Autocorrelation-based Platooning Intensity for Connected and Autonomous Vehicles in a Mixed Traffic Environment

NANYANG TECHNOLOGICAL UNIVERSITY SINGAPORE

Peilin Zhao Yiik Diew Wong Feng Zhu

School of Civil and Environmental Engineering, Nanyang Technological University, Singapore

TRB TRANSPORTATION RESEARCH BOARD

Background

- Mixed traffic composition: Connected and Autonomous Vehicles (CAVs) and Human-driven Vehicles (HVs).
- Pattern of CAV: moving as a platoon with the help of emerging technologies, e.g., Cooperative Adaptive Cruise Control (CACC) [5].
- CAV platoon: a clustering of consecutive CAVs in a coordinated manner.
- Platooning intensity: an indicator to describe CAV clustering strength.
- Higher platooning intensity: CAVs gather together in the mixed traffic.
- Lower platooning intensity: CAVs are scattered.

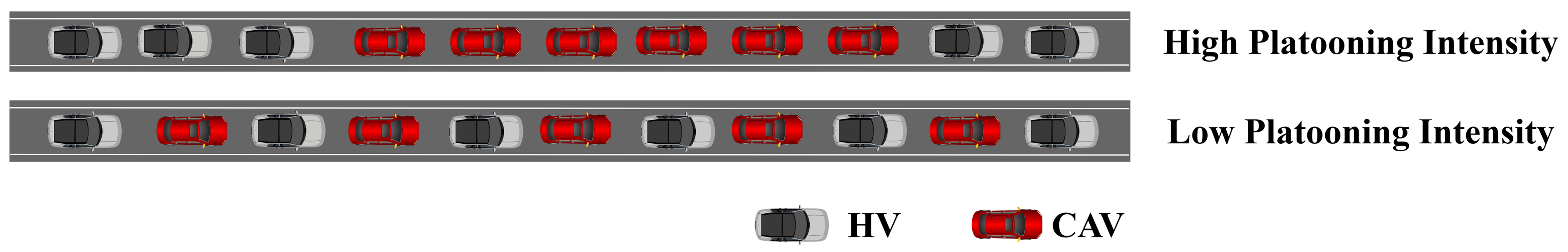

Figure 1. Illustration of different platooning intensity

Impact of platooning intensity on transportation:

- Higher platooning intensity creates opportunities for the entire CAV cluster to communicate and collaborate.
- CAV clustering can enhance highway capacity, energy efficiency, and traffic flow stability

Existing Research on Platooning Intensity

Table 1. Different definitions of Platooning Intensity

Abbr.	Features
MCPI[1]	Based on Markov Chain model Fits the scenario of infinite vehicles May go below its designated minimum for finite vehicles
HUPSPI[3], WPSPI[6]	Average CAV Platoon size Unlimited Range
HEPSPI[2], JPSPI[4]	Proportion of CAVs forming platoons among all CAVs Restricted applicability

Research Objectives

- A effective definition of platooning intensity to capture the CAV clustering strength.
- Analyze the influence of the proposed platooning intensity on mixed traffic flow.
- Compare the performance of the proposed platooning intensity with the existing ones.

Autocorrelation-based Platooning Intensity (API)

- Autocorrelation Function (ACF) measures the relationship between a variable's current value and its lagged values.
- API captures the relationship between the type of the subject vehicle and the type of its following vehicle

Suppose that there is a stream of N vehicles, indexed as $\{1, 2, \dots, N\}$. Let $x_i \in \{0, 1\}$ denote the type of the i^{th} vehicle in the stream, where 0 denotes HV and 1 denotes CAV. Then, the proposed autocorrelation-based platooning intensity (API), ρ, is formulated as follows.

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

API can effectively capture the degree of CAV platoon clustering

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

P_0 is the penetration rate of HV and P_1 is the penetration rate of CAV. N_{sr} is the number of vehicle pairs, $sr \in \{00, 01, 10, 11\}$, s refers to the leading car type, and r indicates the following car type.

- 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 in mixed traffic tend to gather together.

Simulation Settings

Car-following Models

- Intelligent Driver Model (IDM)
- Adaptive Cruise Control Model (ACC)
- Cooperative Adaptive Cruise Control Model (CACC)

Table 2. The application of car-following models

Car Following Scenarios	Car Following Model	Desired Headway
HV followed by HV	IDM	1.6 s
HV followed by CAV	ACC	1.0 s
CAV followed by HV	IDM	1.6 s
CAV followed by CAV	CACC	0.6 s

Simulated Environment

- Ring road test field with a perimeter of 300 meters.
- 10 vehicles are placed uniformly on this road.
- The type of each vehicle is set to be an HV or CAV randomly.
- CAV penetration rate and API of this 10-car sequence are obtained.

Mixed Traffic Emulation

Vehicles are placed on the ring road at a given initial speed, then they will travel based on their specific car-following model and finally reach an equilibrium speed. Mixed traffic flow in this equilibrium state, denoted as q_e, is obtained.

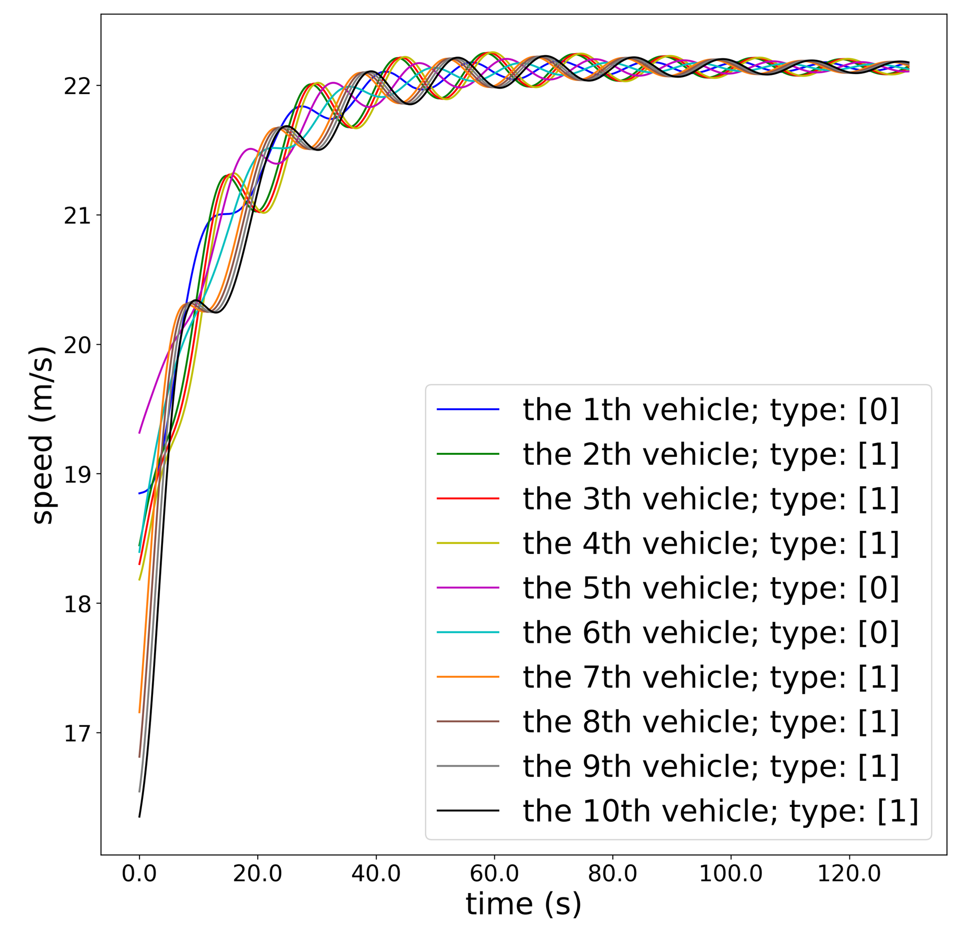

Figure 2. Time-speed diagram

Results and Discussion

Effect of API

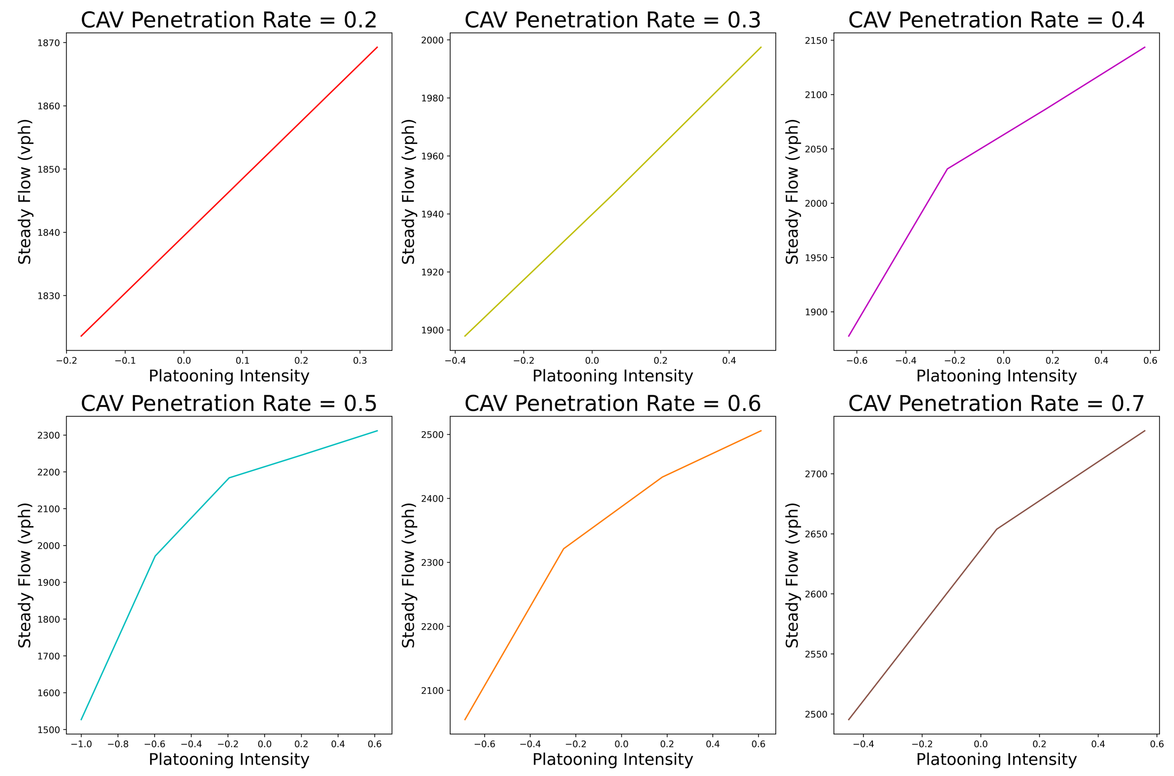

Figure 3. API vs. steady flow

Comparison Analysis

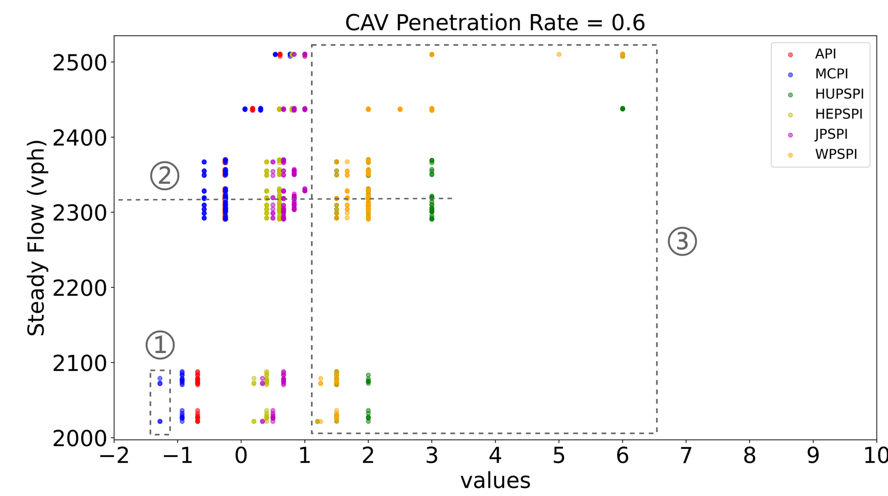

Figure 4. Comparison Analysis

- MCPI [1] may be below the designated minimum value, i.e., -1.
- A specific value of steady flow may correspond to multiple values of MCPI [1], HEPSPI [2], and JPSPI [4].
- HUPSPI [3] and WPSPI [6] do not have an upper limit.
- API, ranging from -1 to 1 strictly, corresponds well to the mixed traffic flow, indicating a higher degree of CAV clustering in alignment with a larger mixed traffic flow.

Conclusion

- A novel calculation method of platooning intensity is proposed based on the sequence autocorrelation, which can effectively capture the level of CAV clustering in the mixed traffic environment.
- Mixed traffic flow rises with the increase of API, demonstrating that a high level of CAV clustering improves the mixed traffic efficiency.
- API can be used as a basic variable in other mixed traffic analyses, e.g., fundamental diagram.

References

[1] Amir Ghiasi, Omar Hussain, Zhen Sean Qian, and Xiaopeng Li. A mixed traffic capacity analysis and lane management model for connected automated vehicles: A markov chain method. *Transportation Research Part B: Methodological*, 106:266–292, 2017.

[2] Shanglu He, Fan Ding, Chaoru Lu, and Yong Qi. Impact of connected and autonomous vehicle dedicated lane on the freeway traffic efficiency. *European Transport Research Review*, 14(1):12, 2022.

[3] Guojing Hu, Feng Wang, Weike Lu, Tor A Kwembe, and Robert W Whalin. Cooperative bypassing algorithm for connected and autonomous vehicles in mixed traffic. *IET Intelligent Transport Systems*, 14(8):915–923, 2020.

[4] Yangsheng Jiang, Fangyi Zhu, Zhihong Yao, Qiufan Gu, Bin Ran, et al. Platoon intensity of connected automated vehicles: Definition, formulas, examples, and applications. *Journal of Advanced Transportation*, 2023, 2023.

[5] Vicente Milanés and Steven E Shladover. Modeling cooperative and autonomous adaptive cruise control dynamic responses using experimental data. *Transportation Research Part C: Emerging Technologies*, 48:285–300, 2014.

[6] Robert W Whalin, Guojing Hu, et al. Macroscopic fundamental diagram approach to traffic flow with autonomous/connected vehicles. Technical report, Southeastern Transportation Research, Innovation, Development and Education, 2020.