

Order from disorder

How time-gap heterogeneity suppresses stop-and-go waves in traffic

Raphael Korbmacher Antoine Tordeux

School of Safety & Mechanical Engineering, University of Wuppertal, Germany

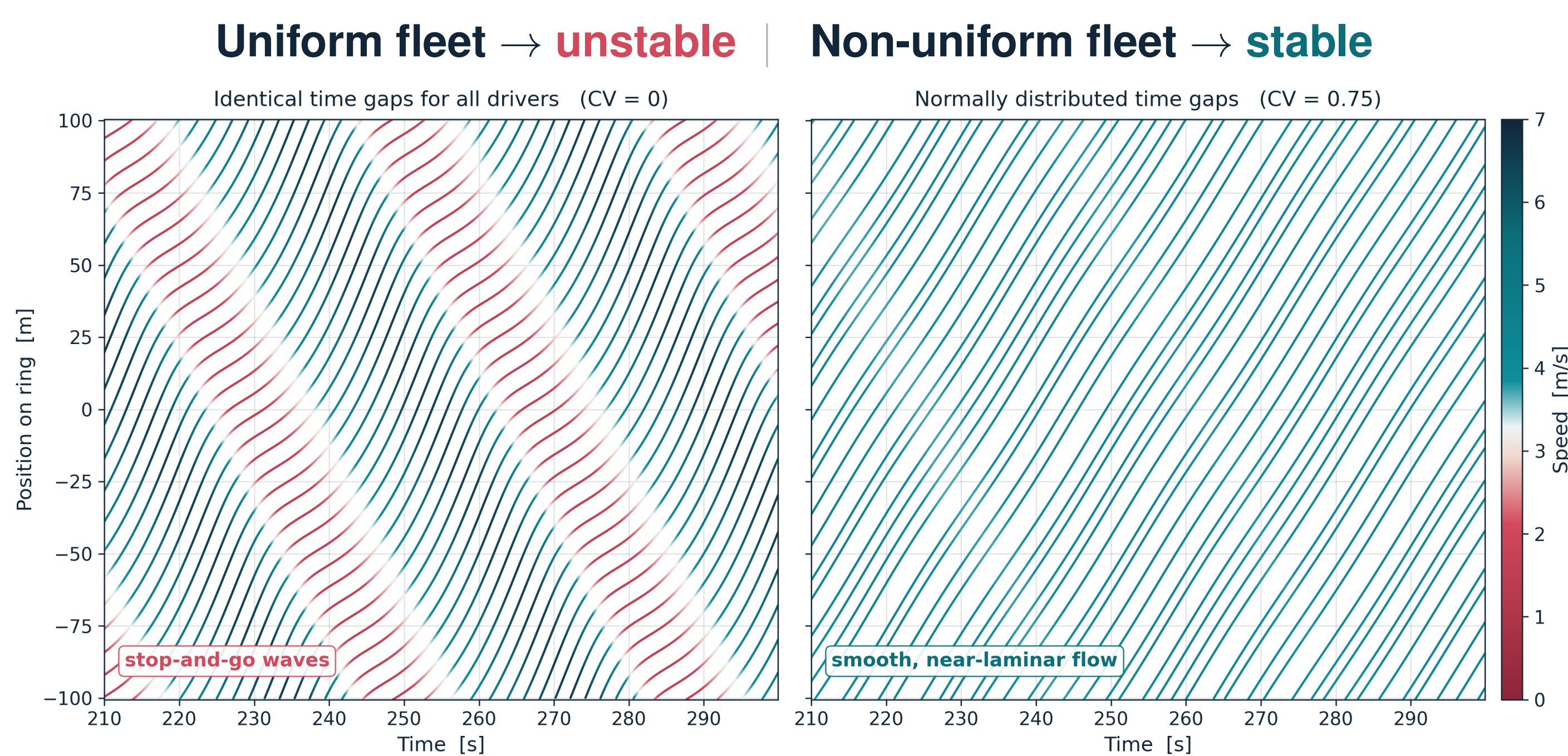


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More disorder, smoother traffic. Drawing desired time gaps from a broader distribution, at the *same* mean gap and mean speed, suppresses speed fluctuations, and enough heterogeneity restores **laminar flow** even in deeply unstable traffic.

The set-up

- **Stop-and-go waves** (phantom jams) arise with no bottleneck or trigger (Sugiyama *et al.* 2008); after 70+ years their self-sustaining emergence is still not fully understood.
- We drop **behavioural homogeneity** in car-following models: each vehicle's desired time gap is drawn *independently* from a truncated normal distribution on $[0.2, 3.0]$ s (mean $\bar{T} = 1$ s), with coefficient of variation $CV = \sigma_T/\bar{T}$.
- The **fleet-mean gap and speed is held fixed**, so any stabilisation *cannot* be a trivial density reduction.
- Analytical optimisation under a stability constraint, confirmed on the **IDM** and **FVDM** — a 205 m ring with $N = 20$ vehicles (Sugiyama set-up).



Proof of concept. Vehicle trajectories on the ring, coloured by speed. Identical time gaps for all drivers ($CV = 0$, left) break into **stop-and-go waves**; normally distributed time gaps ($CV = 0.75$, right) yield **smooth, near-laminar flow** — at the same mean time gap and density.

Analytical proof

1. Linearised dynamics. Linearise *any* car-following model about the uniform equilibrium. On a periodic ring of N vehicles each driver obeys

$$\dot{v}_n = a_n d_n + b_n v_n + c_n v_{n+1}, \quad b_n = -a_n T_n,$$

with gap stiffness $a_n > 0$, speed coupling $c_n \geq 0$, and desired time gap T_n .

2. String stability condition. A circulant/Floquet spectral analysis on the ring gives L^2 string stability *if* (Korbmacher et al. 2025)

$$\sum_{n=1}^N T_n^2 \geq \sum_{n=1}^N \alpha_n \quad \alpha_n := \frac{2}{a_n} + \frac{c_n^2}{a_n^2}.$$

The left side is the fleet's **second moment of time gaps**; each α_n is a driver's intrinsic *instability budget*, fixed by the dynamics alone.

3. Enter the variance. For *any* gap distribution with mean $\bar{T}$, the second moment splits exactly as

$$\frac{1}{N} \sum_{n=1}^N T_n^2 = \bar{T}^2 + \sigma_T^2 \quad (\text{mean square} = \text{square of mean} + \text{variance}).$$

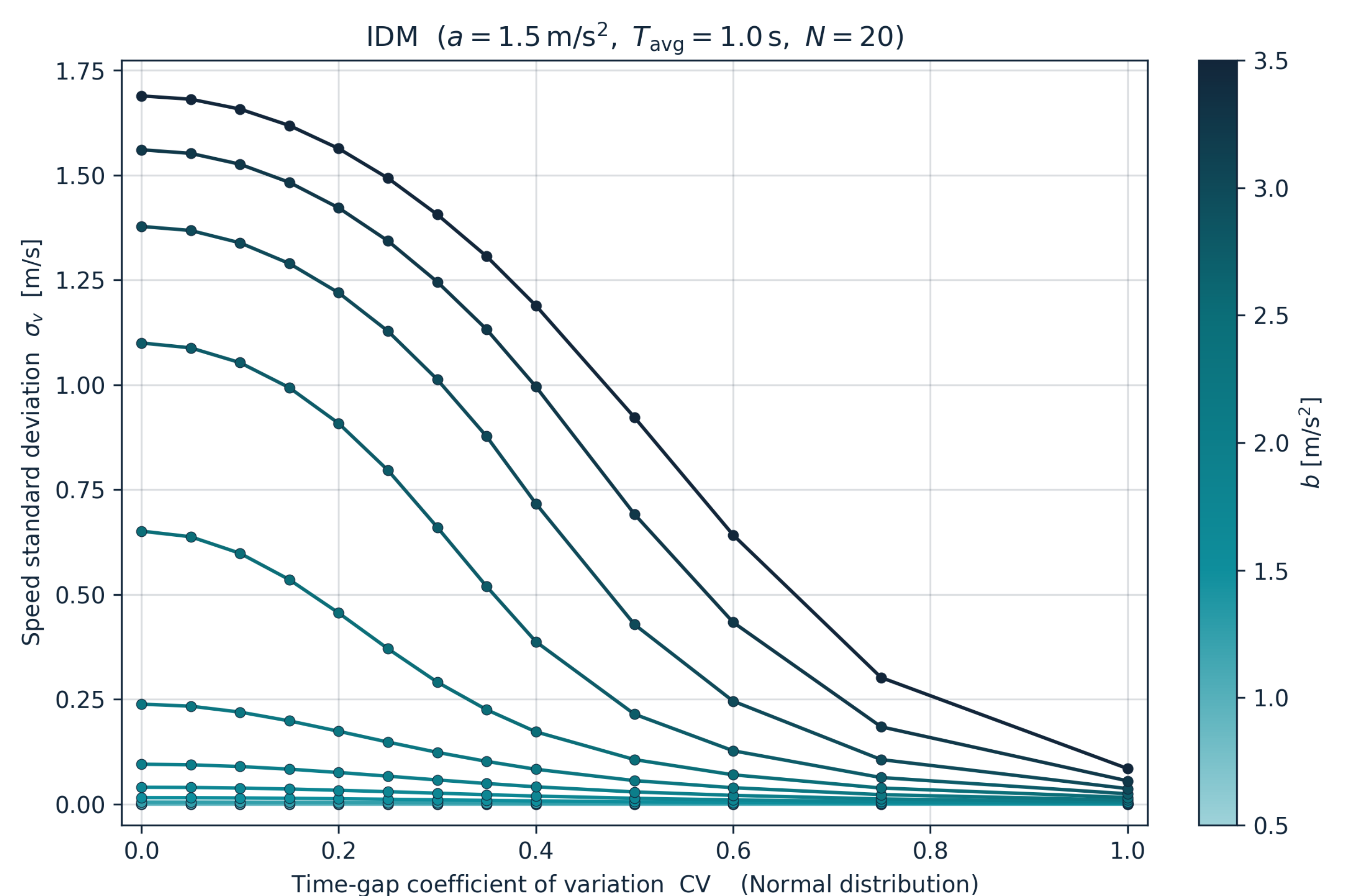
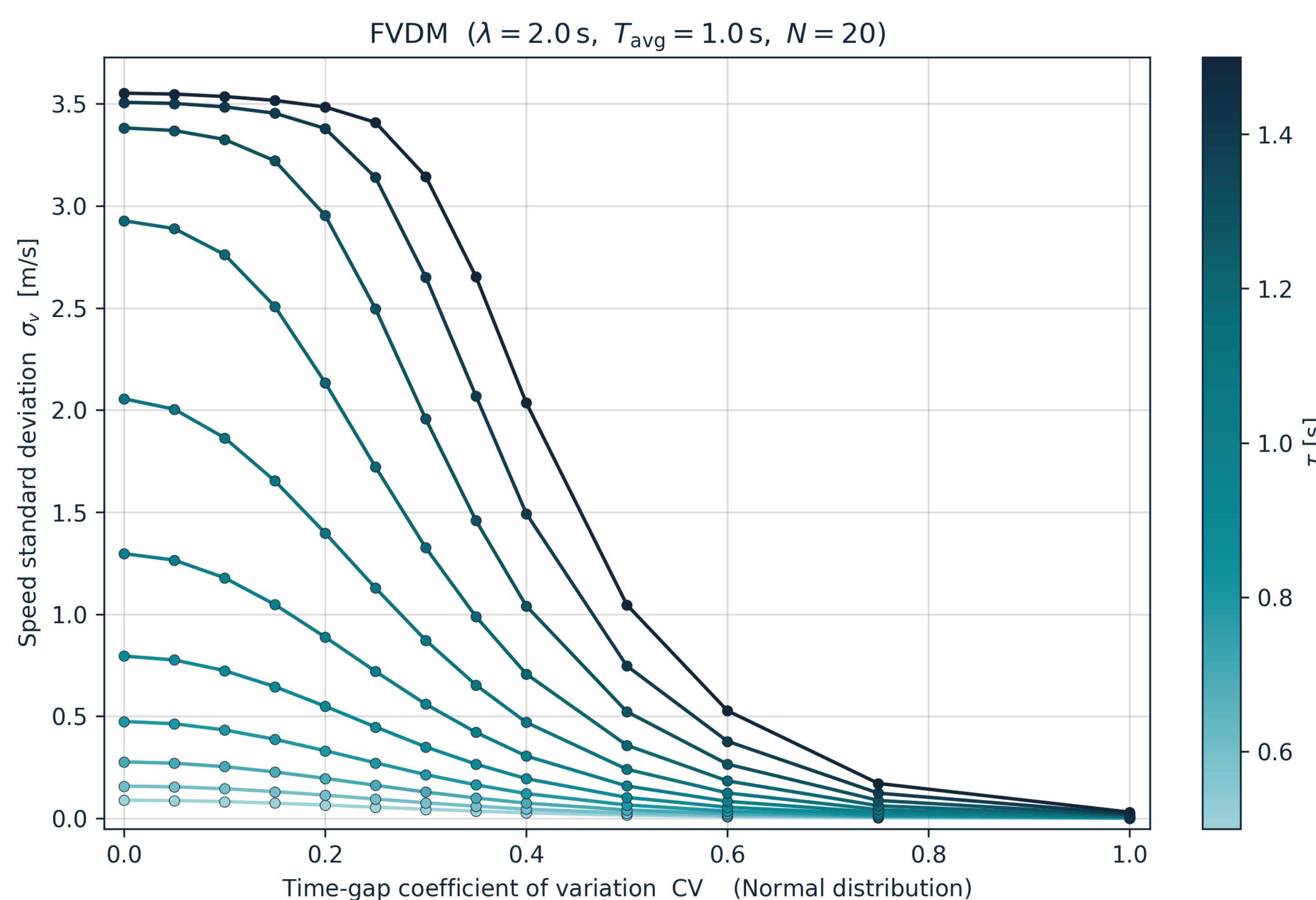
4. Conclusion. For identical drivers ($\alpha_n \equiv \alpha_1$) the condition collapses to a statement about the *spread* alone:

$$\bar{T}^2 + \sigma_T^2 \geq \alpha_1 \iff \sigma_T^2 \geq \alpha_1 - \bar{T}^2$$

At a **fixed mean gap** $\bar{T}$ — hence fixed density and flow $Q = \rho v^*$ — the variance σ_T^2 is the *only* free term, and it enters with a + sign. **More disorder $\Rightarrow$ more stability.**

$$\begin{aligned} &\text{Normalise by } \bar{T}^2, \text{ with } g := \bar{T}^2/\bar{T}^2 = 1 + CV^2 \text{ and } g_c := \alpha_1/\bar{T}^2: \\ &\text{stable} \iff g \geq g_c \iff CV \geq \sqrt{g_c - 1} =: CV_c \end{aligned}$$

Result



Two findings. (i) For every τ (FVDM, left) or b (IDM, right) at which the homogeneous fleet ($CV = 0$) sustains stop-and-go waves, increasing CV *monotonically* lowers the speed standard deviation σ_v . (ii) Sufficient heterogeneity ($CV > 1$) restores essentially **laminar flow** even in deeply unstable regimes — at the same mean time gap.

Driver heterogeneity is *not* noise to be averaged away. It acts as an **control parameter** that tames stop-and-go waves. A free stabilising margin in today's mixed human traffic, and a design lever for **automated and V2V fleets**.

Selected references

- [1] Sugiyama *et al.* (2008): Traffic jams without bottlenecks—experimental evidence for the physical mechanism of the formation of a jam. *New J. Phys.* **10**, 033001
- [2] Korbmacher *et al.* (2025): Emergent Cooperative Driving Strategies for Stop-and-Go Wave Mitigation via Multi-Agent Reinforcement Learning. *arXiv:2511.14378*



Code & live simulation

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Korbmacher & Tordeux, **University of Wuppertal**.