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CONNECTED CITIES WITH SMART TRANSPORTATION
Research Brief

Quantifying Uncertainty and Distributed Control for Unanticipated Traffic Patterns as a Result of Natural and Man-Made Disruptions

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Executive Summary

Natural and man-made disruptions to city traffic flows are increasing, and these disruptions can cause hours of delay in busy urban networks. Incidents already account for more than 50% of day-to-day traffic delays, and standard traffic control strategies often become obsolete or even worsen the situation when disruptions occur. Thus, there is a need to develop data-driven distributed network control techniques that can adapt to these uncertainties in traffic conditions in real-time. As connected/autonomous vehicles (CAVs) begin to appear in real-world traffic flow, they present a new potential source of high-resolution data, such as vehicle trajectories, that can be fused with data from traditional stationary sensors to create comprehensive datasets for traffic state estimation. This fine-grained data from CAVs can allow for the development of new signal control algorithms that clear congestion more quickly, keeping traffic moving in crowded cities, even after an incident.

For this project, the setting envisioned is an urban network with a mix of CAVs and traditional vehicles in which the CAVs serve as probe vehicles that provide indicators of the overall traffic state. This research investigated the levels of penetration of CAVs needed to determine traffic states with sufficient accuracy for effective traffic management, when combined with data from stationary sensors. By fusing data from CAVs with data from traditional sensors, the researchers developed traffic state estimation models that combine traditional car-following theory and simulation with statistical learning techniques to reconstruct microscopic traffic dynamics.

The second part of this project involved developing a new kind of network control algorithm. The algorithm can use data from connected vehicles to capture real-time traffic dynamics, allowing for adaptive signal control to efficiently clear congestion following an incident. This new technique is referred to as position-weighted backpressure (PWBP), which accounts for queue buildup and dissipation dynamics resulting from traffic disruptions and overcomes drawbacks in the original backpressure theory. The researchers combined this proposed control technique with traffic state estimation tools in simulation to demonstrate the ability of their PWBP algorithm to quickly stabilize a network after a disruption and adapt to different traffic conditions.

Findings & Outputs

The researchers tested two methodologies for traffic state estimation to determine adequate levels of probe vehicles to achieve accurate results. One uses random fields to learn traffic flow dynamics, and the other uses stochastic Lagrangian dynamics to estimate traffic states. They observed that the distribution of probe vehicles in a sample can severely impact estimation results, so a single value specifying adequate penetration levels is not sufficient. Experiments using real-world vehicle trajectory data showed that the accuracy of the proposed estimation technique improves significantly as the penetration rate of probe vehicles increases from 5% to 15%.

Figure 1: Simulation street network used for testing the project's traffic control algorithm.

For the proposed network control technique, the research team developed a position-weighted backpressure (PWBP) algorithm. PWBP builds on the original backpressure theory by taking the spatial distribution of vehicles on the road into account. It applies higher weights to queues that extend to the ingress of the road, accounting for potential spillbacks during and after traffic network disruptions.

To evaluate the proposed PWBP control policy, a microscopic traffic simulation model was built using VISSIM. The test network forms part of an urban downtown area and includes two main arterials, each three to four lanes wide, and 11 major signalized intersections. The researchers developed an emulator for the Split Cycle Offset Optimization Technique (SCOOT) adaptive controller, which is the current controller used for the real-world network, and implemented the emulator in VISSIM. In testing, the emulator replicated observed data very well, including adapting to varying traffic conditions and data that was not used to train the model.

The researchers tested various incident scenarios in simulation, evaluating how well PWBP performed when compared to other traffic control strategies, including fixed signal timing, standard BP, and a capacity-aware variant of BP (CABP). In all tested circumstances, PWBP was able to accommodate higher numbers of vehicles, reduce total network delay and congestion propagation speed, and improve the network's recovery from heavy congestion and response to an incident.

It takes about **four hours** to reach total network gridlock under a fixed timing plan when the demand reaches 1225 veh/h-lane in the network. Under BP and CABP it takes about **six hours** at 1570 veh/h-lane to reach gridlock, while for PWBP, it takes approximately **seven hours**. This indicates that PWBP is more resilient than the other policies. PWBP also outperforms the other three control policies in terms of both delay and recovery time from congested conditions, recovering from peak demand of 1620 veh/h-lane in only **30 minutes**.

The researchers also tested PWBP performance after an incident and compared it to BP and CABP performance. For an incident lasting two hours, PWBP needs only **one hour** to completely recover, while congestion persists in the network up to **three hours** after the incident is cleared under BP and CABP.

Under a two-lanes-blocked incident with a demand of 1200 veh/h-lane, the whole network becomes gridlocked under fixed timing, BP and CABP control. Using PWBP, the incident has minimal impact on network delay.

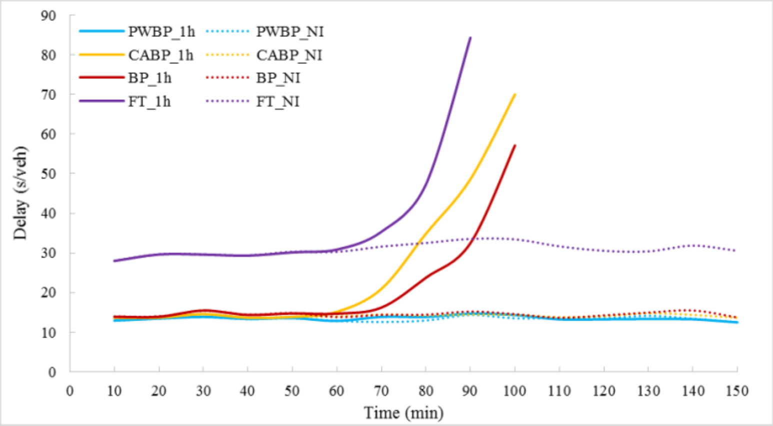

Figure 2: Results of a simulation of an incident that blocks two lanes at a demand level of 1200 vehicles per hour. The network becomes gridlocked when other signal control techniques are used, while the incident hardly has any impact on delays in the network using PWBP control.

This is because PWBP captures spillback dynamics from the incident location and adjusts downstream as well, i.e., PWBP doesn't allocate green time at an intersection downstream with no vehicles near the stop line.

Overall, PWBP's awareness of the spatial distribution of vehicles in the network produces better performance in network delay, congestion propagation speed, and recovery. It demonstrably improves upon existing network traffic control techniques by using real-time data from connected vehicles to optimize the network's signal timings in response to an incident.

Outcomes & Post Project Initiatives

This research customizes data analysis techniques to solve traffic problems in novel ways, including incorporating the potential for new data sources from emerging connected vehicle technology, advancing the state of practice in both traffic engineering and data analysis. Though the algorithm was tested in a simulation of a specific urban network, the findings are applicable to other cities with a similar grid structure. In a city with both CAVs and traditional vehicles in the traffic flow, the PWBP algorithm developed in this study can enhance signal control in busy networks by adapting to changes in the traffic state. Using data from traditional sensors and connected vehicles, this new technique can improve recovery time from a congested state and prevent further delays after an unanticipated incident.

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