From Chaos to Flow: A Decentralised, Data-Driven Approach to Adaptive Traffic Signal Control

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Abstract

Rapid urbanisation and increasing demand exacerbate congestion in cities worldwide, resulting in significant economic, environmental, and social costs. Conventional traffic management strategies struggle to cope with dynamic, large-scale urban networks due to limited adaptability and scalability. We present the Tree Method, a decentralised traffic signal control approach that mitigates congestion using real-time data without additional infrastructure. The method introduces the concept of Jam Trees, spatio-temporal clusters of congested road segments that capture how congestion originates at bottlenecks and propagates upstream across the network. Congestion is identified through deviations from free-flow speeds, and each Jam Tree is assigned an economic cost measured in vehicle hours, enabling prioritisation based on network-wide impact rather than purely local conditions. Building on this representation, the Tree Method dynamically adjusts green phase durations within fixed-cycle, fixed-order traffic signals. Each intersection operates independently, yet its decisions are informed by the structure and cost of identified congestion trees, allowing the system to target critical bottlenecks while maintaining scalability and robustness. The approach was evaluated using agent-based simulations in SUMO, based on calibrated real-world and simulated data, under varying traffic loads. Results show substantial performance gains compared to fixed-time control, SUMO-actuated control, and reinforcement learning-based methods. The Tree Method achieved reductions of up to 43% in average travel time and improvements of up to 35% in throughput under high congestion scenarios. These findings demonstrate that congestion-tree-based prioritisation offers an effective and practical framework for adaptive, decentralised urban traffic management, with strong potential for real-world deployment in smart mobility systems.