Calibrating Car-Following Models using SUMO-in-the-loop and Vehicle Trajectories from Roadside Radar

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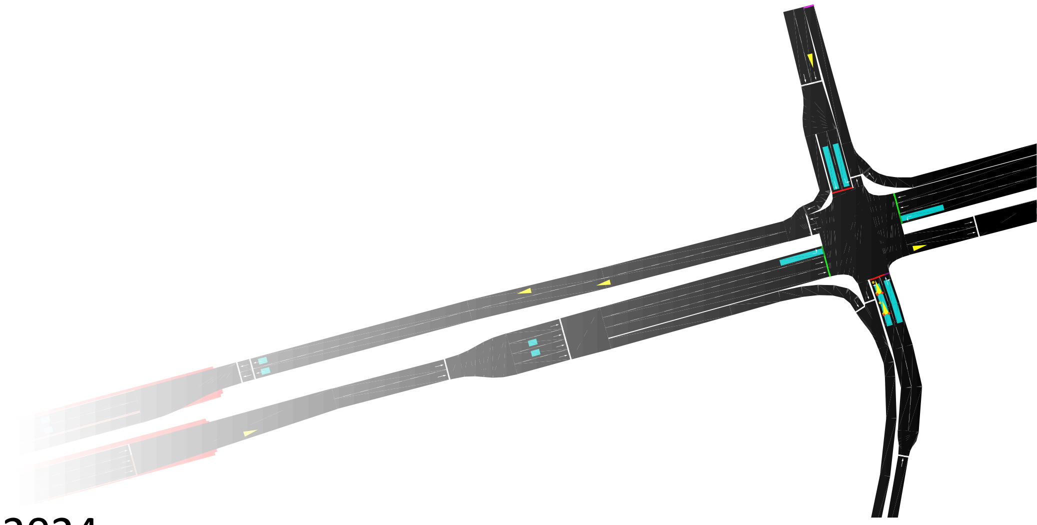
SUMO User Conference 2024

Can we design a pipeline to calibrate SUMO car-following models using roadside radar?



Considered CF-Models

Intelligent Driver Model

- a = maximum acceleration $[m/s^2]$
- b = maximum deceleration $[m/s^2]$
- τ = time headway $[s]$
- v_0 = desired speed $[m/s]$

$$\dot{v}_f(v_f, s, \Delta v) = a\left[1 - \left(\frac{v_f}{v_0}\right)^{\beta} - \left(\frac{s^*(v_f, \Delta v)}{s}\right)^2\right]$$

$$s^*(v_f, \Delta v) = s_0 + \tau + \frac{v_f \Delta v}{2\sqrt{ab}}$$

Krauss Driver Model

- a = maximum acceleration $[m/s^2]$
- b = maximum deceleration $[m/s^2]$
- τ = time headway $[s]$
- v_0 = desired speed $[m/s]$

$$v_{\text{des}}(t) = \min\left[v_{\text{safe}}(t), v_f(t) + a, v_0\right]$$

$$v_{\text{safe}}(t) = v_l + \frac{g(t) - v_l(t) \cdot \tau}{\frac{v_f}{b \cdot v_f} + \tau}$$

W99 Model

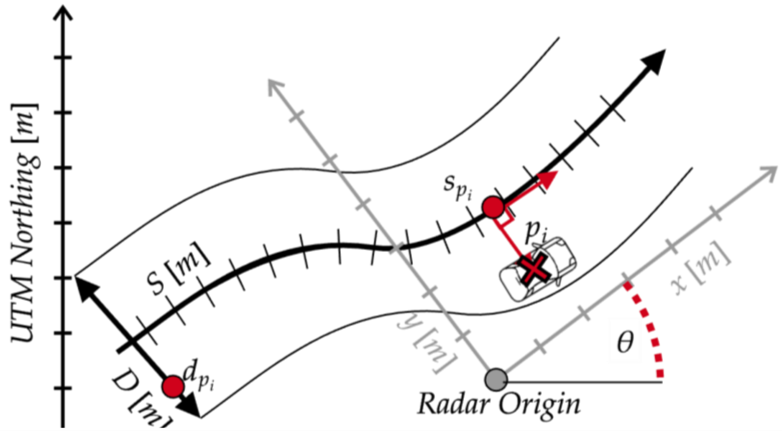
Car-following Models and Calibration Challenges

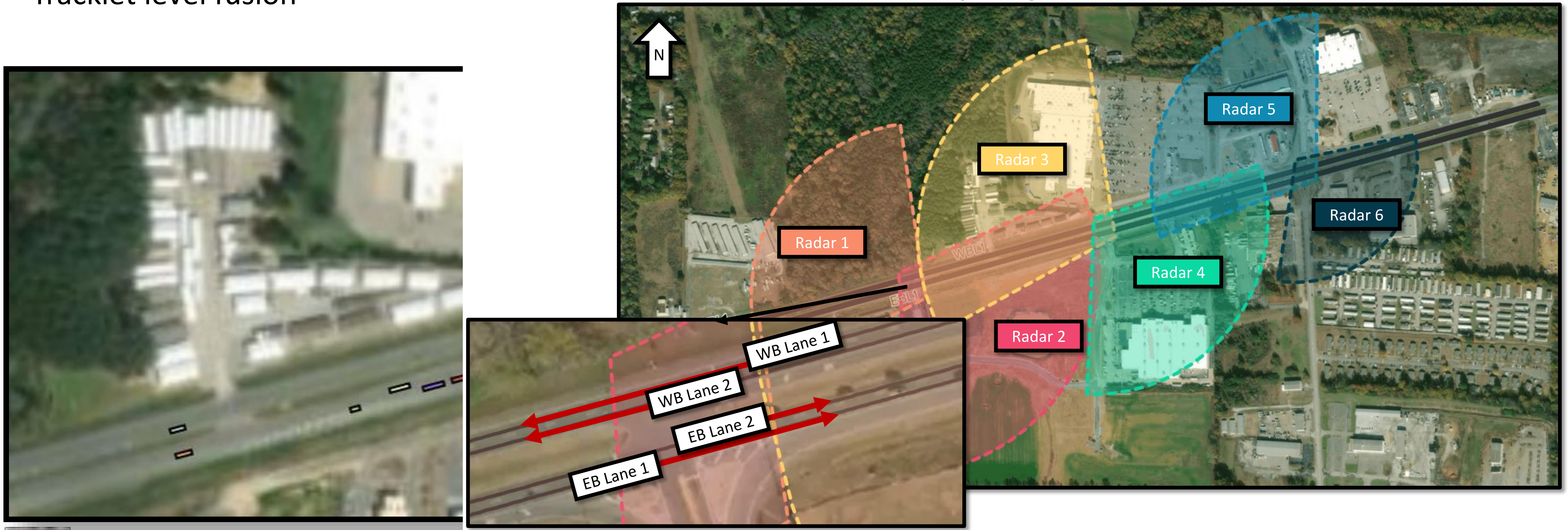
- Car-following models (CF-models) are **essential components** of traffic micro-simulation
- Acceleration, deceleration, and speed are **highly influential in vehicle-level emissions and fuel consumption**[1]
- Calibration is **required** for **model reliability**
- Calibration based on aggregate measures (travel time, queue length, etc..) has a **non-unique solution for CF parameters**[2]
- Trajectory-based calibration requires **detailed trajectories** (NGSIM, etc.) and is **computationally expensive**
- But**, shown to be necessary** [3]

1. Jie, Li, et al. "Calibration of a microscopic simulation model for emission calculation." *Transportation Research Part C: Emerging Technologies* 31 (2013): 172-184.
2. Asamer, Johannes, Henk J. van Zuylen, and Bernhard Heilmann. "Calibrating VISSIM to adverse weather conditions." *2nd International Conference on Models and Technologies for Intelligent Transportation Systems*. 2011.
3. Schrader, M., Al Abdraboh, M., & Bittle, J. (2023, June). Comparing Measured Driver Behavior Distributions to Results from Car-Following Models using SUMO and Real-World Vehicle Trajectories from Radar: SUMO Default vs. Radar-Measured CF model Parameters. In *SUMO Conference Proceedings* (Vol. 4, pp. 41-54).

Radar Data Fusion

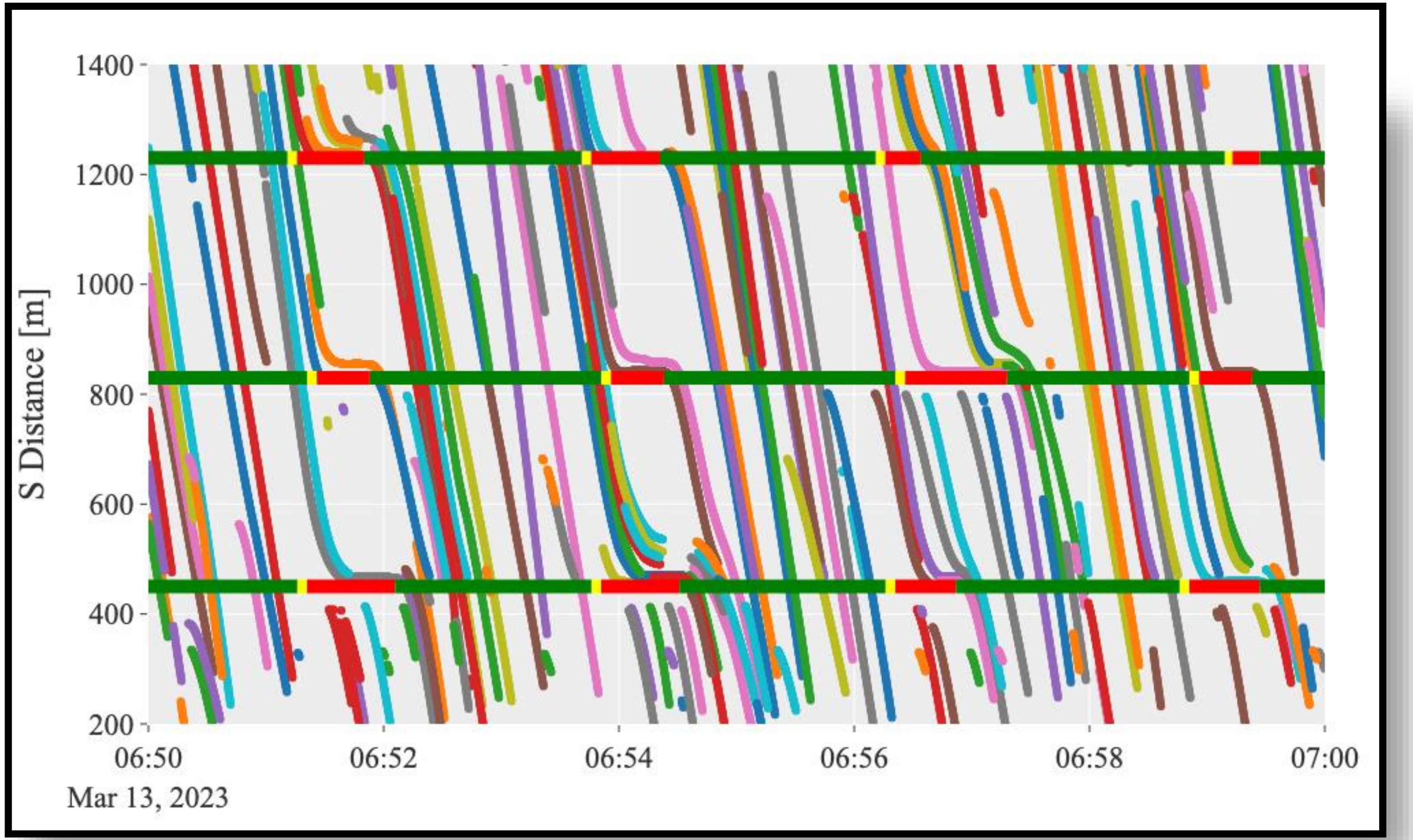
- 6 radars, partially overlapping FOVs
- Vehicle position & velocity recorded every 100ms
- IMM Filtering/Fusion occur in **Frenet Frame** for road-context aware predictions
- Tracklet level fusion





Roadside Radar Fusion, Cont.

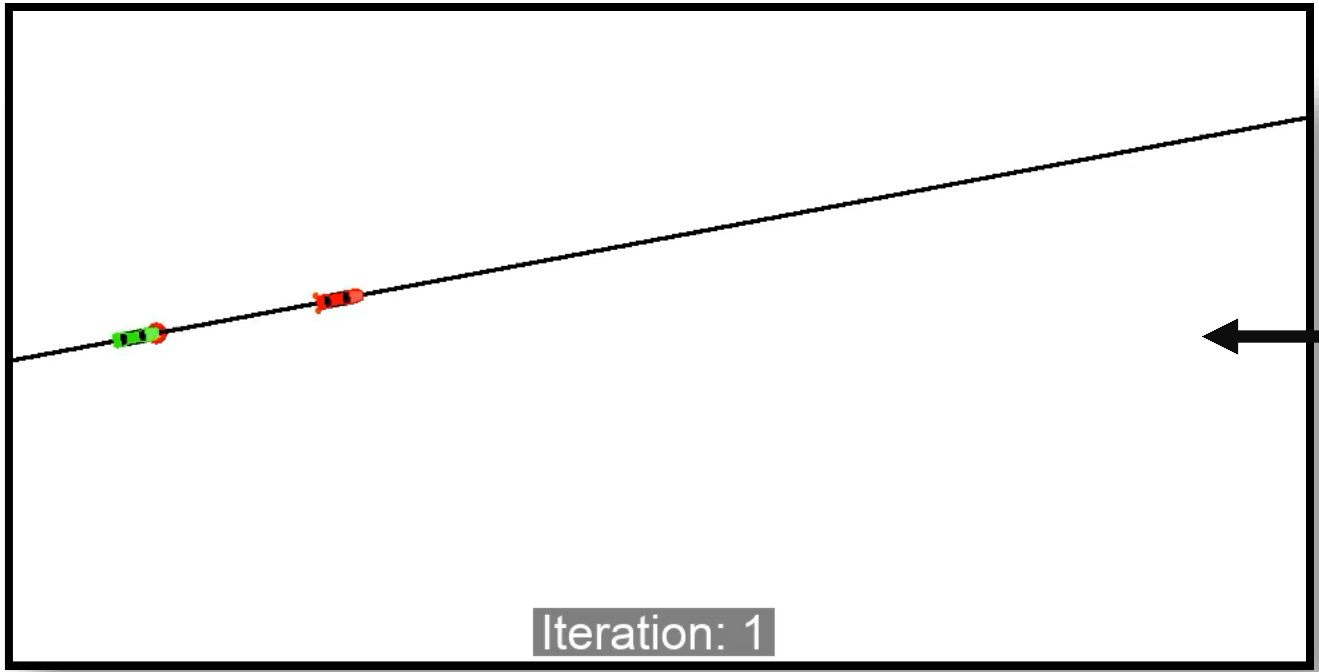
- 26 hour period
- **70,000+ Trajectories**
    - Contain numerous scenarios
        - Lane-change events, signal queuing
    - Open-sourcing the dataset w/ paper
- Calibration-worthy trajectories identified
    - Trajectories should be composed of **many regimes** [1]
    - **2000+ leader-follower pairs**

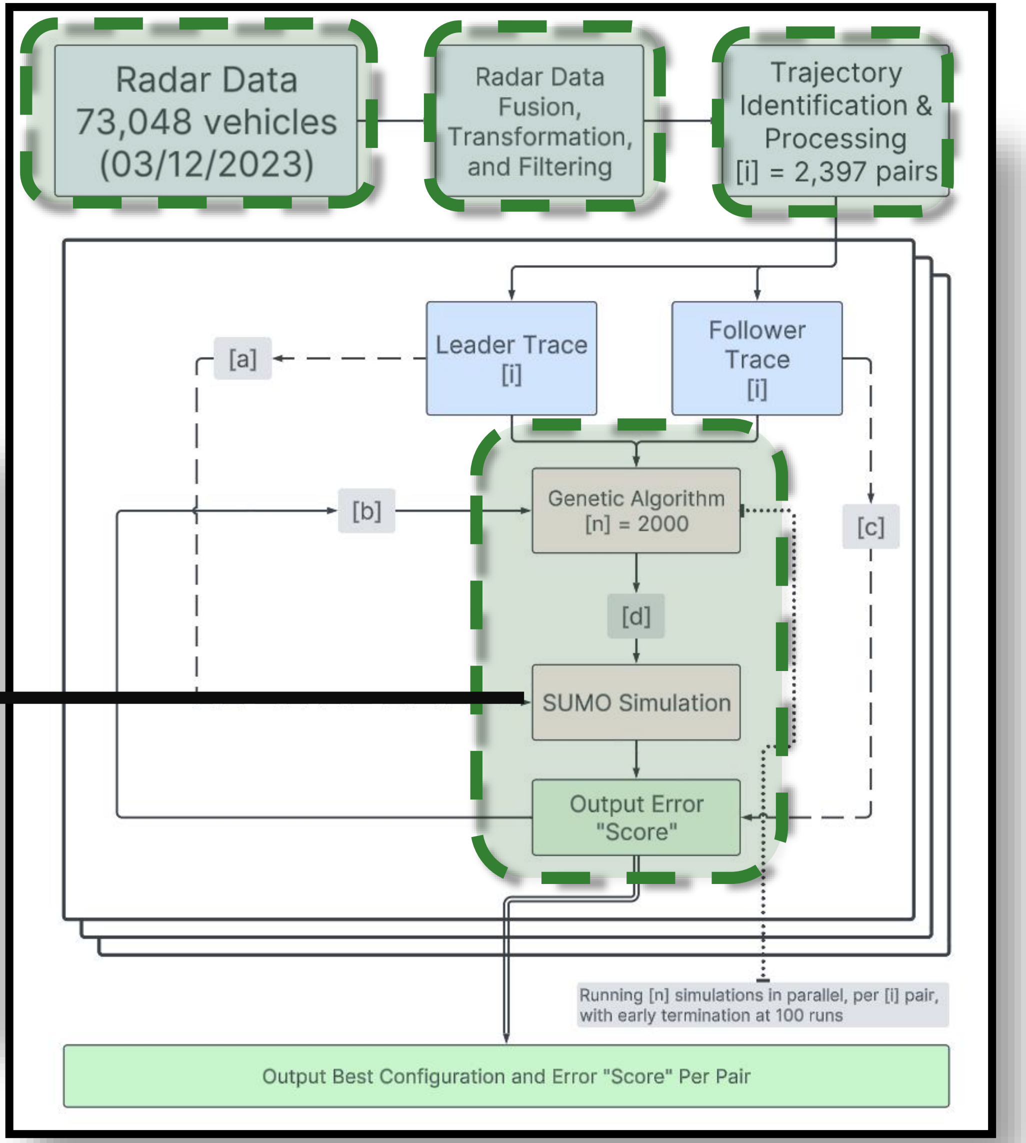


1. Sharma, A., Zheng, Z., & Bhaskar, A. (2019). Is more always better? The impact of vehicular trajectory completeness on car-following model calibration and validation. *Transportation research part B: methodological*, *120*, 49-75

Trajectory Calibration

- Calibration handled via Facebook's Nevergrad Meta-optimizer
  - Each trajectory takes ~40s
- Parallelized at trajectory level using Ray
- NRMSE(s,v,**a?**) [1]

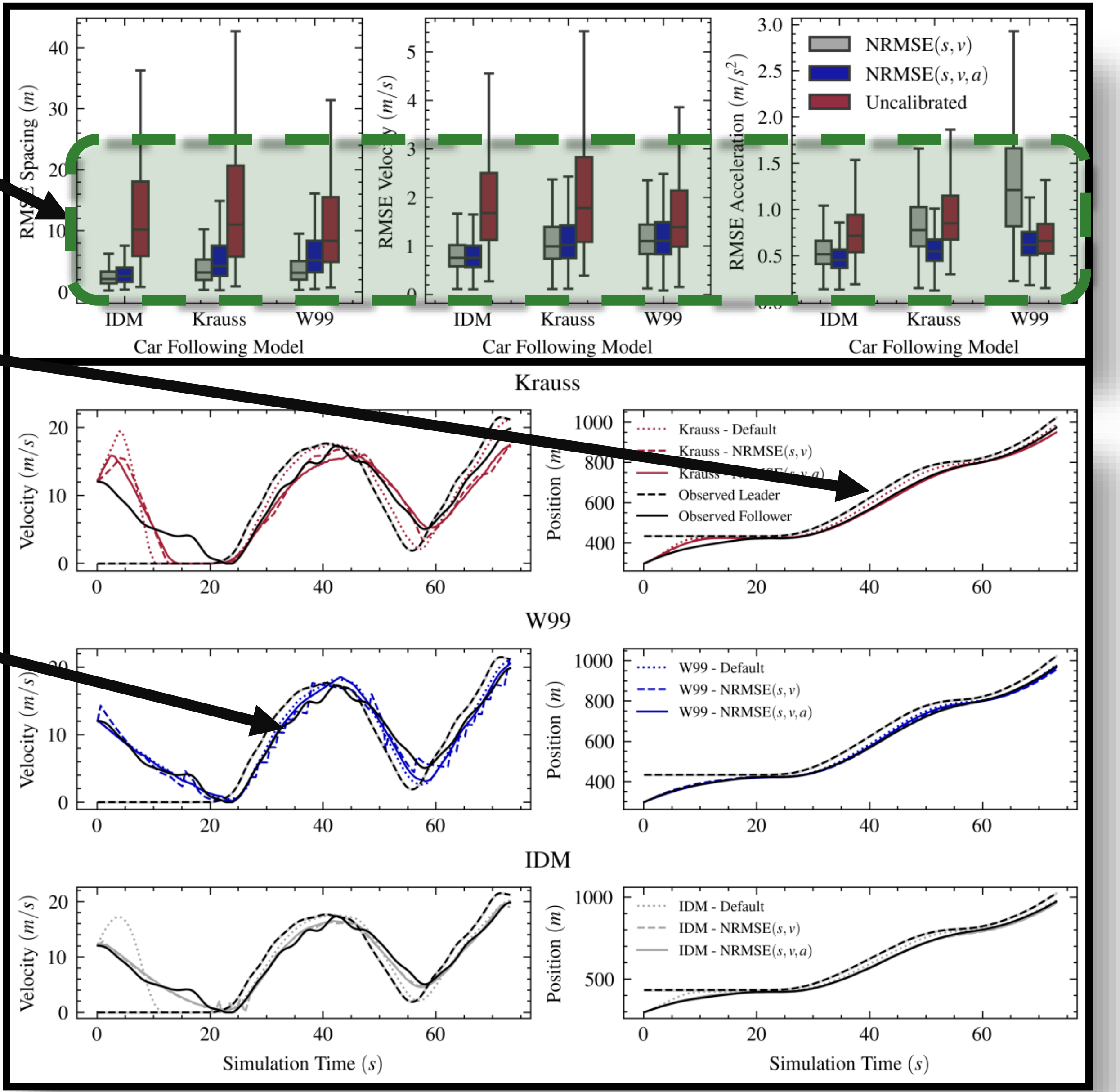




1. Punzo, V., Zheng, Z., & Montanino, M. (2021). About calibration of car-following dynamics of automated and human-driven vehicles: Methodology, guidelines and codes. *Transportation Research Part C: Emerging Technologies*, *128*, 103165

Trajectory Calibration Results

- Calibration significantly reduces error
- IDM model achieves the best performance
  - Best-fit model **for 81% of vehicles**
- Default IDM and Krauss models favor **shorter time headways**
- W99 performs the best of the default models
  - Calibration **without *a*** leads to **jerky acceleration**
- Trade-off between spacing accuracy and acceleration



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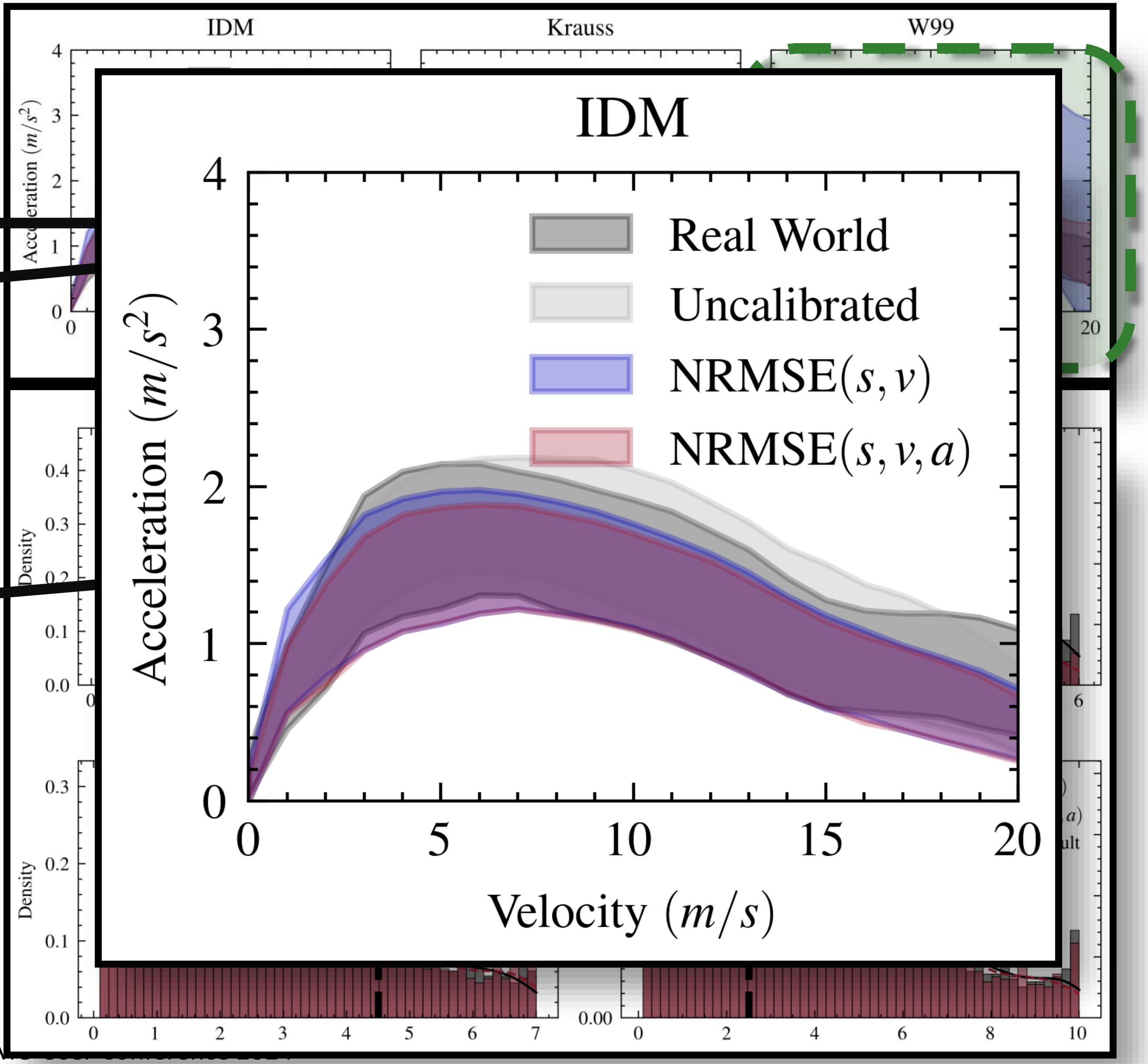
Trajectory Calibration Results, cont.

Implications on Fuel Consumption

- Calibration improves car-following models' energy prediction
  - **Default models over-predict**
- W99 captures speed-acceleration relationship **when calibrated**

Calibrated Parameters

- All calibrated parameters in paper
- IDM parameters show consistency across calibration metrics
- Parameters vs. SUMO default
  - **Accel matches well**
  - Tau / minGap differ slightly
  - Decel quite different, but Krauss aligns
- actionStep – (0.2 – 0.4s) across models
- Calibrated included speedFactor – **not smart**!



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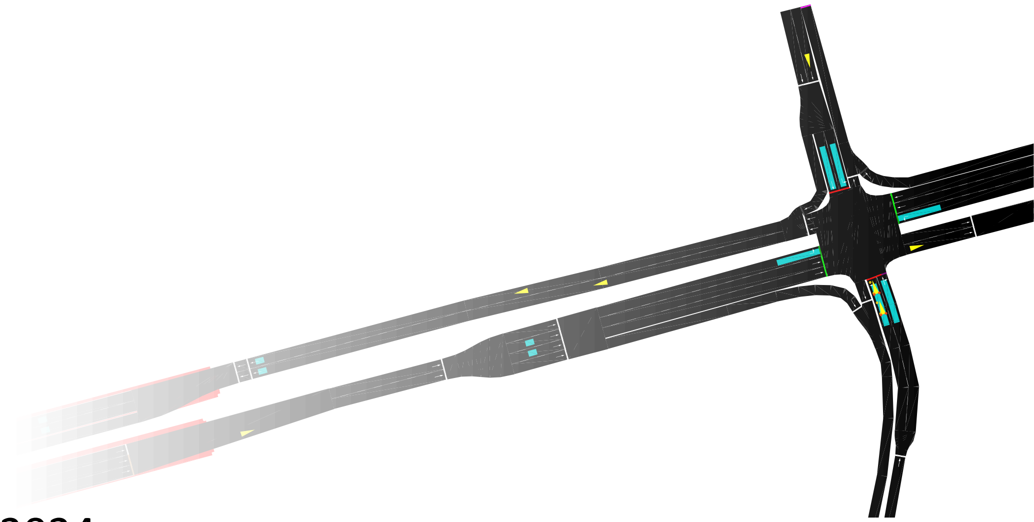
Do trajectory calibrated parameter sets create realistic traffic flow in aggregate?

Does it matter in the context of fuel consumption estimation?

Preview of ext. to paper in SUMO Proceedings



Aggregate Calibration / Assessment

Instead of using trajectory pairs, can we calibrate CF-models using aggregated data?

<u>Two Aggregation Methods:</u>

1. Space-Time aggregation
2. PDF of accel

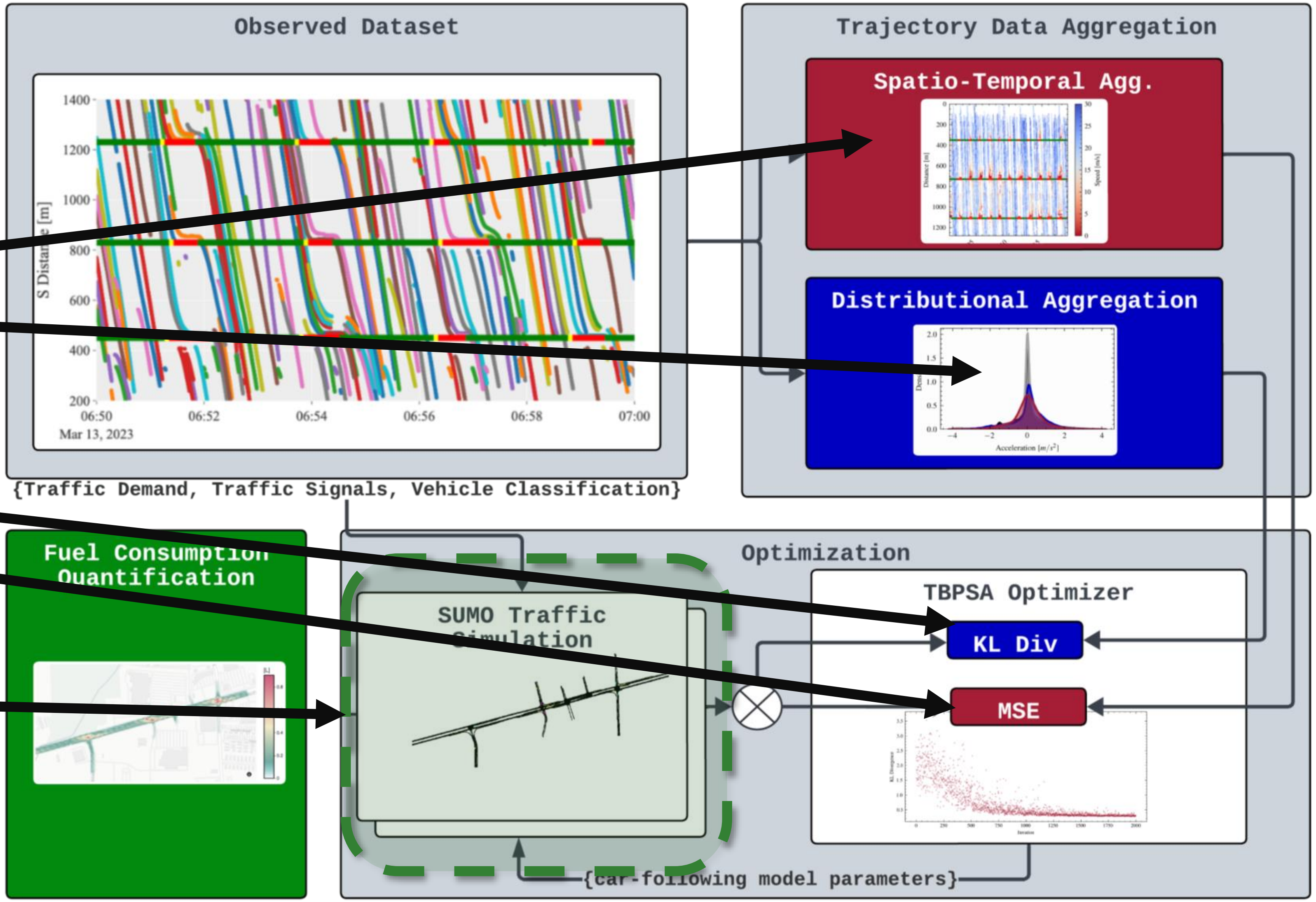
(applied to both sim. & radar)

<u>Two Loss Functions:</u>

1. Kullback–Leibler (KL) divergence
2. Mean-Squared Error

<u>Optimization:</u>

1. Consider stochasticity
2. Mean parameters (speedFactor variance)



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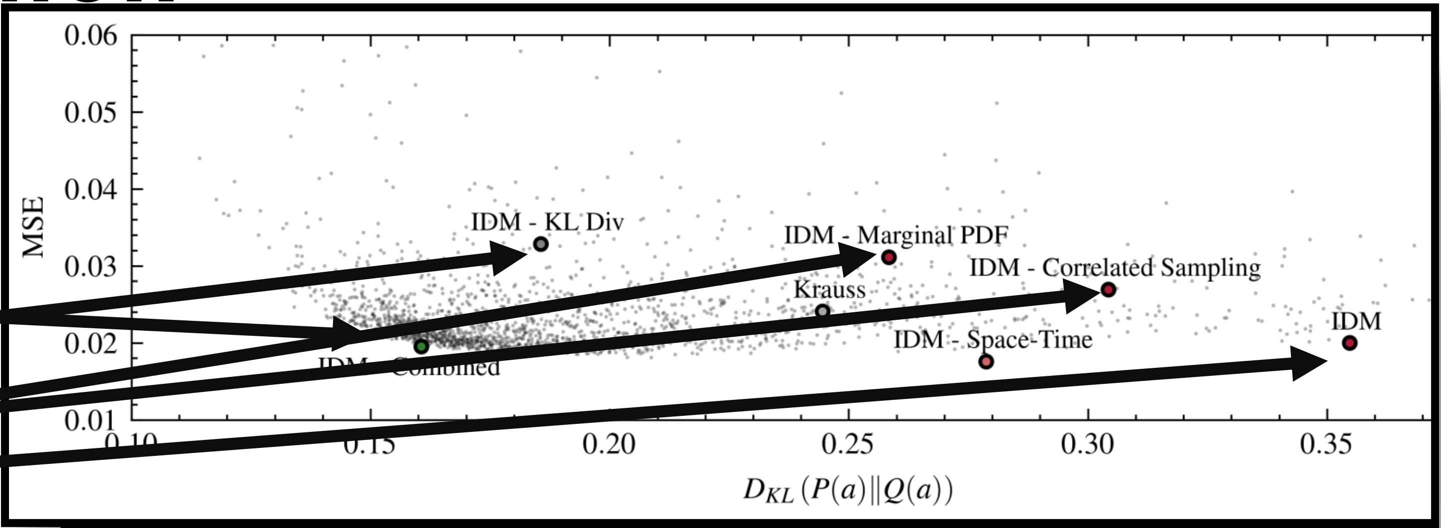
Aggregate Calibration

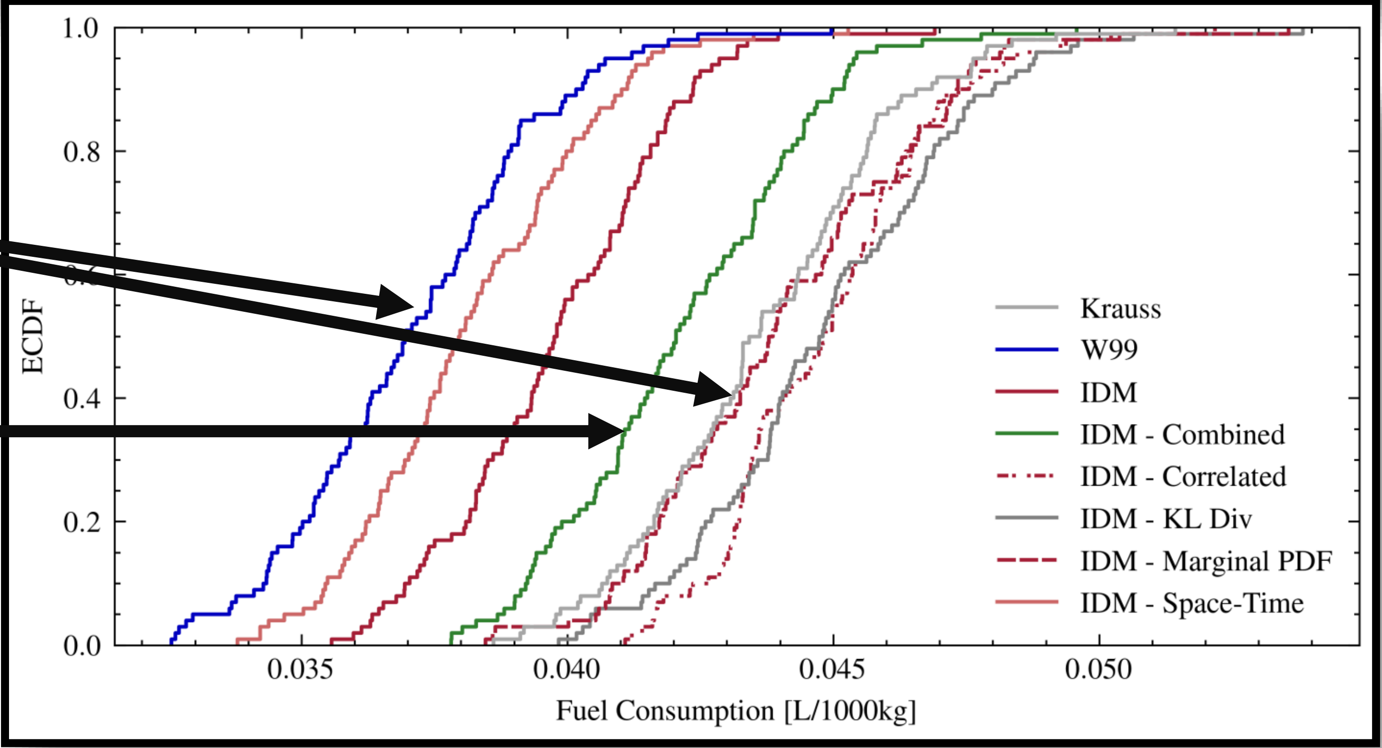
Combined Calib. of Space-Time and KL-Div

- $MSE(V) + \alpha \cdot D_{KL}(a)$
  - During calibration, a Pareto front emerges [1]
- $D_{KL}(v, a)$ suboptimal
- Trajectory Calibration suboptimal
- W99 & IDM high KL Div



Implication on Fuel Consumption

- 1 hour simulation, fuel normalized by mass
- W99 lowest, Krauss highest
  - Nearly 20% difference
- Combined Calibration nearly same as joint of IDM and Krauss
  - Needs further investigation



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Does it matter?

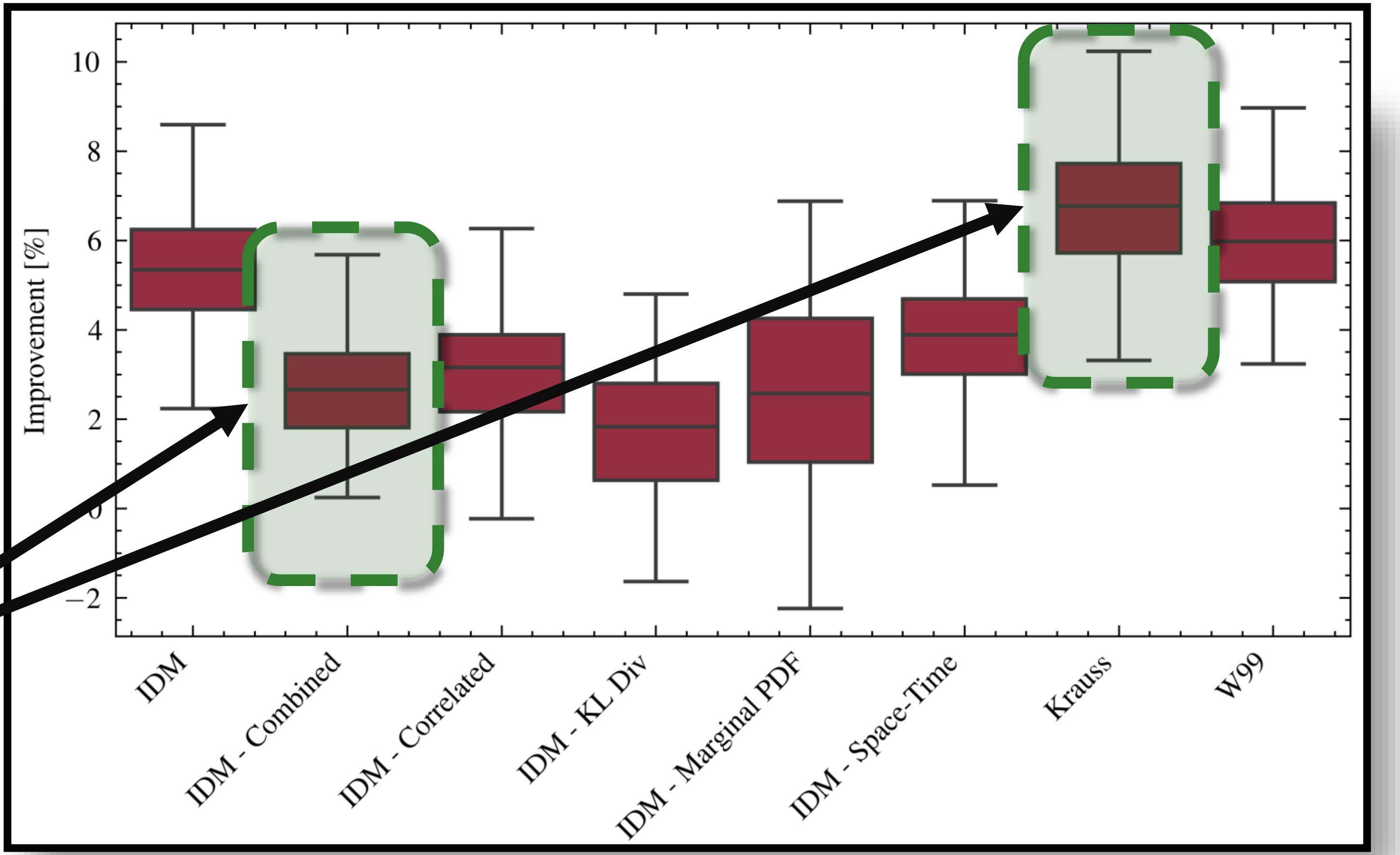
<u>**Fuel Consumption Sensitive to**</u>

1. Volume
2. Fleet Composition
3. CF Model & Parameters
4. Signal Control Method

Absolute Quantity **Uncertain.**

Is **relative** quantity?

- Actuated Coordinated vs. Free
  - Calibrated says ~2.5% decrease in total fuel
  - Krauss says ~6% decrease in total fuel



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Conference Paper

- Maxwell Schrader, Arya Karnik, Alexander Hainen, and Joshua Bittle. (2024) Calibrating Car-Following Models using SUMO-in-the-loop and Vehicle Trajectories from Roadside Radar. Presented at SUMO User Conference.

Questions?

Trajectory Calibration: github.com/UnivOfAlabama-BittleResearchGroup/sumo-cf-calibration

Aggregate Calibration: github.com/UnivOfAlabama-BittleResearchGroup/traffic-simulation-calibration

Parallelized SUMO Pipelines: https://github.com/mschrader15/sumo-pipelines