Emergent Traffic Congestion Dynamics in a Stochastic Agent-Based Simulation

Abstract:
We study the emergence of traffic congestion in a simplified stochastic traffic simulation using agent-based dynamics and Monte Carlo analysis. Despite minimal assumptions and homogeneous agents, the model reproduces key qualitative properties observed in real traffic systems, including a fundamental flow–density relationship, convergence to steady-state velocities, and delayed recovery following exogenous disruptions. The results highlight how macroscopic congestion patterns arise from simple local interactions and provide a foundation for studying feedback-driven decision policies in transportation systems.

1. Model Overview

We consider a single-lane traffic system composed of identical vehicles moving along a one-dimensional road segment. Each vehicle updates its velocity based on local spacing, stochastic perturbations, and system-wide constraints such as maximum speed and safety distance.

Key characteristics:

- Discrete-time dynamics
- Stochastic velocity updates
- No lane changes or overtaking
- Homogeneous driver behavior

The model is intentionally minimal, focusing on emergent system behavior rather than detailed driver psychology.

2. Fundamental Flow–Density Relationship

To characterize steady-state system performance, we simulate traffic at varying vehicle densities and measure the resulting flow.

Results:

- At low densities, traffic flow increases approximately linearly with density.
- A maximum flow is reached at an intermediate critical density.

- Beyond this point, additional vehicles reduce average speed, leading to decreased flow.

This produces a concave flow–density curve consistent with classical traffic fundamental diagrams. While the model does not capture sharp phase transitions, it reproduces the expected qualitative regime structure of free-flow and congested traffic.

3. Monte Carlo Stability Analysis

To assess robustness, we perform Monte Carlo simulations across multiple random initializations.

Findings:

- Average system velocity rapidly converges to a steady-state value.
- Variability across runs diminishes over time.
- The system exhibits a stable attractor, indicating ergodic behavior under stochastic dynamics.

The distribution of steady-state velocities is unimodal with moderate dispersion, suggesting persistent randomness at the agent level without destabilizing the macroscopic system.

4. Transient Dynamics and Shock Response

We introduce a temporary capacity-reducing event (modeled as an accident) during steady-state operation.

Observed behavior:

- Immediate drop in average system velocity during the disruption.
- Gradual recovery after the accident is cleared.
- Recovery occurs more slowly than the initial collapse, indicating hysteresis-like dynamics.

This asymmetric response demonstrates how short-lived local disruptions can have prolonged system-wide effects, even in the absence of heterogeneous agents or strategic behavior.

5. Discussion

Despite its simplicity, the model captures several hallmark features of real-world traffic systems:

- Nonlinear flow degradation at high density

- Stable macroscopic equilibria under stochastic micro-dynamics
- Delayed recovery from exogenous shocks

However, the model does not incorporate adaptive routing, heterogeneous drivers, or endogenous control policies. As such, it is best interpreted as a qualitative and pedagogical simulation rather than a predictive traffic model.

6. Future Extensions

This framework naturally supports extensions in three directions:

1. **Forecasting:** Predict congestion onset using short-horizon time series features.
2. **Decision Policies:** Introduce speed limits or flow control mechanisms.
3. **Feedback Loops:** Study how policy interventions alter long-run system equilibria.

These extensions would allow analysis of learned or optimized decision-making under endogenous congestion feedback.

7. Conclusion

This study demonstrates how complex congestion phenomena can emerge from simple stochastic rules governing individual agents. The results emphasize the importance of system-level analysis and provide a foundation for integrating forecasting and optimization into traffic control problems.