CPS: Synergy:

Design and Control of High-Performance Provably Safe Autonomy-Enabled Dynamic Transportation Networks

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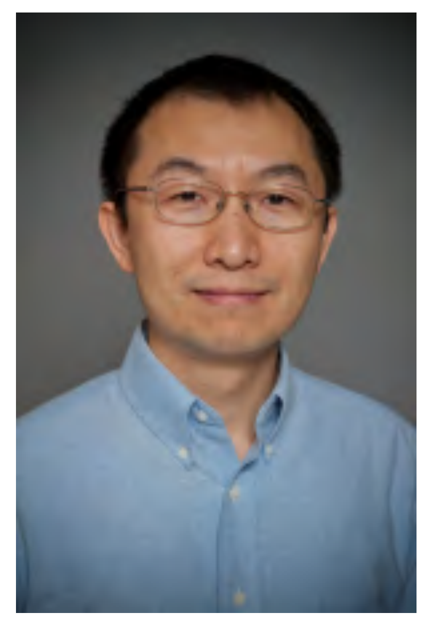

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BIOENGINEERING

Self-Driving Cars

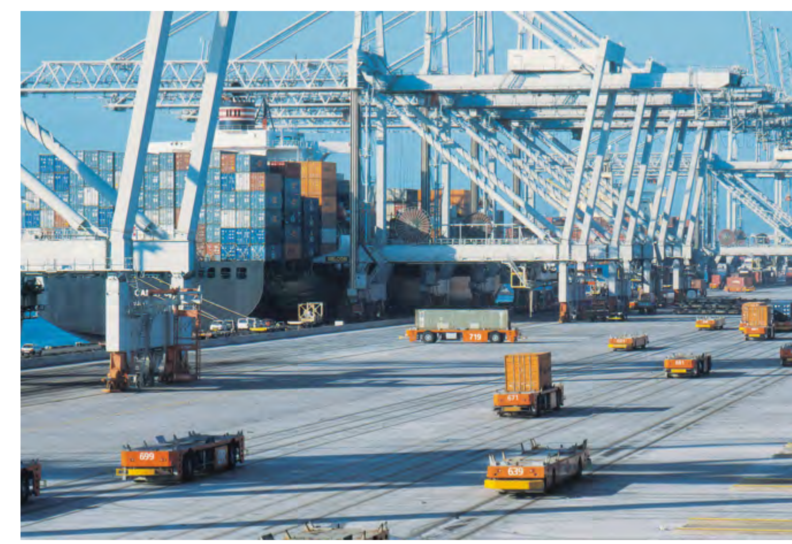
Drone Delivery Platforms

Towards a Foundational Understanding of Autonomy-enabled Transportation Networks

- Vehicles for transportation and logistics are rapidly becoming more autonomous.

- *Systems* that involve several autonomous vehicles may revolutionize transportation.

- They require new coordination algorithms and new infrastructure, which must be co-designed.
    - Human element must be considered carefully.
    - (Often competing) metrics for evaluation:
        - *Efficiency:* Delay, capacity, …
        - *Sustainability:* Energy, environment, social acceptance, …



- **Foundational problems:**
    - Derive fundamental limits of autonomy-enabled transportation systems.
    - Co-design coordination algorithms and infrastructure that guarantee safety and high performance.

Autonomous vehicles shuttle goods in Kiva Systems warehouses.

Autonomous vehicles in the Port of Rotterdam.

Amazon’s drones may enable same-hour delivery.

Google’s autonomous vehicle may move people and goods.

Research Objectives

- **Objective 1:** To develop a foundational understanding of how automated vehicles can interact in hubs to maximize their performance
    - 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?

Research Objectives

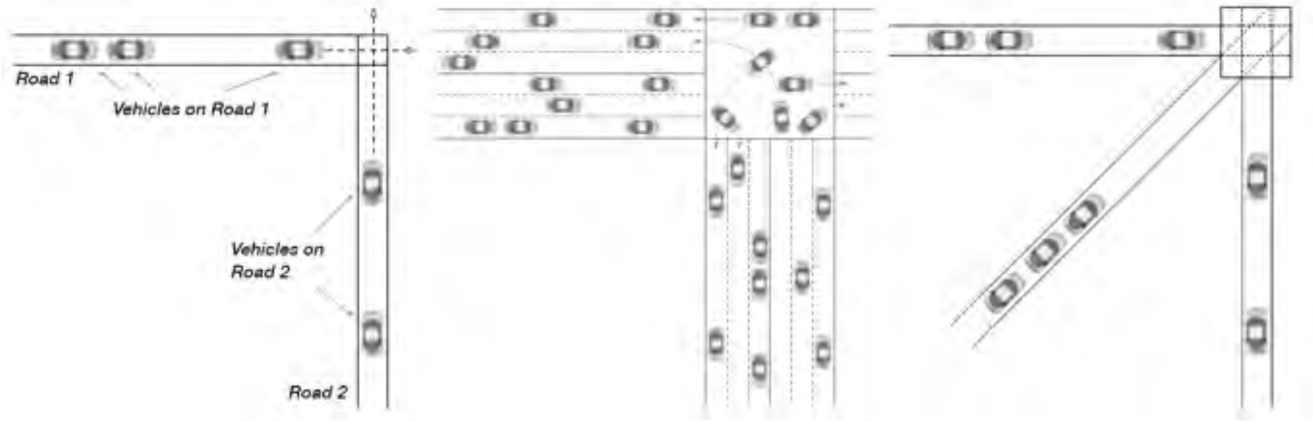
- **Objective 1:** To develop a foundational understanding of how automated vehicles can interact in hubs to maximize their performance

- **Objective 2:** 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.
  - 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?

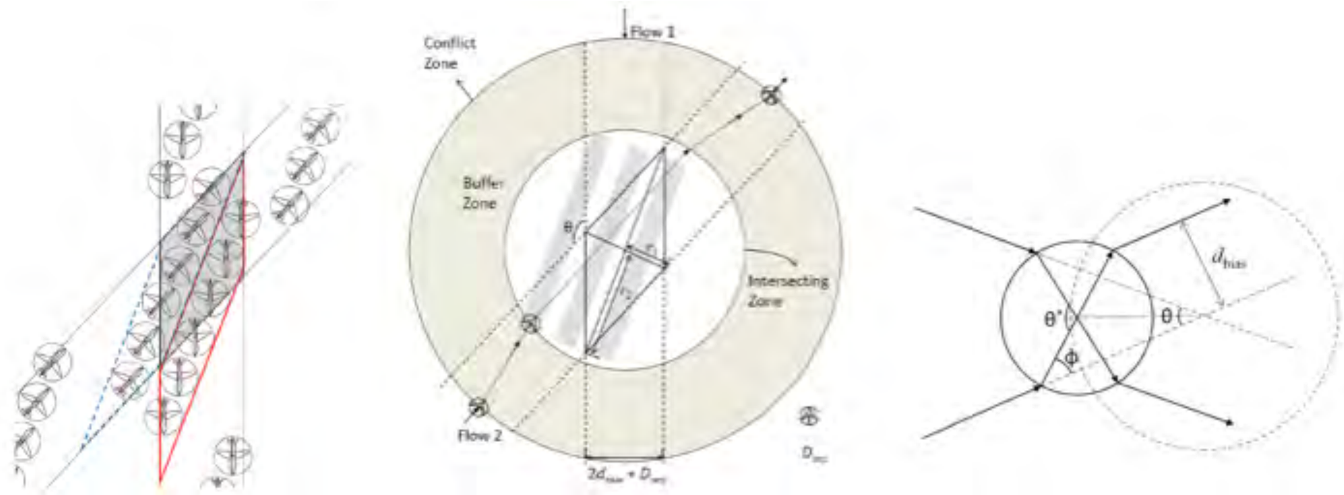
Research Approach

- Split design to: hubs, links, and network design

Hubs (intersections) as building blocks:



[Karaman '14]



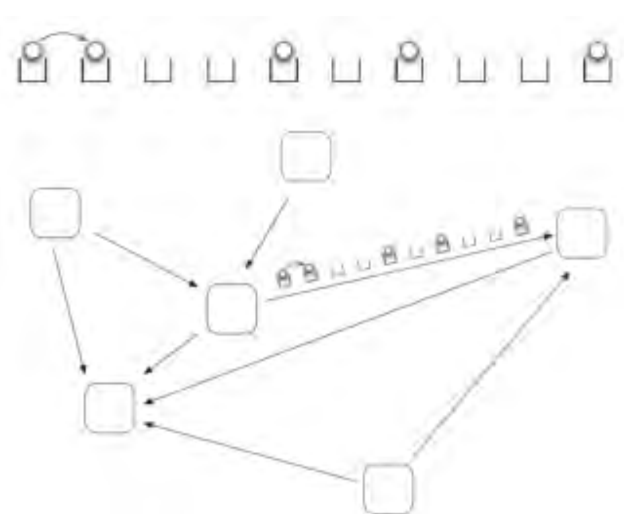
[Zhi-Hong '12]

Research Approach

- Use methods from various disciplines (particularly physics) to understand design autonomy-enabled transportation networks

Methods and analysis:

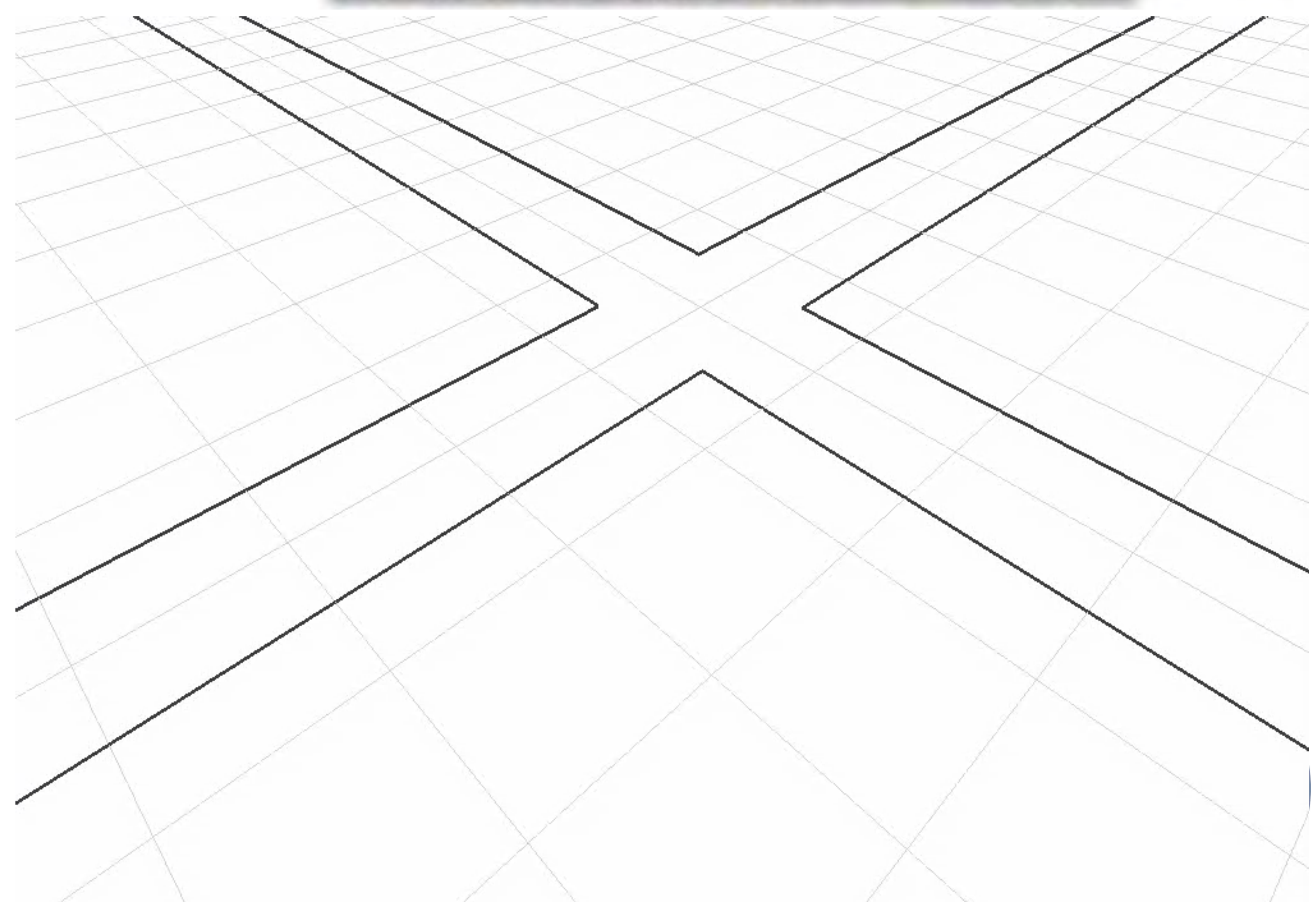
Extract (local) self-organizing principles and learn from expert humans



Use non-equilibrium statistical mechanics for the design of architecture and algorithms

Focusing on Intersections

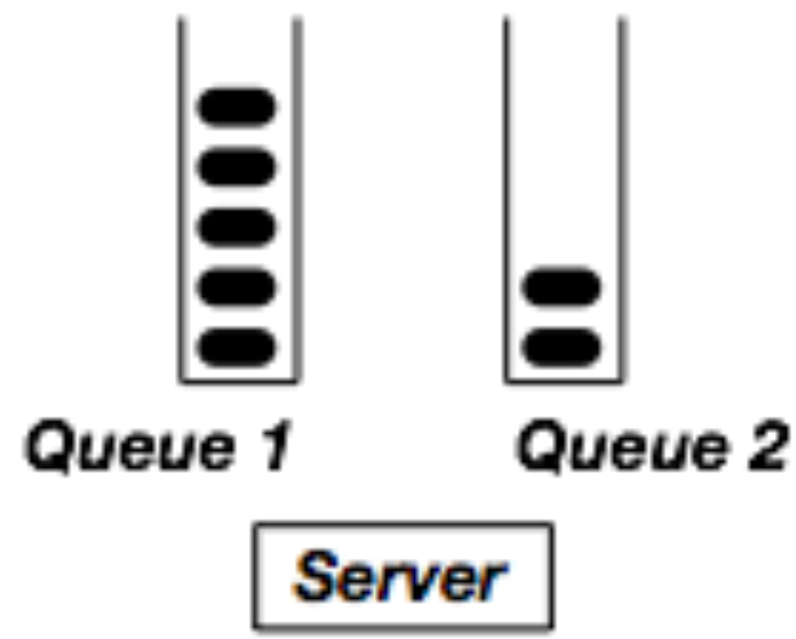
- **Motivation:**
  - Large amounts of time spent in intersections.
    [Pandian et al., 2009], [Ban et al., 2009], …
  - Complex, costly road networks designed to alleviate this problem.
- **Research questions:**
  - Understand the fundamental limits of intersections.
  - Design algorithms that operate close to fundamental limits.
- **Existing work studies:**
  - Agent-based simulations with no guarantees
    [Dresner & Stone, 2006], …
  - Deterministic arrival models to understand worst case [Mao et al., 2001], [Hafner et al., 2013], …



[Miculescu and Karaman,'16]

Polling Systems in Data Networks

- Customers arrives in two queues with rates λ_1 and λ_2
- The server can choose to serve customers from either queue; each service incurs service time s_1 or s_2
- But, switching queues requires some additional setup time r

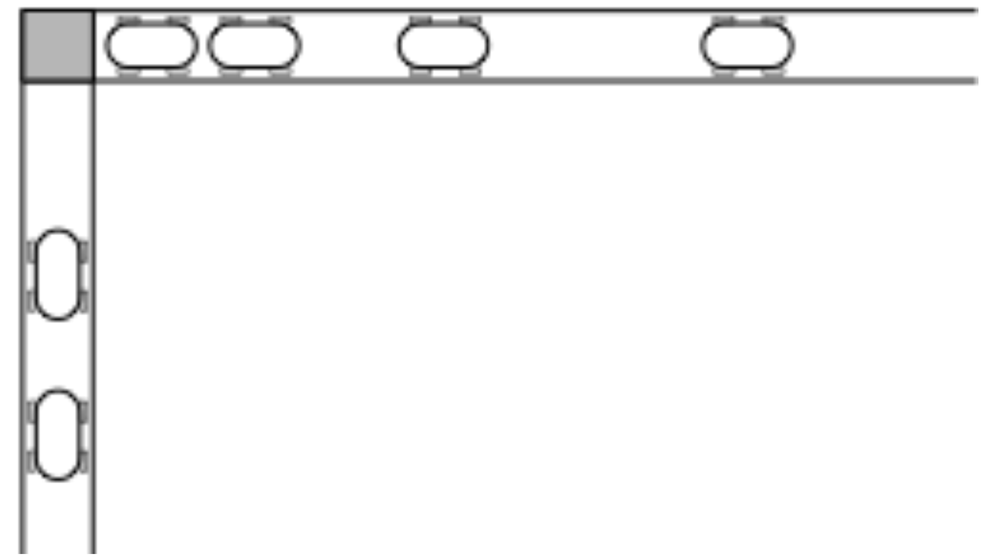


Polling Policies

- **Exhaustive policy:** Serve until all customers in the queue are exhausted; then switch to the next queue.
- **Gated policy:** Right after arrival take a snapshot, and serve all customers in the queue that are in this snapshot; then switch to the next queue.
- **k-limited policy:** Exhaustive or gated, but limited to *k* servings after switchover.

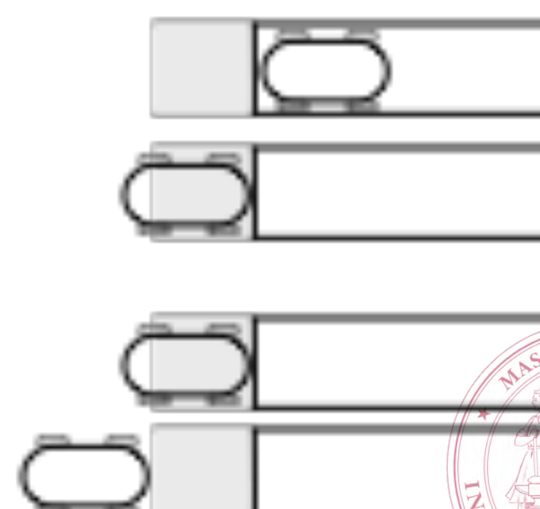
Polling Systems involving Customers subject to Differentially Constraints

- Customers arrive at the "control region" at random times; their motion is subject to differential constraints:
  $$\ddot{x}(t) = u(t), \quad |\dot{x}(t)| \leq v_{\max}, \quad |u(t)| \leq a_{\max}$$
- Design a planning/scheduling algorithm that ensure **safety** and provides provable guarantees on **performance**.



Polling System Relationship

- **Service time** is the time required to go into the intersection area, when the vehicle is right in front of the intersection area.
- **Setup time** is the time required to go outside of the intersection area, when the vehicle is right in the intersection area.



Algorithms with Provable Guarantees on Safety and Performance

- **Each time a new vehicle arrives:**

1. Simulate the corresponding polling system to schedule the times that vehicles use the intersection.
2. Plan the vehicles paths to ensure that they make their slots:

$$
\begin{aligned}
\underset{x:[t_0,\tau]\to\mathbb{R}}{\arg\min} \quad & \int_{t_0}^{\tau} |x(t)|\,dt \\
\text{subject to} \quad & \ddot{x}(t) = u(t), \ \text{for all } t \in [t_0,\tau]; \\
& 0 \le \dot{x}(t) \le v_{\max}, \ \text{for all } t \in [t_0,\tau]; \\
& |u(t)| \le a_{\max}, \ \text{for all } t \in [t_0,\tau]; \\
& |x(t) - x'(t)| \ge l, \ \text{for all } t \in [t_0,\tau]; \\
& x(t_0) = -L; \quad \dot{x}(t_0) = v_{\max}; \\
& x(\tau) = 0; \quad \dot{x}(\tau) = v_{\max}.
\end{aligned}
$$

KEY IDEA

- The vehicles always pass through the intersection with maximum speed.
- The optimization algorithm ensures that the vehicles travel at maximum speed as long as possible after their arrival in the system.

Safety and Performance Guarantees

- **Assumption:** The road length satisfies $L \geq v_{\max}^2 / a_{\max}$

- Then, the proposed coordination algorithm guarantees:

Theorem 1 (Safety) No collisions occur surely.

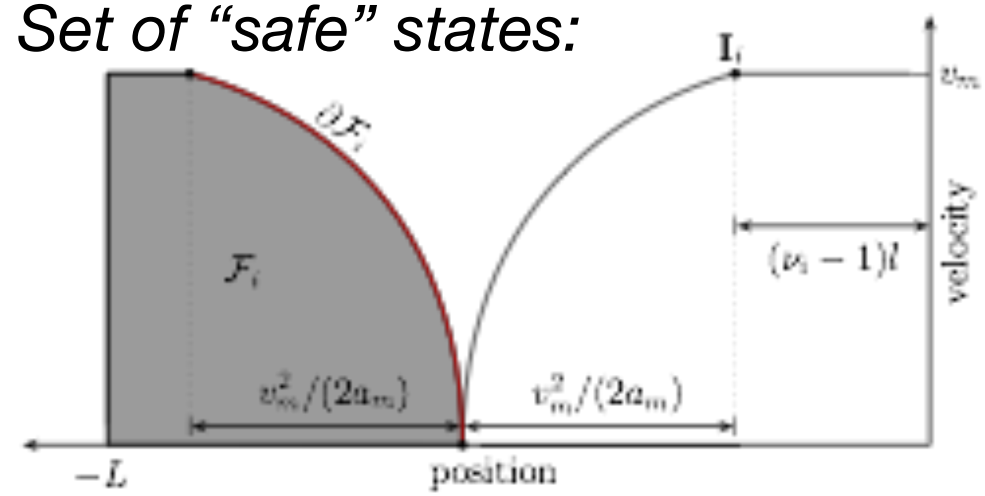
Theorem 2 (Performance) The expected delay* in the differentially-constrained polling system is no more than the polling system (and polling policy) that the control system simulates.

***Expected delay** is the difference between the time required to cross the control region had it been completely empty and the actual time.*

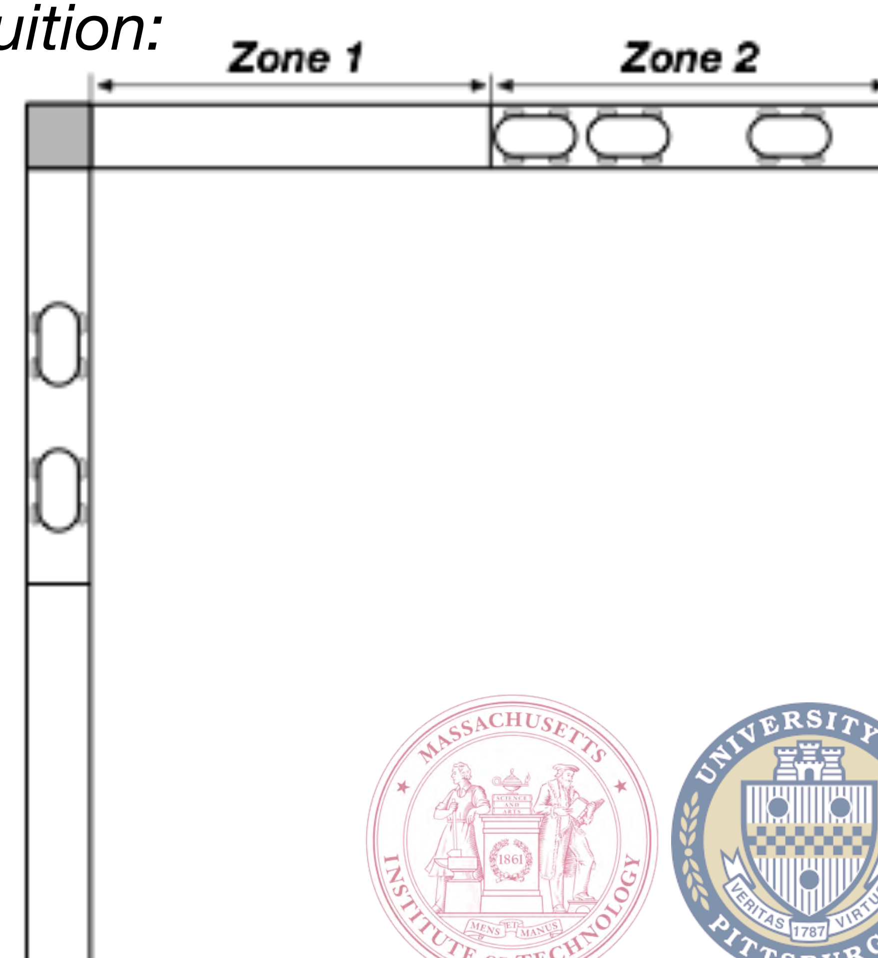
Why Does It Work?

- The proof follows an invariance argument.
- The main hurdle arises when a new vehicle arrives and all of the schedules are updated.
- Roughly speaking, the following ensures no problems arise:
  - Once a vehicle is in Zone 1, its scheduled time to cross the intersection does not change.
  - If a vehicle is in Zone 2, it can delay its schedule as much as it wants.
  - Both of these work because $L \geq v_{\max}^2 / a_{\max}$
- The proof is technical. But, essentially, the intuition for the proof is the same as the argument above.

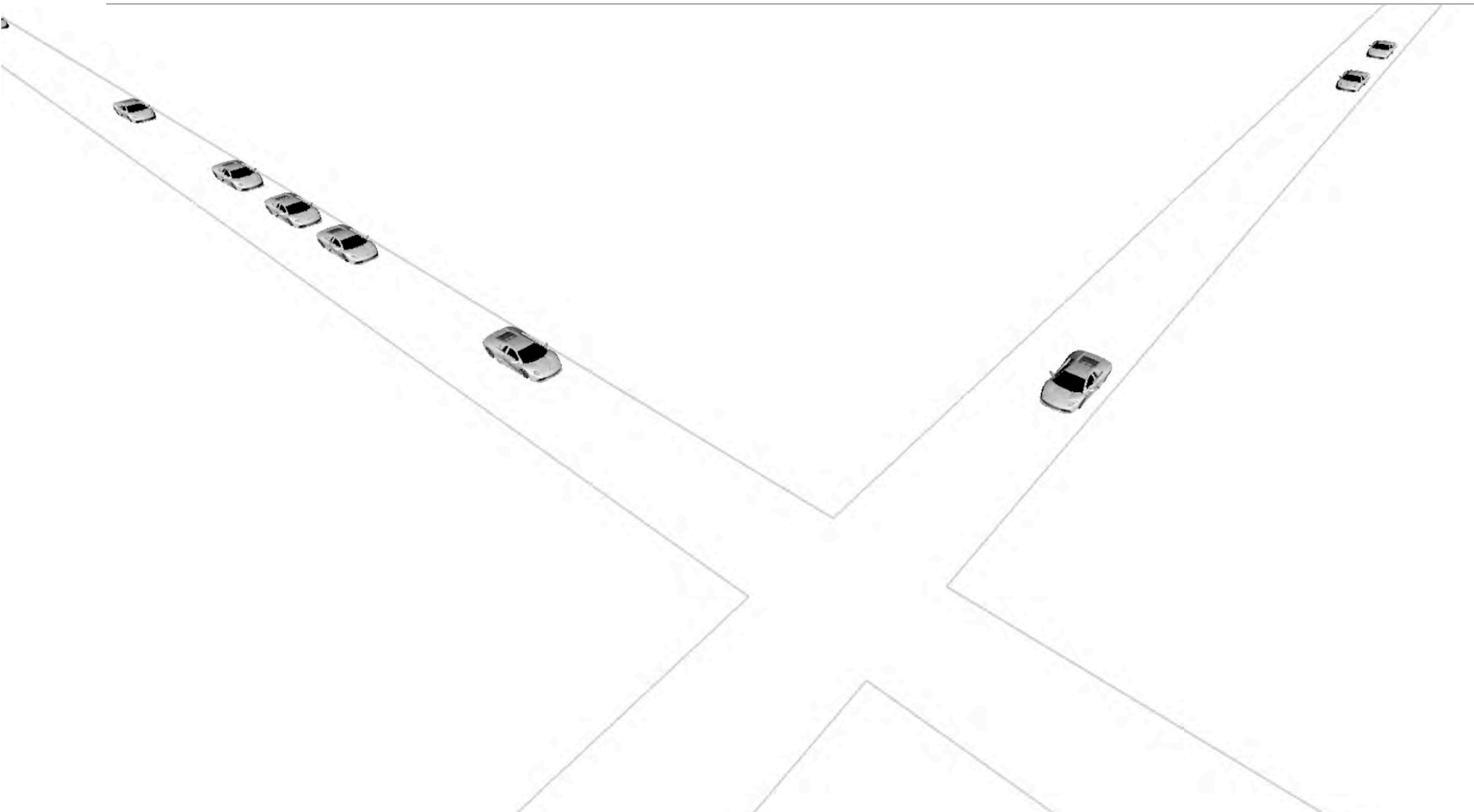
Set of "safe" states:

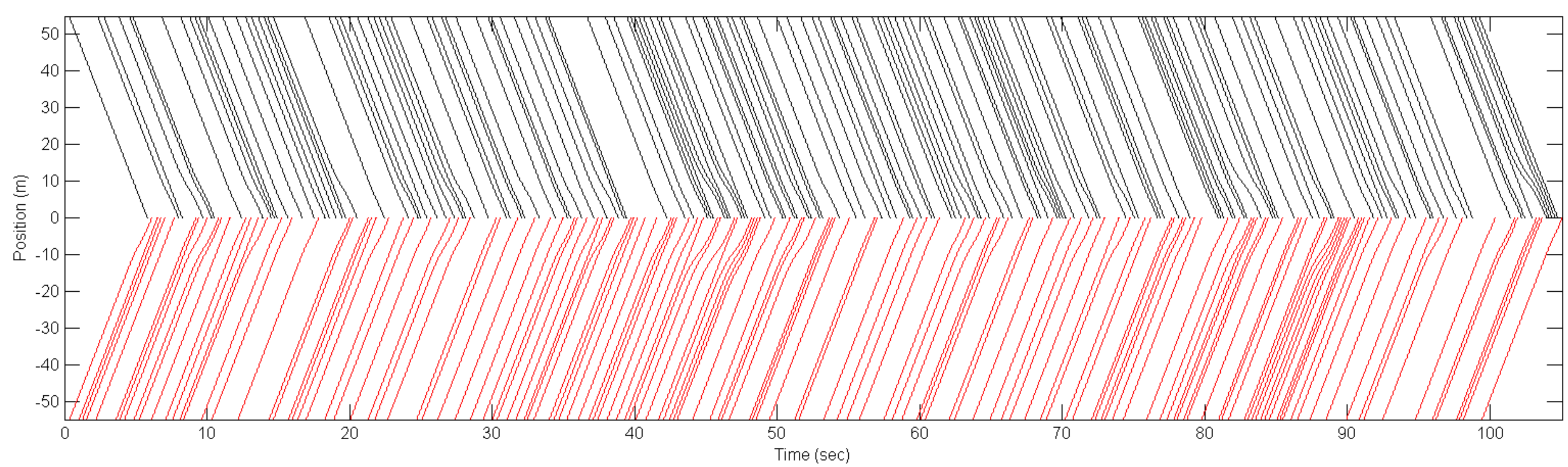


Intuition:

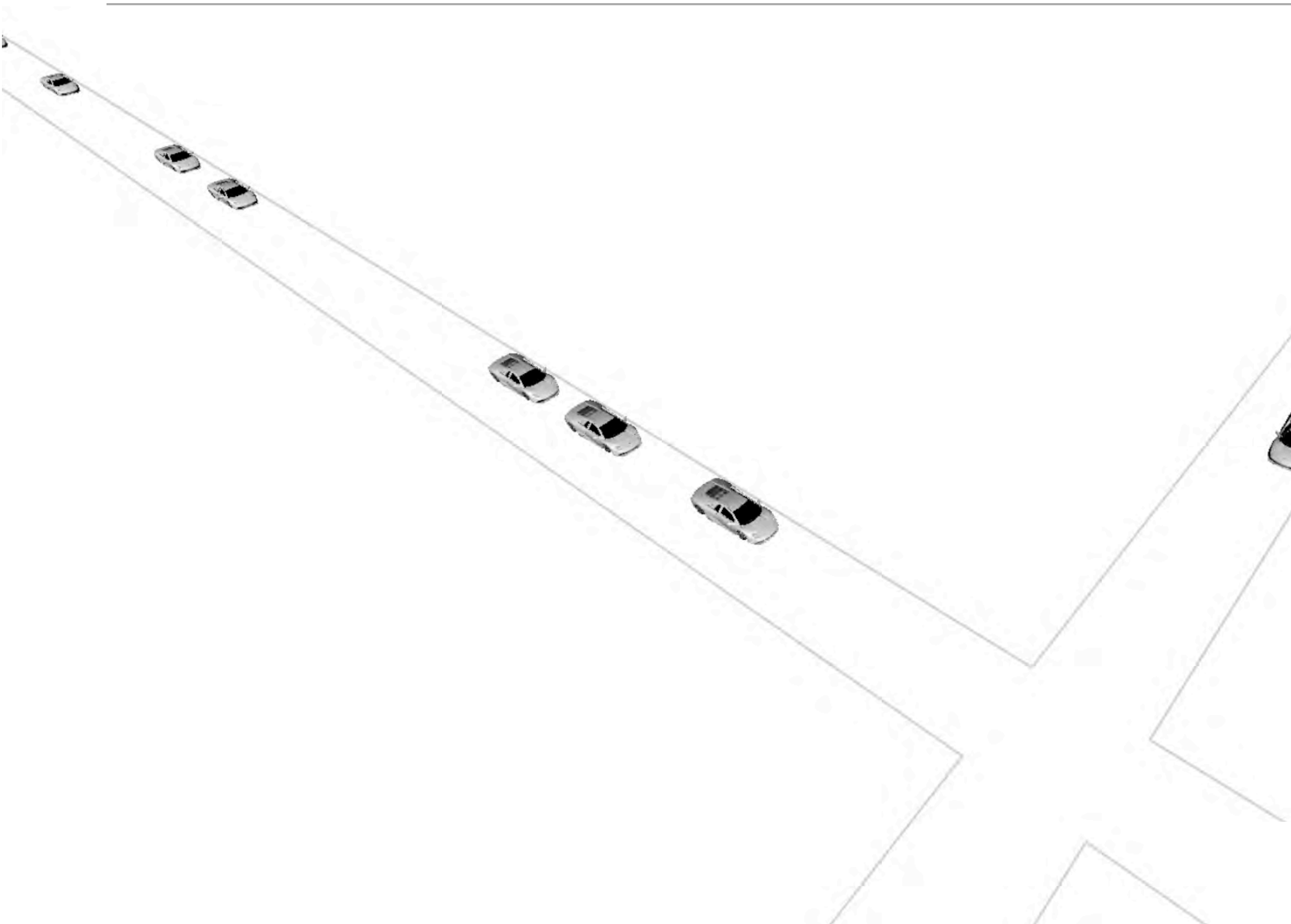


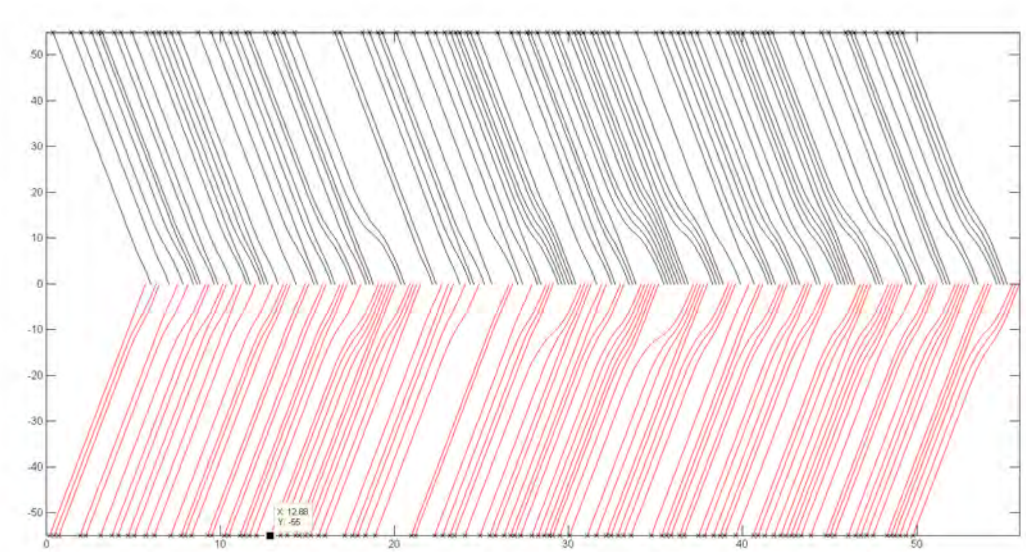
Exhaustive Policy: Light Load Case



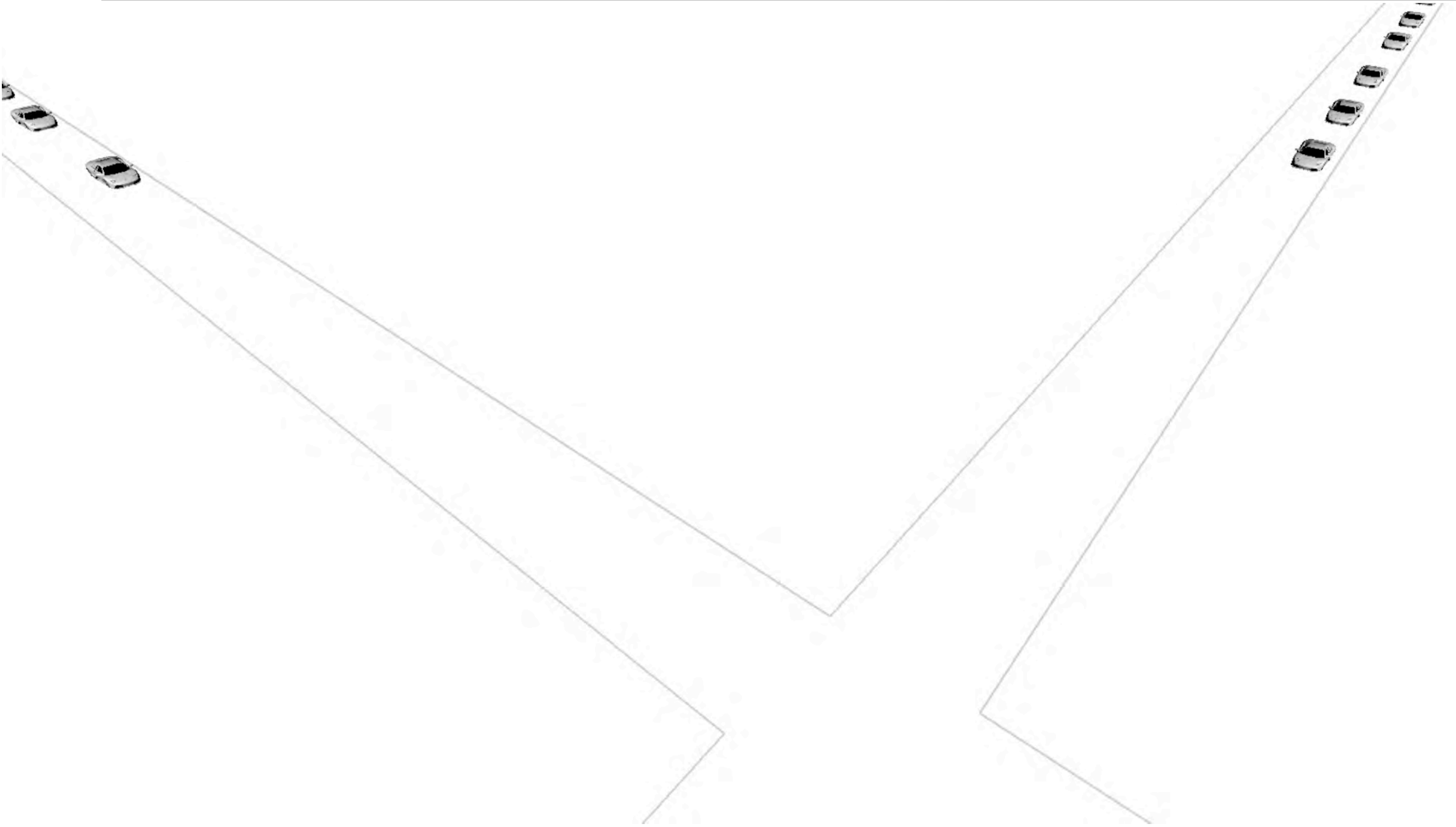


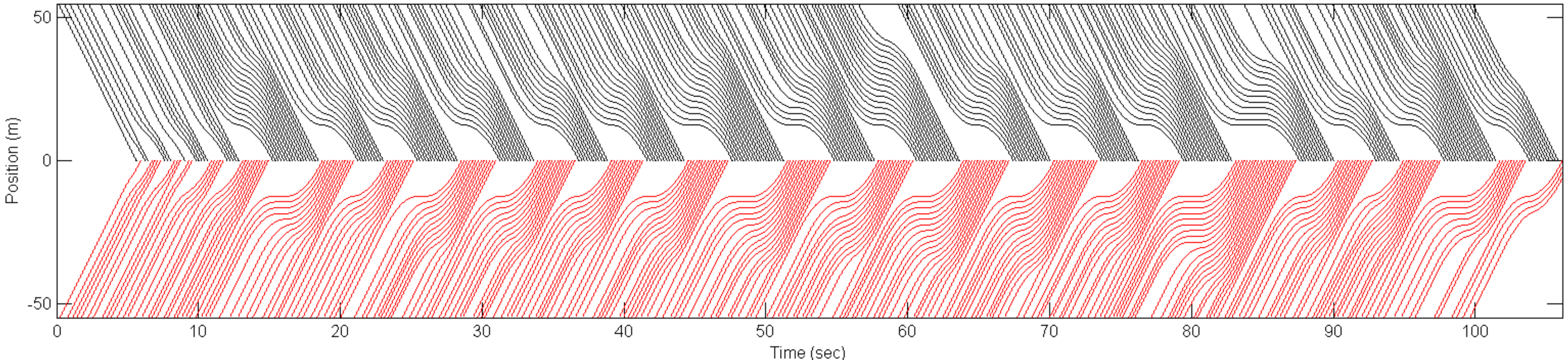
Exhaustive Policy: Medium Load Case





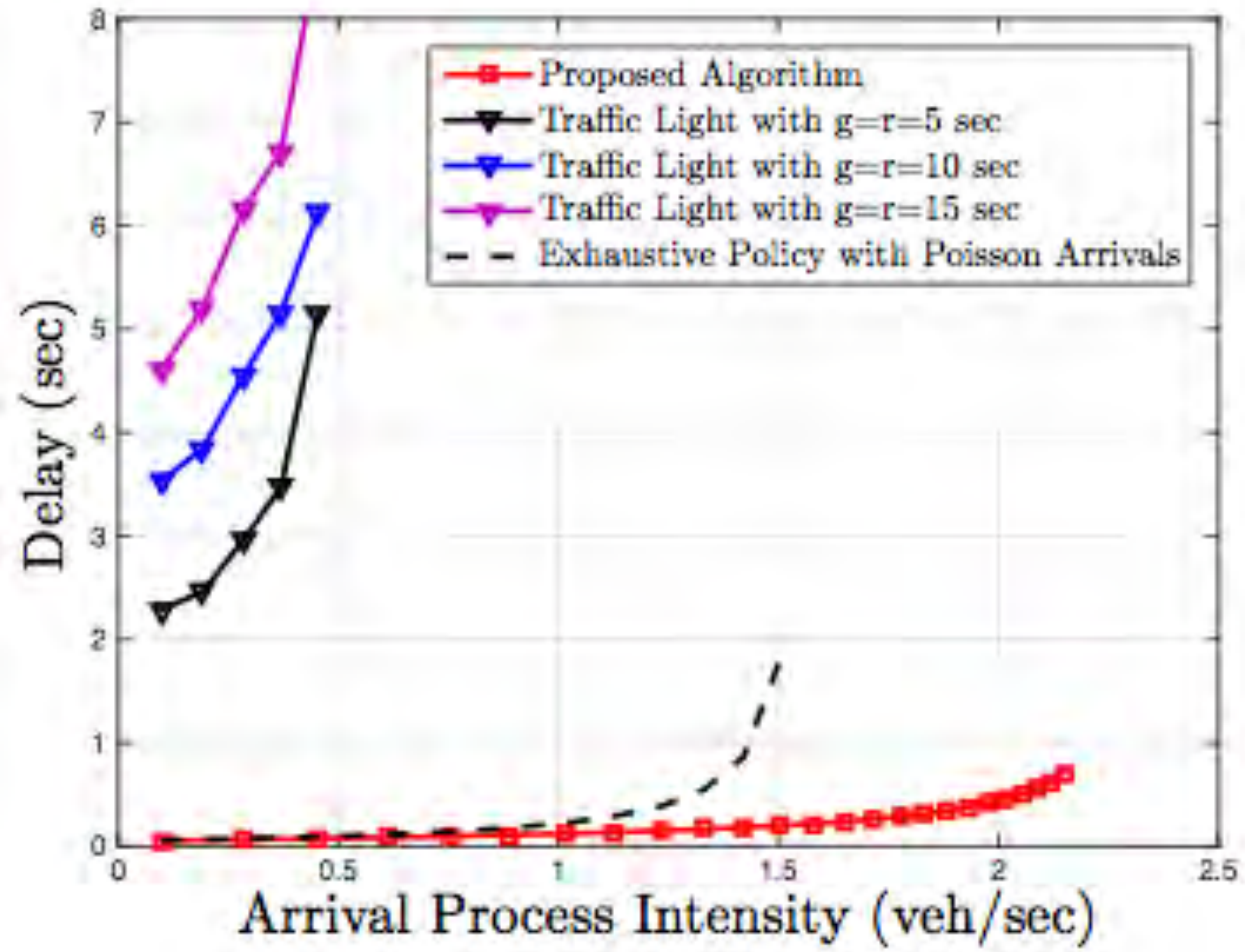
Exhaustive Policy: Heavy Load Case





Comparison with the Traffic Light

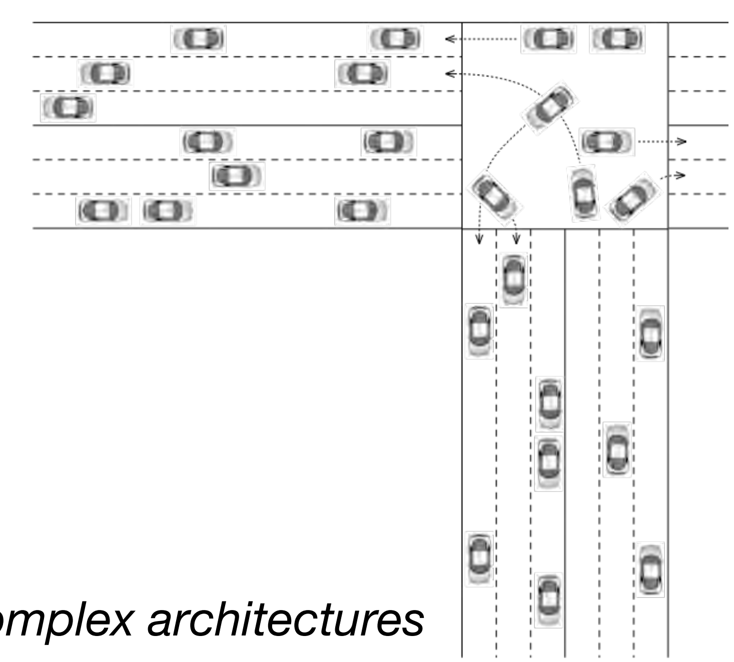
- The proposed algorithm provides substantial gains in expected average delay, when compared to the current traffic-light-based control systems.



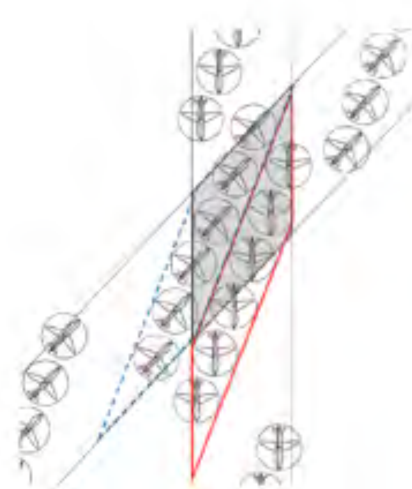
- **Stability:** The traffic light and the new system have similar stability properties. But, the difference in delay in relevant regimes seems to be different!

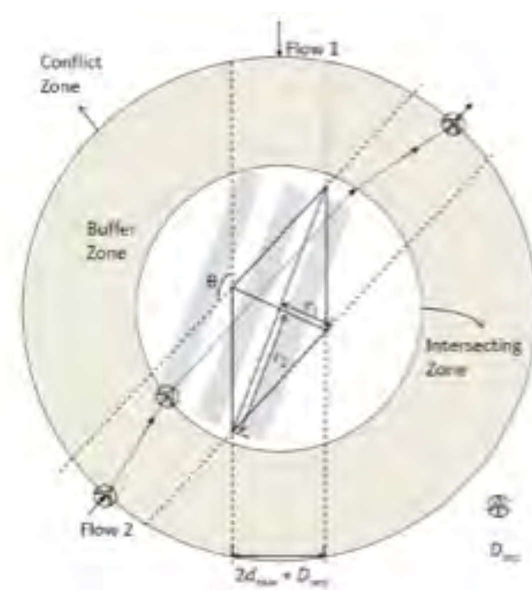
Polling-system-based Coordination Algorithms for Autonomous Intersections

- **Current and future work:**
  - Complex intersection architectures? How do they help?
  - Analyze resilience/robustness for networks of intersections.
  - How can we integrate human-driven vehicles?
  - What are efficiency-sustainability tradeoffs?



complex architectures



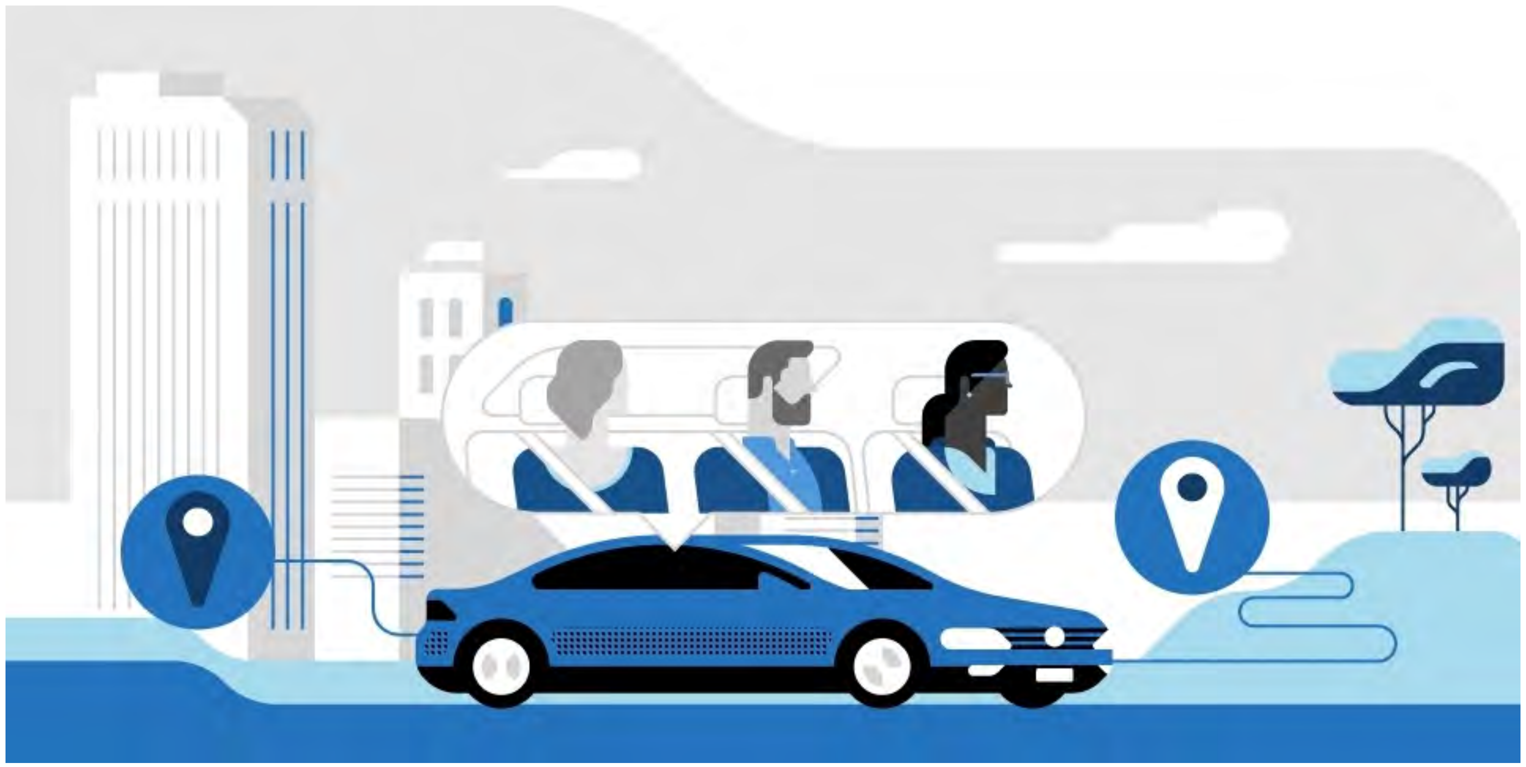


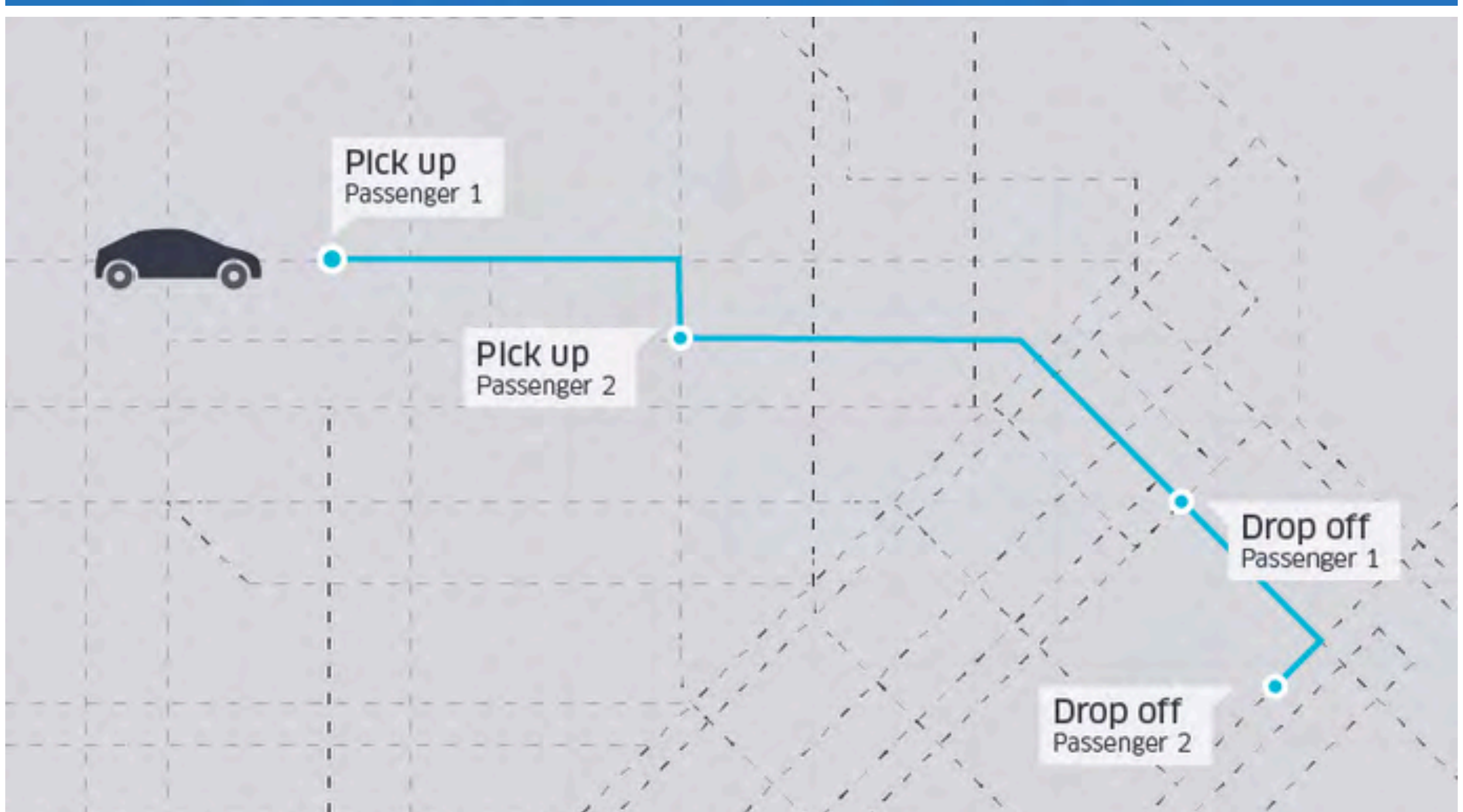
complex architectures

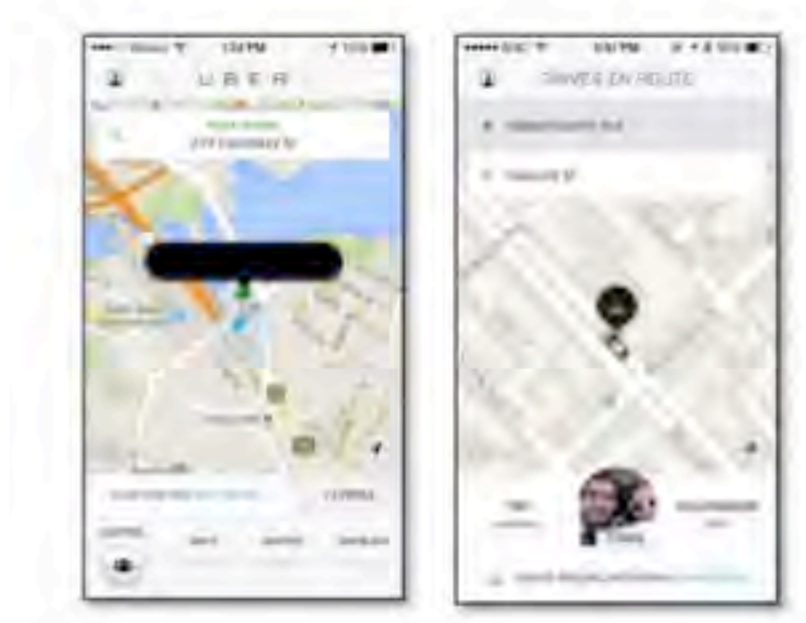
Saving Energy with Better Aerodynamics: Truck Platooning, Bike Drafting, Aircraft Vortex Surfing

[Adler, Miculescu and Karaman, WAFR'16]

Saving Energy with Pooling:
Ride Sharing, Less-than-truck-load Shipping







A Systems Perspective for Platooning, Ride Sharing and Pooling

- Trucks/passengers arrive at a station; all headed to the same destination.
- We assume stochastic arrival process with known statistics.

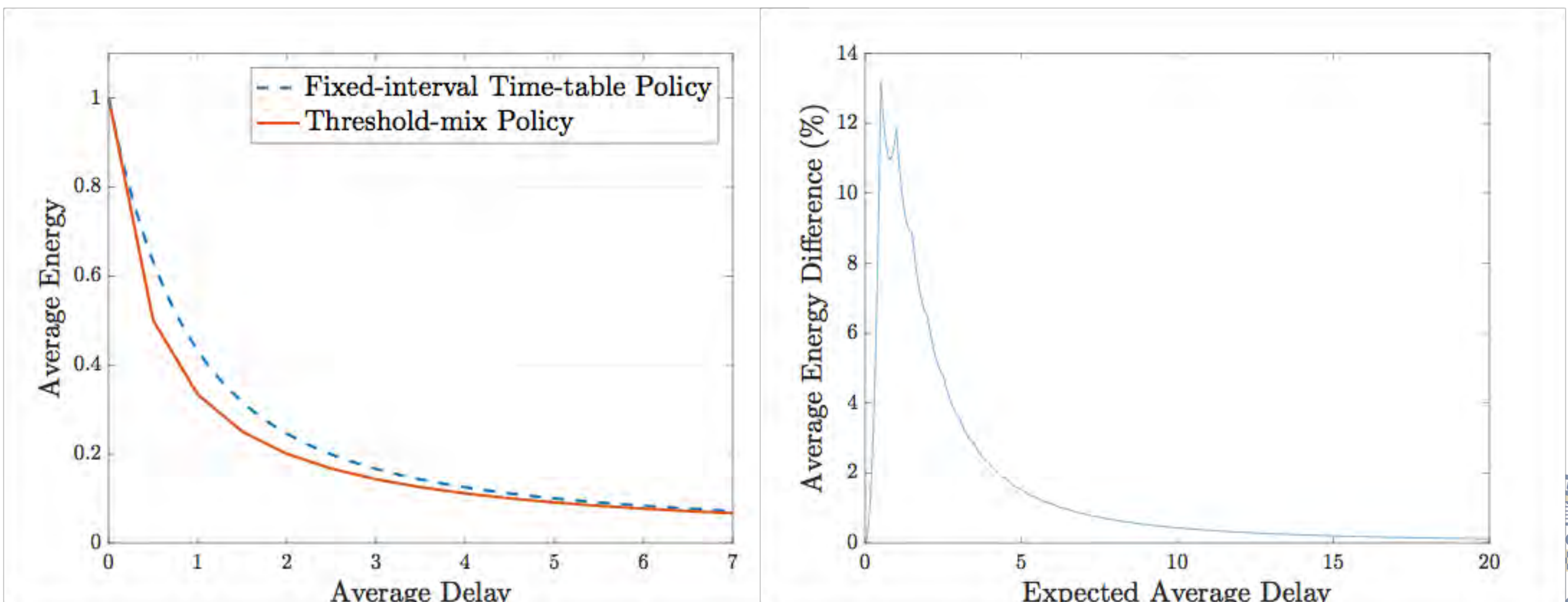
- Trucks/passengers can
  - Save energy: by waiting for other trucks to form large groups;
  - Save time: by heading out in small groups.

- *What is the tradeoff between delay and energy?*

Open-loop (time table) vs. Closed-loop Policies

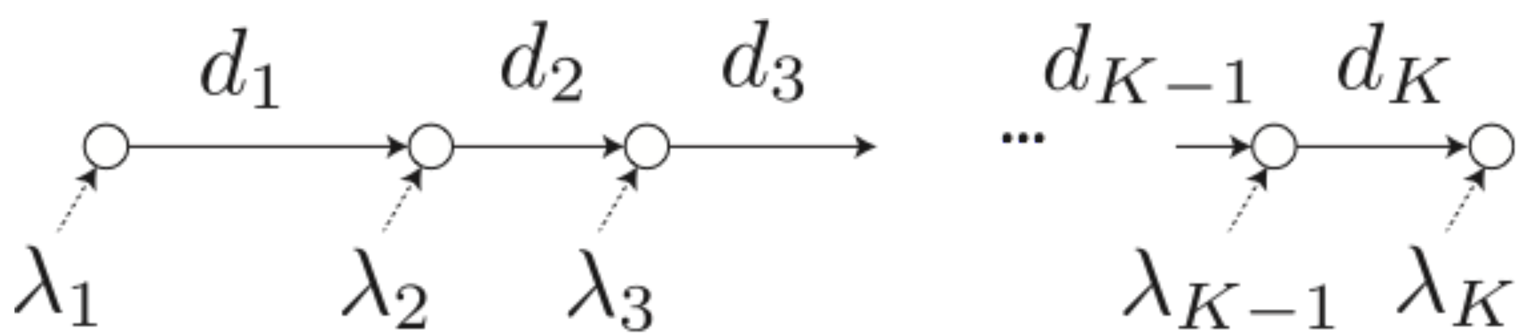
- **Theorem 1:** Optimal open-loop policies are fixed-interval time-table policies.
- **Theorem 2:** Optimal closed-loop policies are threshold mix policies
  (sends out *k* vehicles with prob *p* and *k+1* vehicles with prob *1-p*).

- The performance difference between open-loop vs. closed loop policies: 1 truck/passenger!



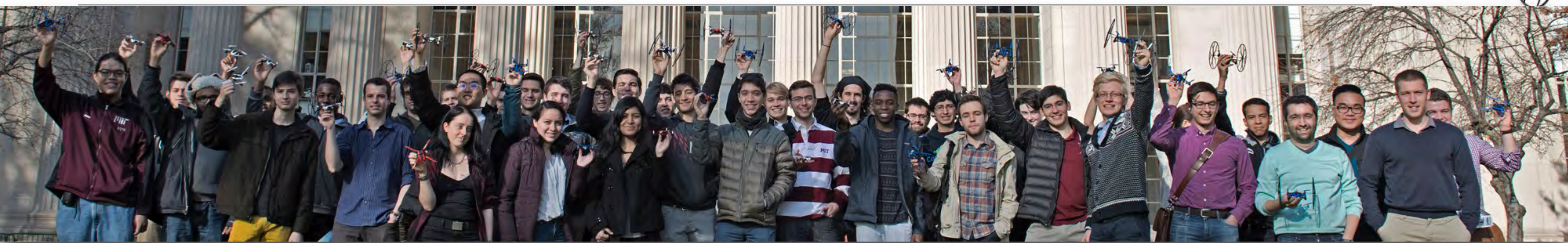
Energy-Delay Tradeoffs for Platooning/Pooling

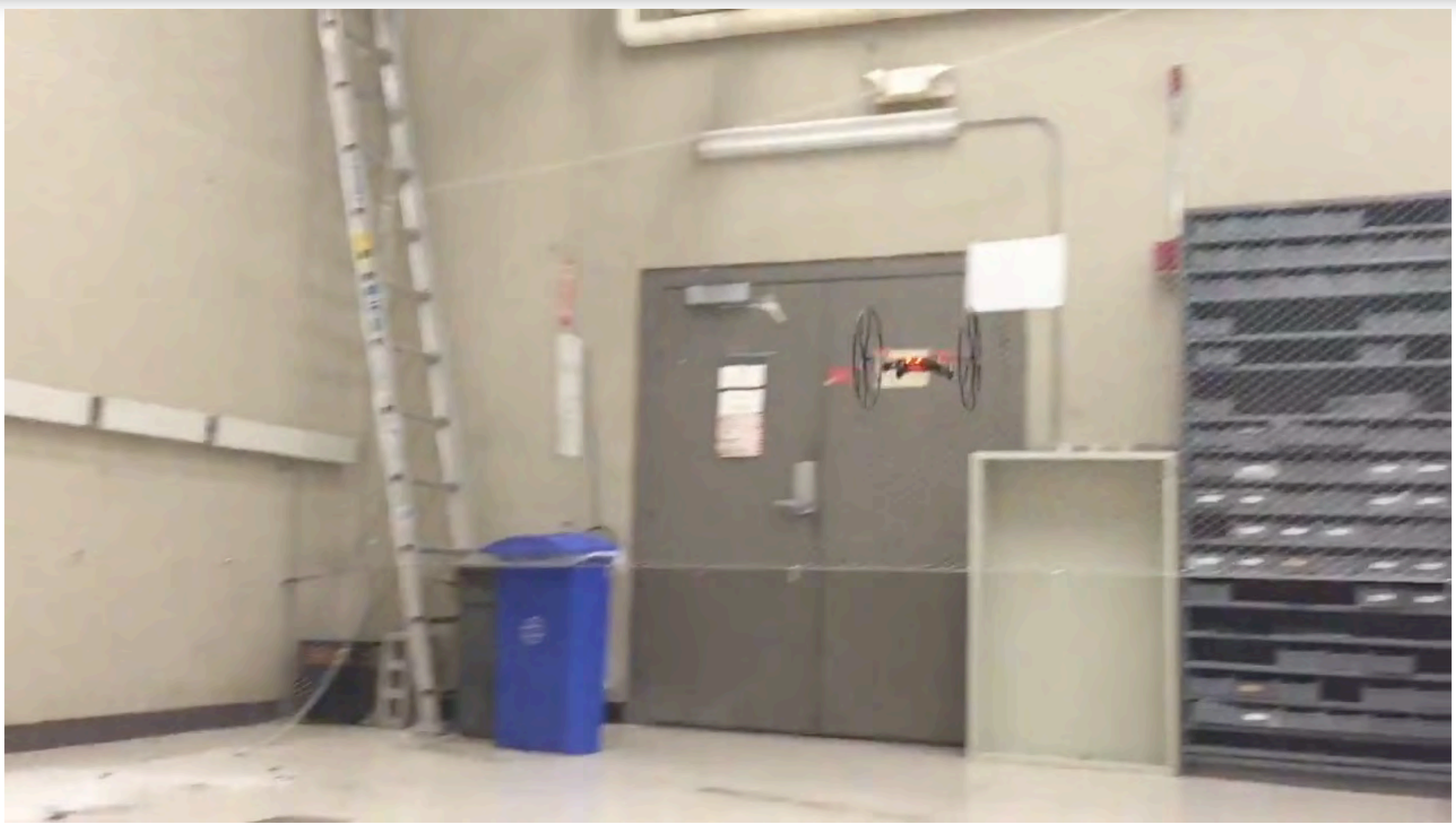
- **Current and Future Work:**
  - Consider multiple stations where trucks/passengers need to wait for each other and synchronize.
  - Consider co-design of infrastructure and algorithms.
    For instance: Where do we place the stations?



Teaching Control Theory with Palm-size Drones:

16.30 Feedback Control Systems





- Each student is given a mini drone.
- Students do the labs at home and come to school for hackathons.

https://github.com/Parrot-Developers/RollingSpiderEdu

Teaching Robotics with Mini Race Cars:
Hackathons, undergraduate, high school courses

- Started Fall 2014.
- Annual MIT Hackathon: January 2015, 2016, 2017, …
- (6.141/16.405) Robotics: Science and Systems (undergraduate EECS/AeroAstro robotics course at MIT) teaches with racecar.

https://github.com/mit-racecar

Completely autonomous cars programmed by high school students!

Questions?

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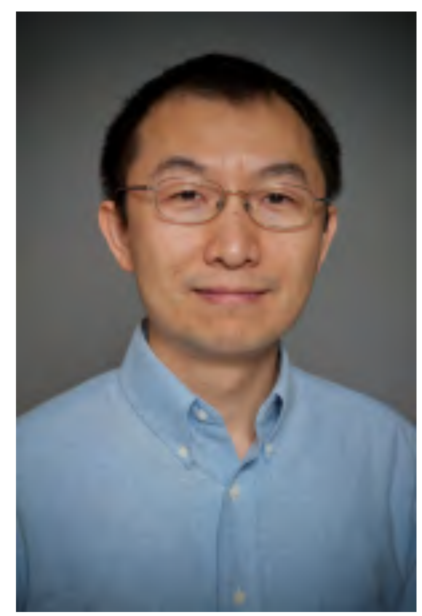

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