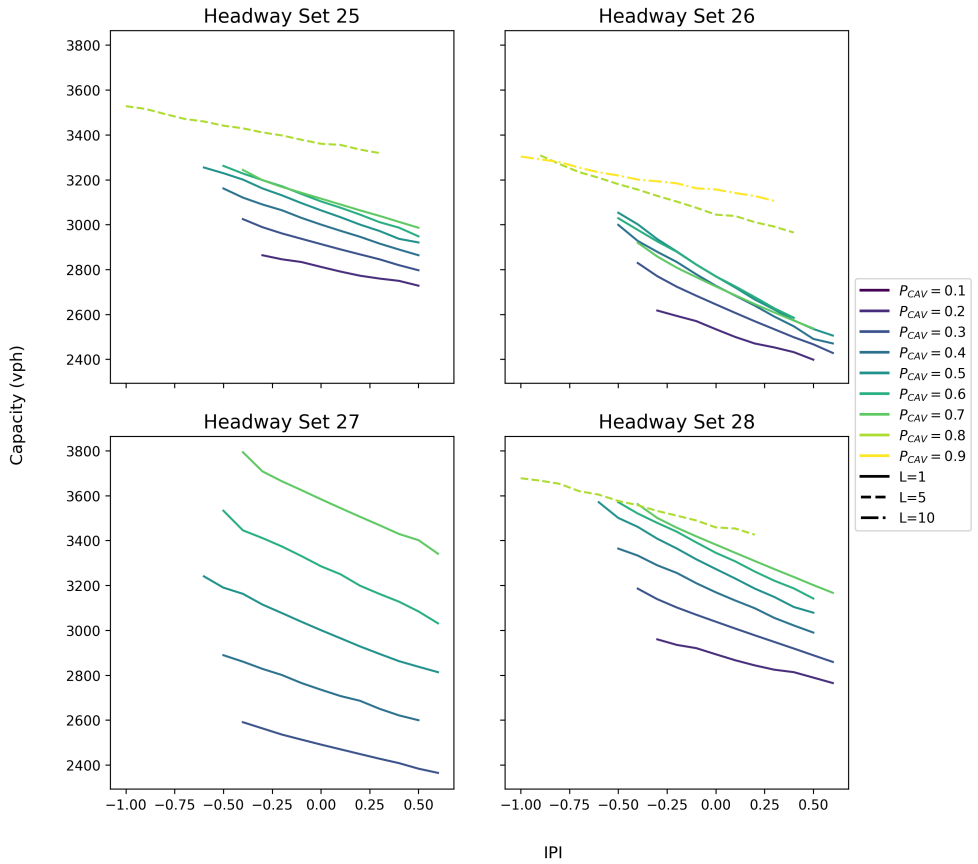
High clustering strength → higher capacity $\frac{\partial C}{\partial \gamma} > 0$

- $h_{HV-HV} + h_{plt-plt} < h_{plt-HV} + h_{HV-plt}$
- Homogeneous headway < heterogeneous headway

Higher clustering strength → lower capacity $\frac{\partial C}{\partial \gamma} < 0$

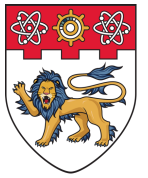
- $h_{HV-HV} + h_{plt-plt} > h_{plt-HV} + h_{HV-plt}$
- Homogeneous headway > heterogeneous headway





Key conclusions

1. The proposed capacity model demonstrates higher accuracy compared with other models, achieving a relative error of < 1% to the benchmark for mixed traffic scenarios involving more than 50 vehicles.
2. Traffic capacity does not uniformly increase with a larger Maximum Platoon Size (MPS). The impact heavily depends on the relative values of various headways.
3. Under specific headway conditions, an optimal MPS critical value can be mathematically determined to maximize the mixed traffic capacity.
4. The effect of clustering strength on capacity is also non-monotonic; it enhances capacity only when the sum of heterogeneous headways are larger than the sum of homogeneous ones.



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Thank you

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