From Micro Interactions to Traffic Flow: Stochastic Driver Models for Realistic Traffic Simulation

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- **Goal:** Model and simulate human driving 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 (Heterogeneity as Identity)

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

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

Reference	$f_{\mathrm{CF}}(\boldsymbol{x}_t; \boldsymbol{\theta}_d)$	δ_t	Inference Method
Zhang and Sun (2024)	IDM	Gaussian processes (GPs)	Full Bayesian (MCMC)
Zhang et al. (2024)	IDM	Autoregressive (AR) processes	Full Bayesian (MCMC)
Zhang et al. (2025a)	NN	Nonstationary GPs	Point estimate (gradient descent)
Kong et al. (2026)	IDM	GPs	Likelihood-free (SBI)

1. Chengyuan Zhang and Lijun Sun. (2024). Bayesian calibration of the intelligent driver model. *IEEE Transactions on Intelligent Transportation Systems*.
2. 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.
3. 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 *(Accepted at ISTTT26 and TR Part B)*.
4. Menglin Kong, Chengyuan Zhang, and Lijun Sun. (2026). Active Simulation-Based Calibration of Car-Following Models via Amortized Bayesian Inference. *(under review)*

2 Latent Variable Modeling (Heterogeneity as Composition)

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

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

(Zhang et al. 2025b)

5. 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.
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7. 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.
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→ stochastic, interpretable human-like simulators

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