- **Goal:** Model and simulate car-following behaviors with heterogeneity and stochasticity.
- **Challenge:** Traditional models learn a *one-to-one mapping*

$$f_{\mathrm{CF}} : (s_t, \Delta v_t, v_t) \mapsto a_t$$ (deterministic) ✗

but real drivers induce a *one-to-many mapping* with uncertainty

$$f_{\mathrm{CF}} : (s_t, \Delta v_t, v_t) \mapsto \{a_t^{(1)}, a_t^{(2)}, \dots\}$$ (stochastic) ✓

- **Solutions:**

1 Explicit Uncertainty Modeling (continuous variability)

$$a_t \approx f_{\mathrm{CF}}(\boldsymbol{x}_t; \boldsymbol{\theta}) + \delta_t,$$ (Zhang and Sun 2024, Zhang et al. 2024, Zhang et al. 2025a)

Table 1: Modeling of temporal correlations in my previous work.

Reference	$f_{\mathrm{CF}}(\boldsymbol{x}_t; \boldsymbol{\theta})$	δ_t
Zhang and Sun (2024)	IDM	Gaussian processes (GPs)
Zhang et al. (2024)	IDM	Autoregressive (AR) processes
Zhang et al. (2025a)	NN	nonstationary GPs

[Chengyuan Zhang and Lijun Sun. (2024). Bayesian calibration of the intelligent driver model. *IEEE Transactions on Intelligent Transportation Systems*.]
[Chengyuan Zhang, Wenshuo Wang, and Lijun Sun. Calibrating car-following models via Bayesian dynamic regression. (ISTTT25 Special Issue) Transportation Research Part C: Emerging Technologies 168 (2024): 104719.]
[Chengyuan Zhang, Zhengbing He, Cathy Wu, and Lijun Sun. (2025a). When Context Is Not Enough: Modeling Unexplained Variability in Car-Following Behavior. arXiv preprint arXiv:2507.07012 (*under review*).]

2 Latent Variable Modeling (discrete variability)

$$a_t \approx f_{\mathrm{CF}}(\boldsymbol{x}_t; \boldsymbol{\theta}_{z_t}),\ z_t \sim \begin{cases} \text{Gaussian Mixture} & \text{(i.i.d.)} \\ \text{Markov Chain} & \text{(temporal dependence)} \end{cases}$$

(Chen et al. 2023, Zhang et al. 2024) (Zhang et al. 2025b)

[Xiaoxu Chen, Chengyuan Zhang, Zhanhong Cheng, Yuang Hou, and Lijun Sun. A bayesian gaussian mixture model for probabilistic modeling of car-following behaviors. IEEE Transactions on Intelligent Transportation Systems 25, no. 6 (2023): 5880-5891.]
[Chengyuan Zhang, Kehua Chen, Meixin Zhu, Hai Yang, and Lijun Sun. Learning car-following behaviors using bayesian matrix normal mixture regression. In 2024 IEEE Intelligent Vehicles Symposium (IV), pp. 608-613. IEEE, 2024.]
[Chengyuan Zhang, Cathy Wu, and Lijun Sun. (2025b). Markov Regime-Switching Intelligent Driver Model for Interpretable Car-Following Behavior. arXiv preprint arXiv:2506.14762 (2025b). (*under review*) .]

→ stochastic, interpretable car-following simulators

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