Research Statement
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My research focuses on resilient operations and control of increasingly automated transportation systems with efficiency and safety guarantees. In my PhD research, I developed a design framework to evaluate the macroscopic impact of a broad range of cyber-physical disruptions on the performance of transportation systems. Examples of such disruptions include traffic incidents, platoon merges of connected heavy-duty vehicles, traffic signal malfunctions, and security failures. My framework explicitly models the uncertainty in the timing and location of this class of disruptions, and enables design of resilience-improving operations using modern sensing and controlling capabilities. To evaluate the benefit of these designs, I developed efficient algorithms to obtain performance guarantees (throughput and/or delay). The main advantage of my approach is that it combines the model of cyber-physical disruptions and assesses their impact using tractable dynamic flow models. In the near future, I aim to develop an end-to-end computational design framework to evaluate resilience-improving operations in smart transportation systems, including semi-autonomous and multimodal systems.

Most of my PhD research is motivated by the need to design capacity allocation strategies to manage the effect of capacity failures (incidents, weather, signal malfunction) or heterogeneous demand (connected/autonomous vehicles vs. ordinary vehicles). I developed new stochastic dynamical models to analyze the behavior of transportation networks under such disruptions. Specifically, I used stochastic switching models to study the congestion effects of disruptions that are potentially recurrent in nature. The discreteness of disruption events is captured by introducing switches in the traffic flow dynamics. Traffic queues at critical locations initiate, propagate, and vanish as the dynamics switch. I derived easily verifiable criteria under which the disruption-induced traffic queues (or their moments) are bounded on average. A key finding is that recurrent stochastic disruptions may lead to bottlenecks and congestion that do not exist in the nominal/average setting. Therefore, operations designed using classical deterministic or scenario-specific approaches can be highly inefficient. My ultimate goal is to influence the practice of capacity operations by designing disruption-aware strategies that are provably efficient and resilient.

My research is supported by NSF-CPS FORCES (www.cps-forces.org) and Future Urban Mobility (ares.lids.mit.edu/fm). My PhD work contributes to three problems in smart transportation systems:

1. Capacity-aware highway traffic management [1, 2, 3, 4, 5].
2. Efficient and safe vehicle platooning operations [6, 7].
3. Resilient response to cyber-physical disruptions in automated urban roads [8].

Capacity-aware highway traffic management

How to efficiently allocate highway capacity under stochastic disruptions?

Although data evidence suggests that highway capacity is inherently stochastic, most highway traffic management approaches consider capacity as a deterministic and a priori known quantity. In contrast, I proposed stochastic switching models that explicitly relate key characteristics of capacity fluctuations (frequency, duration, and intensity) to delay/throughput [1, 2]. My modeling approach can admit a broad class of dynamic flow models, including the classical cell transmission model (CTM), the fluid queueing model, and multi-class flow models. For the
CTM-based stochastic model, I developed an automatic calibration method [5]. I showed that the calibrated model well captures the capacity fluctuations observed on a California highway.

Based on the approach that I introduced in [1], I quantitatively characterized the impact of capacity disruptions and demand patterns on the throughput of a multi-cell highway [3]. I showed that capacity disruptions lead to not only local congestion, but also additional bottlenecks and congestion elsewhere (possibly far away from the location of disruptions) on the highway. I provided a mathematical proof showing that the joint effect due to capacity fluctuations and spillback may even destabilize the on-ramp queues that would be stable in the nominal/average setting. This implies that ignorance of capacity fluctuations may lead to highly inefficient operations.

Based on my analysis results, I am working on the design of highway traffic management strategies that improve throughput under stochastic capacity disruptions. In a joint work with Dr. Alexander A. Kurzhanskiy from UC Berkeley [4], we consider a basic but still unanswered question for highway operations: how should we allocate the limited capacity between mainline traffic and on-ramp traffic? My investigation provides a rather surprising conclusion: under stochastic disruptions, whether or not an on-ramp should be metered does not depend on the utilization ratios of the on-ramp and of the mainline, but on the capacity-demand margins. Hence, the conventional traffic management strategies, which simplistically prioritize the mainline, can be highly suboptimal for a disruption-prone highway. In contrast, I propose a capacity-aware strategy that provably achieves performance guarantees. In my working paper [4], I use the model of the Interstate 210 to demonstrate that our capacity-aware strategy is able to improve throughput by up to 20% and reduce travel time by up to 15%.

In addition, I have investigated the performance of feedback routing over networks of parallel traffic links in stochastic settings [2]. I focused on improving network throughput under a variety of practically relevant routing policies. I found that throughput can be maximized by appropriately tuning these routing policies; however, delay is very sensitive to the form and parameters of the routing policy. I aim to synthesize my work on serially connected highway links [3, 4] and on parallel routes to build a control design framework for general networks. To approach this problem, I am developing a hierarchical control strategy which, at the network level, determines the allocation of demand over various links via a routing policy, and, at the link level, ensures efficient transmission of the allocated demand via ramp/speed limit control.

**Efficient and safe vehicle platooning operations**

*How to implement vehicle platooning on mixed-traffic highways with efficiency and safety guarantees?*

We have recently started to collaborate with Dr. Karl H. Johansson’s group at KTH on designing operations for connected heavy-duty vehicles in mixed-traffic conditions [6, 7]. Based on evidence from a field experiment by our collaborators, I developed a novel, two-class traffic flow model that captures the macroscopic interaction between connected vehicle platoons and ordinary traffic in terms of capacity sharing mechanisms. My model provides a tractable modeling framework by focusing on the congestion effect due to vehicle platooning [6]. My study suggests that, when the fraction of connected vehicles is within a certain range (5%–15% in the scenario we considered), vehicle platooning may lead to throughput loss compared to the baseline case where no vehicles are connected; however, beyond this range, vehicle platooning can significantly improve the overall throughput. This estimate can be further revised to arrive at the critical penetration rate of connected vehicles to fully realize their benefit toward improved
efficiency. I also considered efficient allocation of highway capacity to the two classes of traffic and identified the set of scenarios where prioritization of connected vehicles is advantageous or disadvantageous.

In an ongoing work, I am extending this research in two aspects. First, I am relating the microscopic interaction between human drivers and connected vehicles to features of the macroscopic flow model. My model particularly emphasizes the effect of speed difference between these two classes of vehicles, which is the major reason why connected vehicles may act as moving bottlenecks. Second, I am studying vehicle platooning operations that are resilient against demand uncertainty and spillback. My calculations indicate that the lengths (i.e. numbers of vehicles) of platoons can have a major impact on throughput and travel time: long platoons, on the one hand, enable higher fuel savings, but, on the other hand, intensify fluctuation in traffic flow and thus may induce additional congestion. I am quantifying this tradeoff and designing resilient control strategies with throughput guarantees.

Resilient response to cyber-physical disruptions in automated urban roads

How to efficiently respond to cyber-physical disruptions in smart transportation systems?

In an ongoing collaboration with Dr. Patrick Jaillet (MIT ORC/EECS), we focus on the cyber-physical vulnerabilities in smart transportation systems (e.g., failed/compromised traffic signals, spoofed sensor). My goal is to design attack-resilient response operations from the perspective of the system operator (SO). A distinctive feature of our work is that it considers the strategic interaction between a malicious attacker and the SO over an automated road network. Since such disruptions can impact network operations for a prolonged period of time, I consider the throughput loss as the cost metric. I am focusing on the setting where the attacker randomizes the location and timing of attacks, and the SO can proactively allocate resources (response units, personnel, etc.) for recovery processes and adaptively react to detected attacks. I show that the attacker-defender interaction can be instantiated on a multi-class queuing network, and the outcome can be obtained by considering a sequential (minimax) problem where the attacker minimizes the maximum margin to instability. One of our initial findings is that the attacker does not necessarily focus on the link with the highest load or utilization ratio. Instead, the optimal attack strategy depends on not only the load, but the recovery time and the travel time of the response units between multiple sites. I am currently working toward characterization of optimal attack strategy by studying key parameters affecting the margin to instability.

Future research

I plan to continue my work on resilient operations of smart transportation systems. Some topics of future work include:

End-to-end capacity-aware traffic management tool: I will explore how the increasing availability of data can be used to improve operations of urban roads under demand/supply uncertainty. I am interested in collaborating with traffic control software developers on effective retrieval of useful information from traffic data and translation of this information to practical guidelines and control policies. I am also interested in collaborating with transportation agencies (FHWA, state DOTs, etc.) on traffic data collection and field experiment to validate and evaluate my approach.

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1 Some real-world examples have been reported by LA Times and Washington Post.
Modeling and analysis of efficiency gain from autonomous vehicles: I am interested in exploring the impact of connected/autonomous vehicles under the broader agenda of NSF’s Smart Cities Initiative. Based on my current work on vehicle platooning, I want to develop modeling and analysis approaches to evaluation of the impact of integrating autonomous vehicles into current transportation systems. I will particularly focus on relating microscopic interaction and macroscopic interaction between autonomous vehicles and human drivers; this contribution will enable assessment of network-wide efficiency gain from autonomous vehicles.

Cyber-physical security of transportation systems: I will continue studying cyber-physical vulnerability of smart transportation infrastructures. This work will fit well in NSF’s agenda on Cyber-Physical Systems. I plan to study how the cyber vulnerabilities in individual vehicles and in automated highways could be exploited to cause significant disruption or accident. I aim to design control architecture that provides resilience guarantees under these vulnerabilities. I am also interested in collaborating with road agencies on field experiments in operations under cyber-physical security failures.

Resilient multimodal transportation systems: Finally, I am interested in expanding the scope of my research to dynamic capacity management issues in multimodal transportation systems. Based on my previous experience in air transportation [9, 10], I plan to collaborate with the FAA on design of resilient airport systems under the joint impact of disruptions in multiple travel modes affecting airport operations (terminal-area operations, ground operations, transit, and highways). I will develop new tools to facilitate the management of inter-connected transportation systems with performance and safety guarantees.

References


