Recovery Dynamics Influence in Urban Traffic Capacity and Resilience

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Extended Abstract

Motivation. Urban traffic is a network system that can undergo regime shifts between macroscopic free-flow and congested states. It is crucial to understand and predict such transitions for urban operations and planning. Epidemic models, classifying road segments into congested and free-flow states based on vehicle speed, have been effective in describing congestion spreading at the network level[1]. Nonetheless, they generally do not explicitly account for history-dependent behaviours in the metastable functional states[2][3], which have been increasingly observed in real urban traffic systems. Such phenomena, known as multi-metastability and hysteresis, usually indicate higher risk of functionality collapse and weaker resilience. This study aims to uncover the mechanisms responsible for this multi-metastability and hysteresis in urban traffic.

Approach and Methodology. We analyze city-scale traffic data from Singapore consisting of average vehicle speeds on road segments. Each road segment is classified into either a free-flow or congested state based on its speed. We examine the local recovery dynamics of congested segments. Based on this observation, we construct a dynamical network model in which recovery probability is parameterized as a function of downstream congestion. Both linear and nonlinear forms of this dependency are tested through numerical simulations to examine their impact on the macroscopic functional states of the network.

Results. Our empirical analysis of real-world traffic data from Singapore suggests that the local recovery of a congested road segment is not spontaneous. The recovery rate negatively depends on the number of congested downstream neighbours. Such dependency could be either linear or nonlinear. Simulations of this dynamical model show that the macroscopic functionality of the network can have hysteresis, only when the recovery is nonlinear. Furthermore, we find that network topology has a significant influence on the strength of hysteresis, indicating that structural properties of urban road networks modulate system-level resilience and effective traffic capacity. These results demonstrate that multiple functional metastable states and hysteresis can arise from local recovery dynamics interacting with network structure.

Conclusions and Outlook. By linking empirical observations with a mechanistic network model, this work advances theoretical understanding of the origins of history-dependent behaviour in urban traffic functionality and provides a framework for urban planners and

policymakers to better assess operational limits of traffic capacity and resilience under dynamic operating conditions.

References

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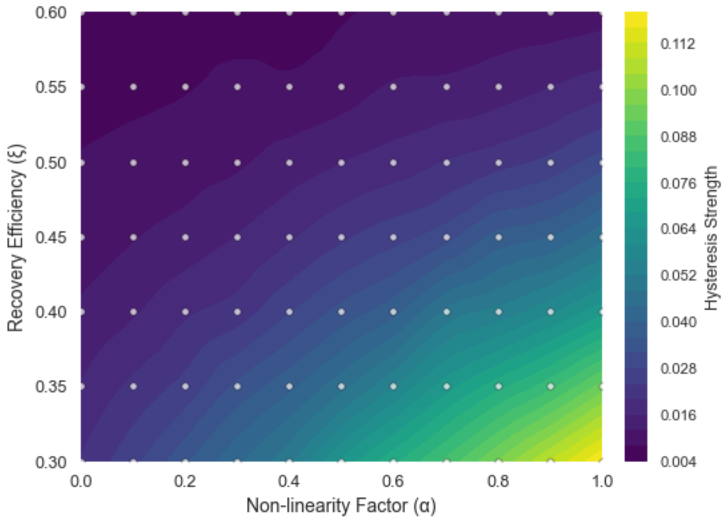
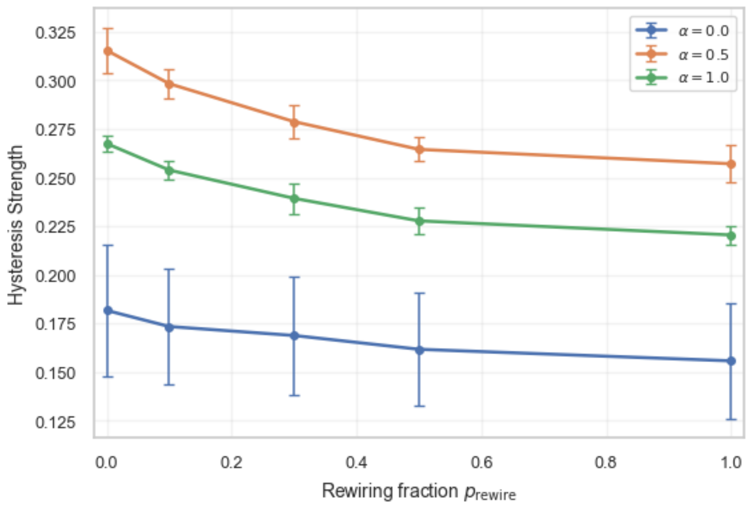


- Figure 1. 2D-Grid Hysteresis Strength Across Nonlinearity and Recovery Efficiency.



- Figure 2. Preliminary Evidence for Topological Effects on Traffic-Congestion Hysteresis Under Degree-Preserving Rewiring (2D-Grid).