CPS: Synergy: Collaborative Research: Design and Control of High-performance Provably-safe Autonomy-enabled Dynamic Transportation Networks

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Lead PI (Massachusetts Institute of Technology): **Sertac Karaman**, Department of Aeronautics and Astronautics
PI (University of Pittsburgh): Zhi-Hong Mao, Departments of Electrical & Computer Engineering and Bioengineering

Research Opportunity

Autonomy-enabled transportation networks are rapidly becoming a prominent Cyber-Physical-Systems (CPS) application area with tremendous potential for societal impact, as the autonomous systems technology penetrates into aerial/road vehicles and as the concept of connected vehicles emerge. The potential opportunities are not gone unnoticed. For example, unmanned aerial vehicle (UAV) based delivery networks has already attracted innovative companies like Amazon, Google, and Matternet (e.g. Fig. 1). Autonomous vehicles and vehicle sharing technologies may offer efficient and safe transportation infrastructure in the future. However, a deep understanding of the fundamental limits of and practical algorithm for autonomy-enabled transportation networks is essential for the large-scale deployment of these networks.

Fig. 1. Matternet envisions a team of small UAVs that can form a network to deliver much needed medicine in Africa. UAV network (left) and Matternet UAVs (right) are shown.

Research Objectives

This project has two research objectives. First is concerned with the design and control of individual hubs and links. Second considers the network as a whole.

The first research objective is to develop a foundational understanding of how automated vehicles can interact in hubs to maximize their performance, while guaranteeing safety at all times. This research objective addresses scientific questions such as: How does the performance of an individual hub scale with varying system parameters? What is the fundamental limit on performance metrics for a given system? How does the presence of human-operated vehicles among autonomous ones impact the system performance?

The second research objective is to develop rigorous bounds on performance with respect to the network variables including the number and the kinds of hubs and links, their connection structure, their dynamic nature, etc. This research objective addresses scientific questions such as: How does the performance of the whole network scales with varying network structure? Under what conditions a certain level of resilience or robustness is guaranteed? How can we quantify the systemic risk of local failures in the system? What are the optimal network coordination algorithms that guarantee high performance and safety?

Research Task 1: Design and Operation of High-performance and Provably-safe Hubs of Autonomous and Semi-autonomous Vehicles

This task considers the design, operation, and control of the hubs. Hubs are "intersection points" that may be utilized for several purposes, such as executing assigned tasks, interacting with other vehicles, and changing their routes. We view the hubs as shared resources, where some concentrated activity takes place. This research task aims to (i) develop a design and modeling paradigm that can encompass the seemingly-different hubs that are observed in a variety of applications, ranging from airports to urban traffic intersections, and (ii) identify the fundamental limits of the hubs given their design, and develop planning and control algorithms that can perform very close to these fundamental limits.

Subtask 1.1: Quantifying the fundamental limits of and developing coordination algorithms for hubs under stochastic arrivals. We will study various intersection topologies (e.g. Fig. 2).

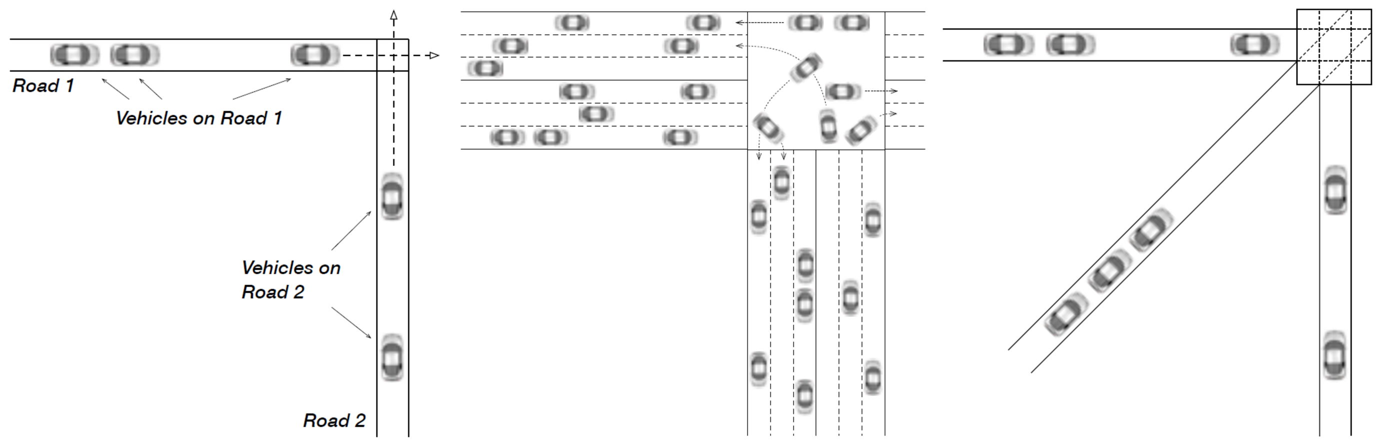

Fig. 2. Three examples of urban traffic intersection designs are shown. The first design features single lane on each road, the second design with multiple lanes, and the third design with intersecting roads. More examples can be constructed with the addition of overpasses, stopping points, fast and slow lanes, etc.

Subtask 1.2: Developing decentralized hub control laws with provable guarantees on performance and safety using a vehicle flow model. We will propose systematic guidelines for the design of self-organizing traffic control architectures (e.g. Fig. 3) and use both analysis-based and simulation-based methods to determine the traffic capacities at the hubs.

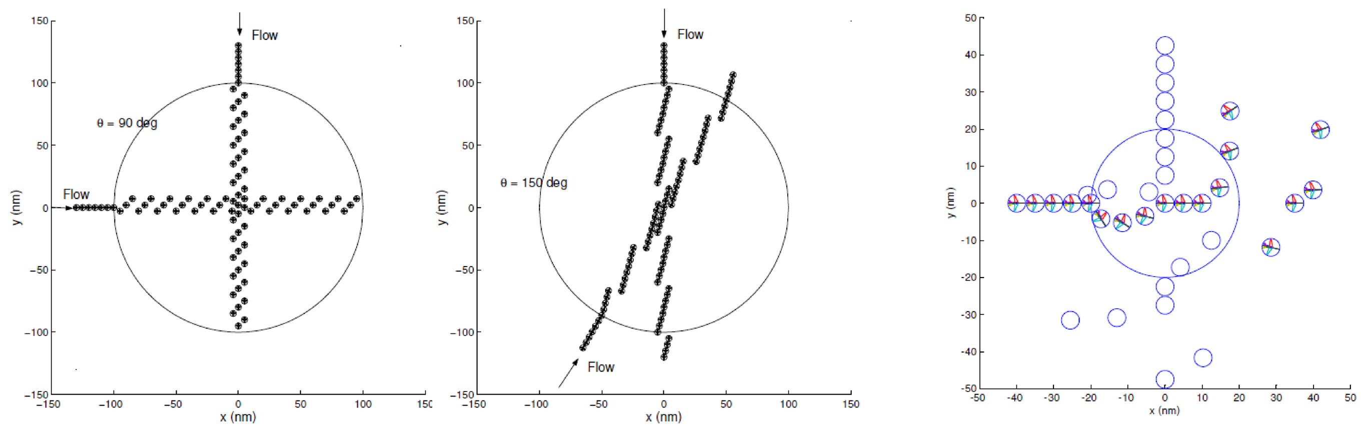

Fig. 3. The left and middle figures are two cases of intersecting aircraft flows with different encounter angles. The aircraft follow a simple decentralized rule of conflict resolution, which resolves the conflict. The aircraft are self-organized into "platoons." On the right, unstable aircraft flows under decentralized control.

Subtask 1.3: Identifying self-organizing decentralized control laws for hubs from human behavior in vehicle intersections. We will investigate the self-organizing pattens observed in crowded pedestrian or ground-vehicle at intersections, and model the cooperative interactions among the mobile agents.

Research Task 2: Design and Operation of Large-scale Autonomy-enabled Transportation Networks for Performance and Resilience

This task is to develop unifying design methodologies and planning algorithms for dynamic networks of human-operated and autonomous vehicles. We are particularly interested in developing design methodologies and planning algorithms that provide rigorous guarantees on network performance (e.g., resilience to local failures and attacks) as well as the usual vehicle performance (e.g., throughput, delays), while ensuring safety.

Subtask 2.1: An optimization-based approach for the development of guidelines for transportation network traffic design. We aim to provide guidelines for the design of efficient and robust traffic networks with hubs (e.g., traffic intersections, Fig. 4) as their basic building blocks. The network design problem can be formulated as an optimization problem for hub design and hub arrangement. This optimization problem is constrained by the estimated traffic capacities at the hubs. We also design adaptive algorithms for the estimation of overall traffic capacity of a network with many hubs.

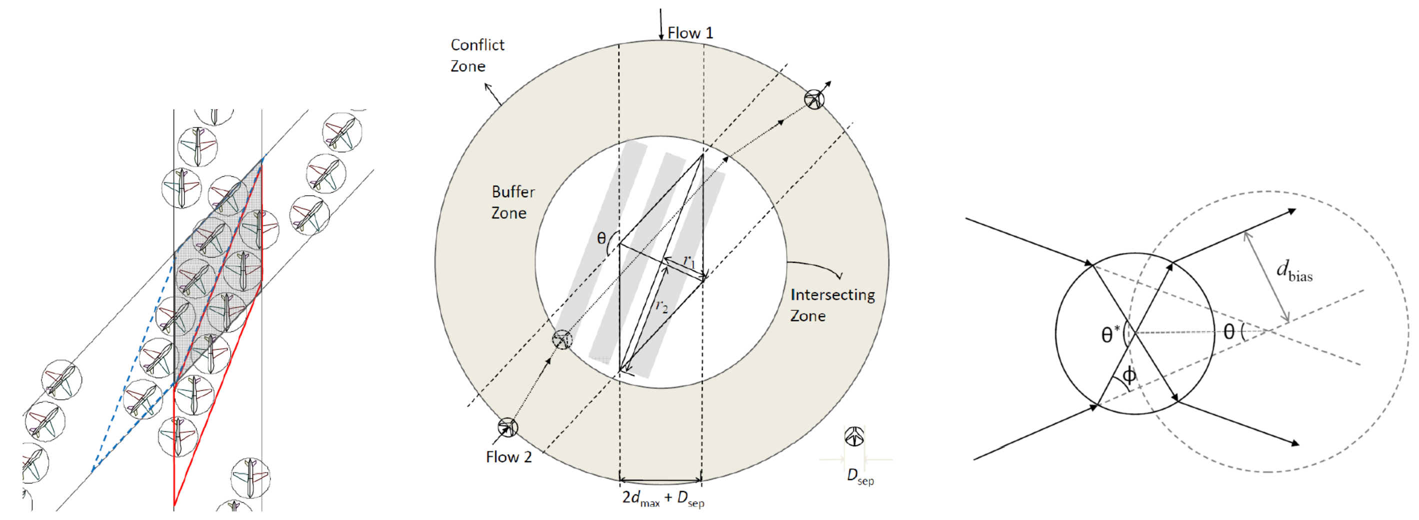

Fig. 4 Traffic intersections as building blocks for air traffic network design. (Left) An example of two intersecting flows. (Middle) A conflict zone centered at the intersection of a pair of flows. (Right) More compact conflict zone at an intersection can be achieved by rearrangement of two flows.

Subtask 2.2: A nonequilibrium-statistical-mechanics-based approach for the design of transportation Networks for stochastic demand and supply models. This research task considers mixed traffic involving both autonomous and human-driven vehicles. We model the human driven models with stochastic dynamics in the direction motion. The autonomous vehicles must consider this motion as they coordinate their actions. Our investigation is inspired by the recent advances in nonequilibrium statistical mechanics (e.g. Fig. 5).

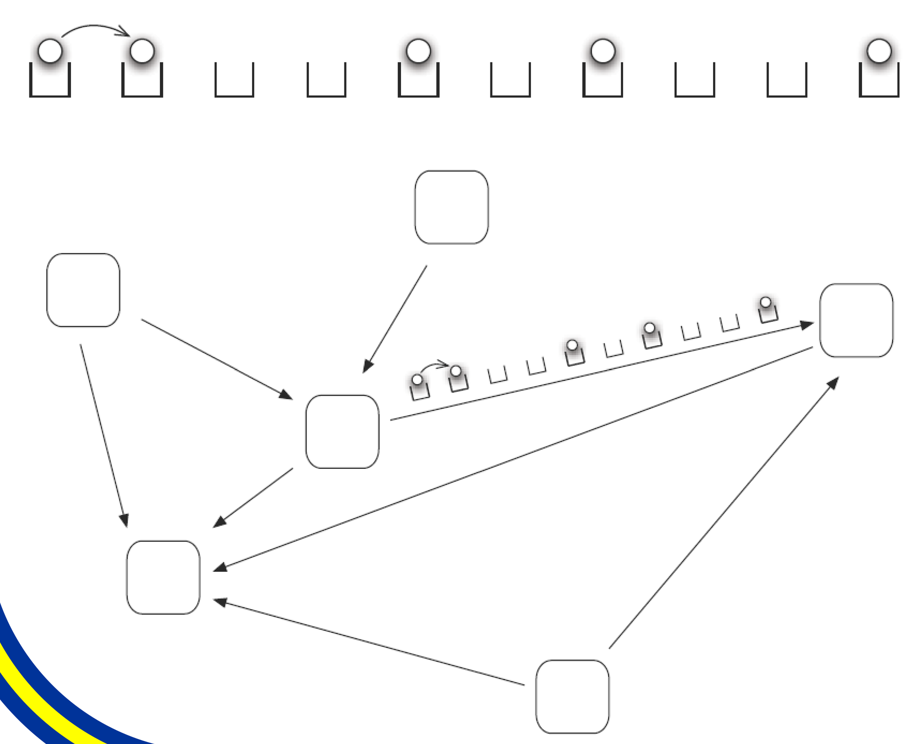

Fig. 5. One of the prominent models of nonequilibrium statistical mechanics—the Totally Asymmetric Simple Exclusion Process (TASEP) model—has been considered to model highway traffic. The TASEP model is depicted on the top figure, and the TASEP on a network depicted in the bottom, where the nodes of the network are shown as boxes and the links connecting the nodes are shown as arrows. Each link is an independent TASEP processes.