From traffic estimation to macroscopic traffic control via multi-commodity back-pressure

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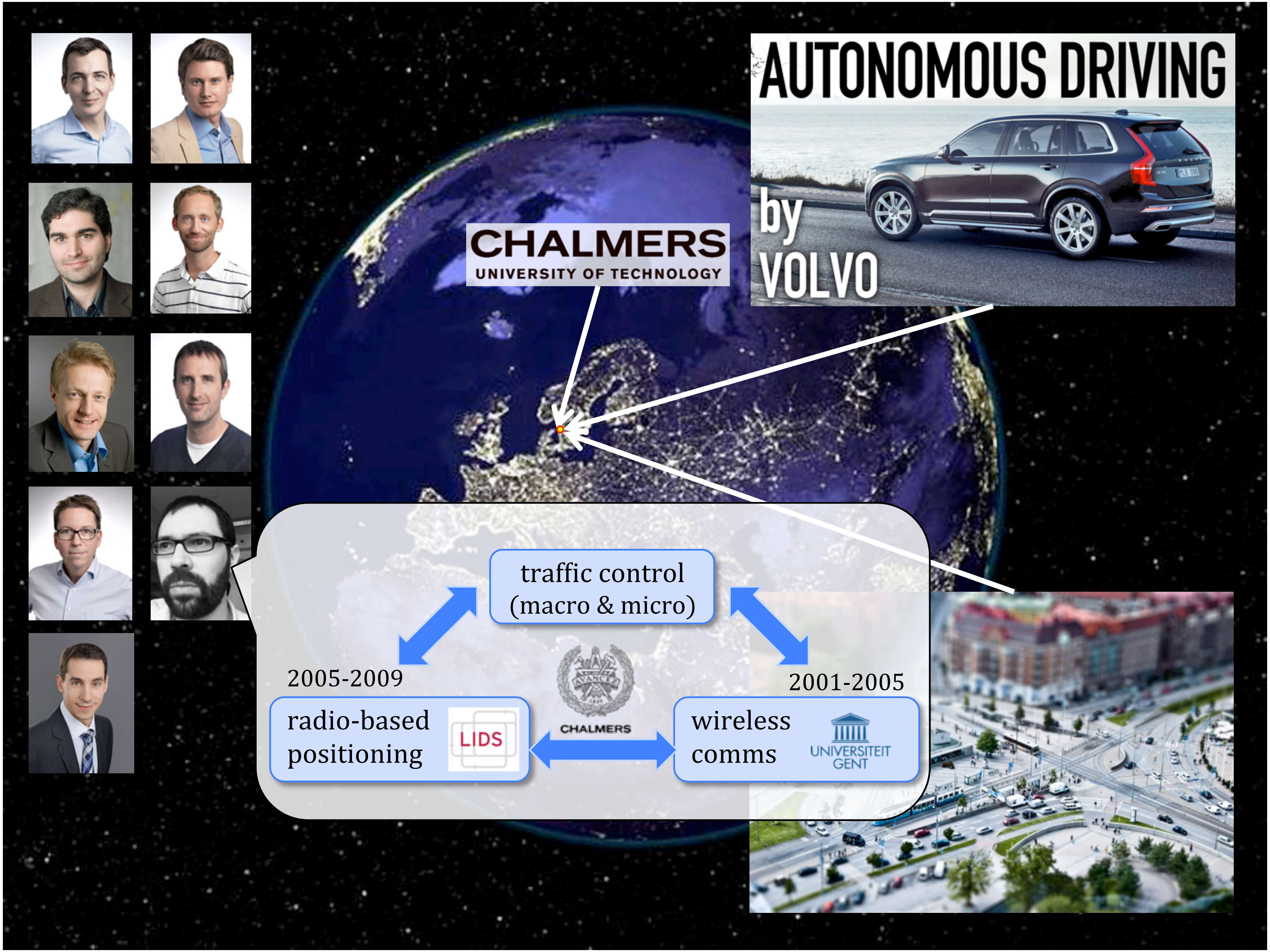
CHALMERS

*Joint work with Balazs Kulcsar, Ali Zaidi, Hamed Farhadi, and Themistoklis Charalambous


AUTONOMOUS DRIVING
by
VOLVO
CHALMERS
UNIVERSITY OF TECHNOLOGY
traffic control
(macro & micro)
2005-2009
2001-2005
radio-based
positioning
LIDS
CHALMERS
wireless
comms
UNIVERSITEIT
GENT

Motivation

Urban traffic predicted to increase

- Limited possibility to build more roads
- Non-invasive methods needed
- Leverage communication capabilities
- Future-proof in combination with autonomous drive

Outline

- Scheduling and routing: problem solved?
- From communication networks to transportation networks
- Traffic flow optimization
- Dealing with uncertainty
- Future work
- Conclusions

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- **Scheduling and routing: problem solved?**
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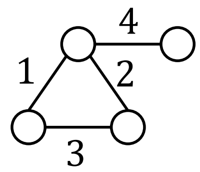
L. Tassiulas and A. Ephremides, "Stability properties of constrained queueing systems and scheduling policies for maximum throughput in multihop radio networks." *IEEE Transactions on Automatic Control*, vol. 37, no. 12, pp. 1936-1948, Dec. 1992.

Single hop communication: max-weight scheduling

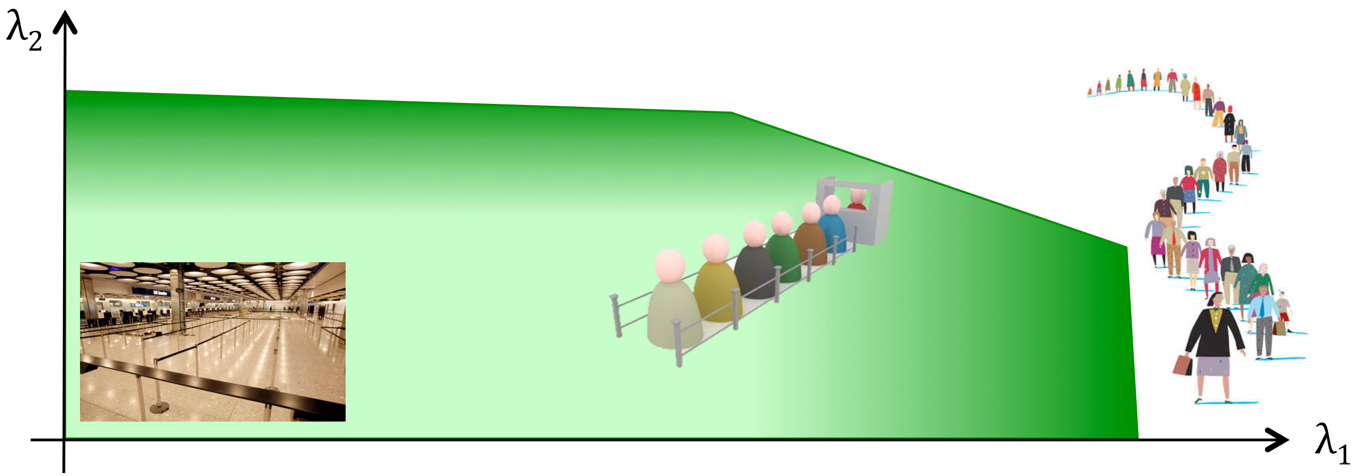
- Ad-hoc network, link *l* has queue $Q_l(t)$ and arrival $A_l(t)$ with rate λ_l
- S = set of feasible schedules (e.g., S={1,2,3,4,(3,4)}) with associated link rates r_l (s)



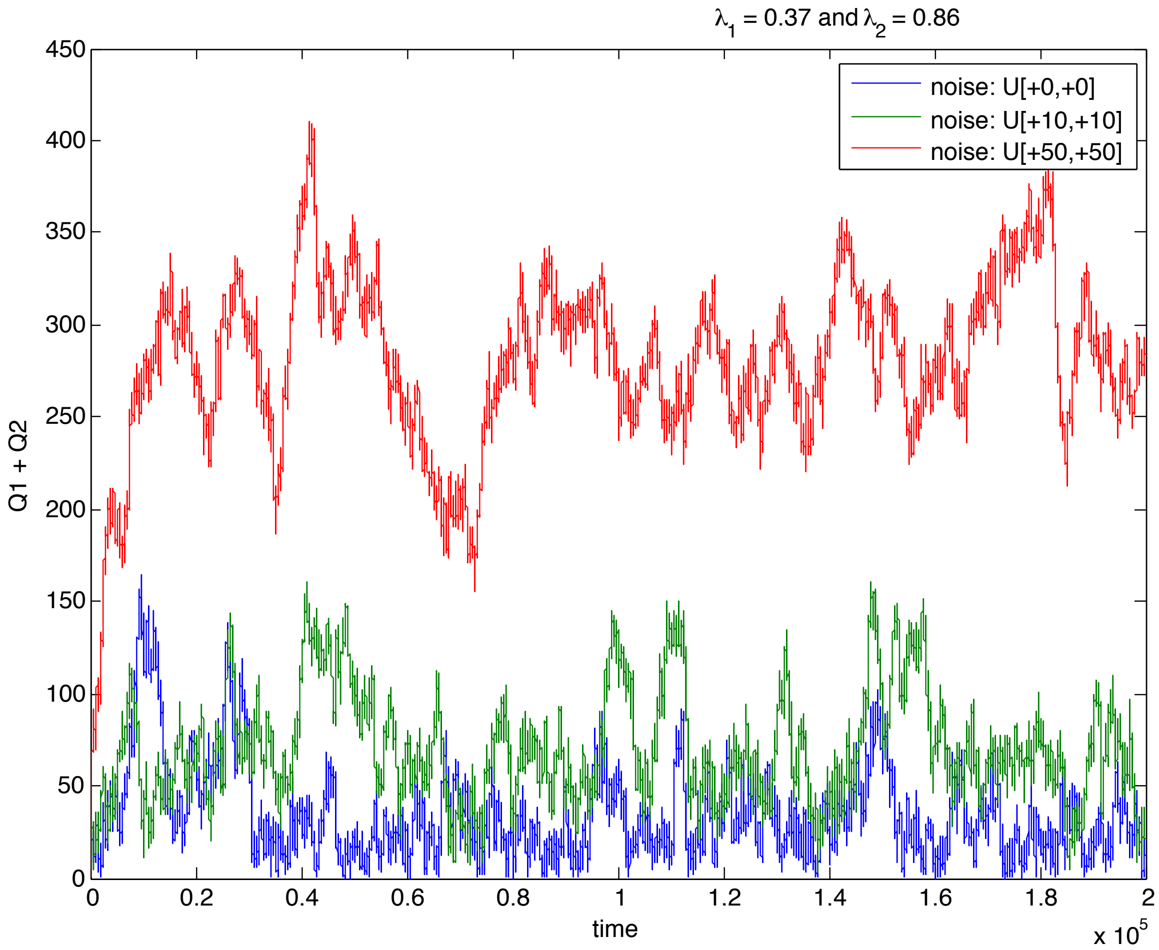
$$Q_l(t+1) = \max(Q_l(t) - r_l(s), 0) + A_l(t)$$

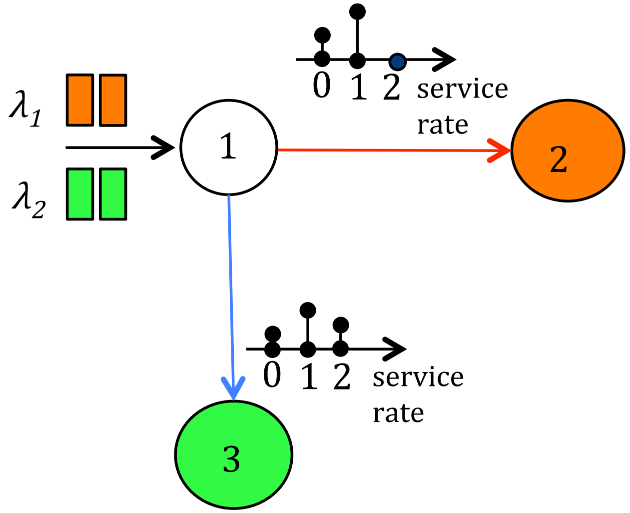
- Max-weight scheduling decision: $s^*(t) \in \arg\max_{s \in S} \sum_l r_l(s) Q_l(t)$
- Stabilizes the network for any $\boldsymbol{\lambda}$ in capacity region

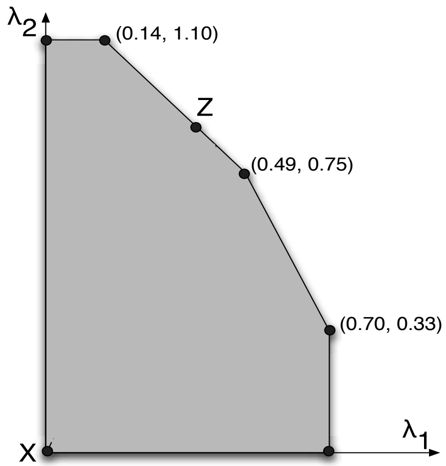
Global knowledge ☹



Max-weight scheduling: performance in noisy conditions







Multi-hop communication: backpressure routing

- Packets arrive at source nodes with rate λ_i
- Flows with same destination: commodity c (destination d(c))
- Each node keeps queue per commodity $Q_i^{(c)}(t)$ with $Q_{d(c)}^{(c)}(t) = 0$
- Control actions $I(t) \in \mathcal{I}$ with resulting rates $\mu_{ij}(I(t))$
- Queue dynamics:

$$Q_n^{(c)}(t+1) = \max(Q_n^{(c)}(t) - \sum_j \mu_{nj}^{(c)}(t), 0) + \sum_i \mu_{in}^{(c)}(t) + \sum_{m \in \mathcal{M}_n^{(c)}} A_m(t)$$

- Links that are allowed to transmit commodity c can be predetermined (e.g., to limit delay)
- **Backpressure:** control policy that stabilizes the network within the capacity region

Multi-hop communication: backpressure routing

- Determine optimal control action:
  1. find optimal commodity for each link (ij): $c^*_{ij}(t) = \arg\max_c (Q_i^{(c)}(t) - Q_j^{(c)}(t))$
  2. find optimal weight for each link (ij): $W^*_{ij}(t) = \max(Q_i^{(c^*_{ij}(t))}(t) - Q_j^{(c^*_{ij}(t))}(t), 0)$
  3. find optimal control action: $I^*(t) = \arg\max_{I \in \mathcal{I}} \sum_{ij} W^*_{ij}(t)\mu_{ij}(I)$

Global knowledge ☹

- Routing: for each link (ij) send $\mu_{ij}(I^*(t))$ of commodity $c^*_{ij}(t)$

Backpressure routing: example

- Control: $\mathcal{I} = \{I_{\text{clock}}, I_{\text{c-clock}}\}$
- Rates: 1 for each link, except 5 for (1→2) and (2→1)
- Optimal commodity:

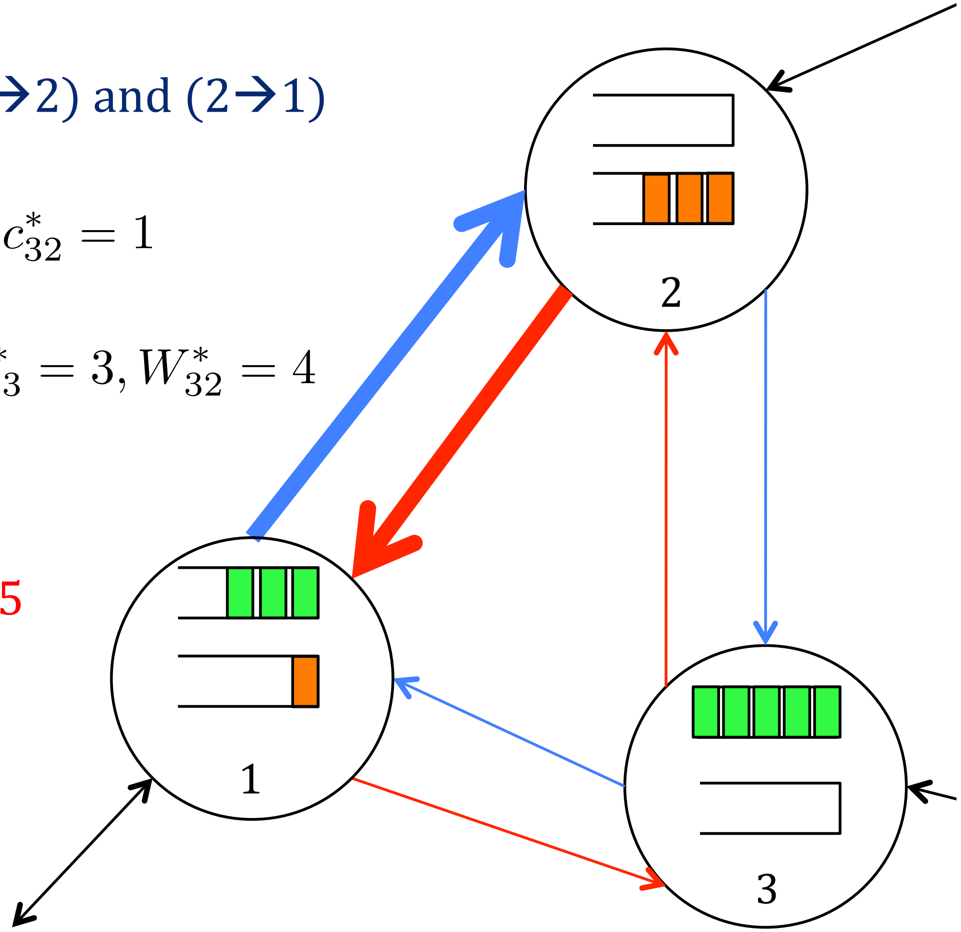
$$c^*_{12} = 1, c^*_{21} = 2, c^*_{13} = 2, c^*_{31} = 1, c^*_{23} = 2, c^*_{32} = 1$$

- Optimal weights:

$$W^*_{12} = 3, W^*_{21} = 2, W^*_{13} = 1, W^*_{31} = 1, W^*_{23} = 3, W^*_{32} = 4$$

- Optimal control: *clockwise*
  - Clockwise: 5×3+3+1=19
  - Counter clockwise: 5×2+1+4=15

$$I^*(t) = \arg\max_{I \in \mathcal{I}} \sum_{ij} W^*_{ij}(t)\mu_{ij}(I)$$



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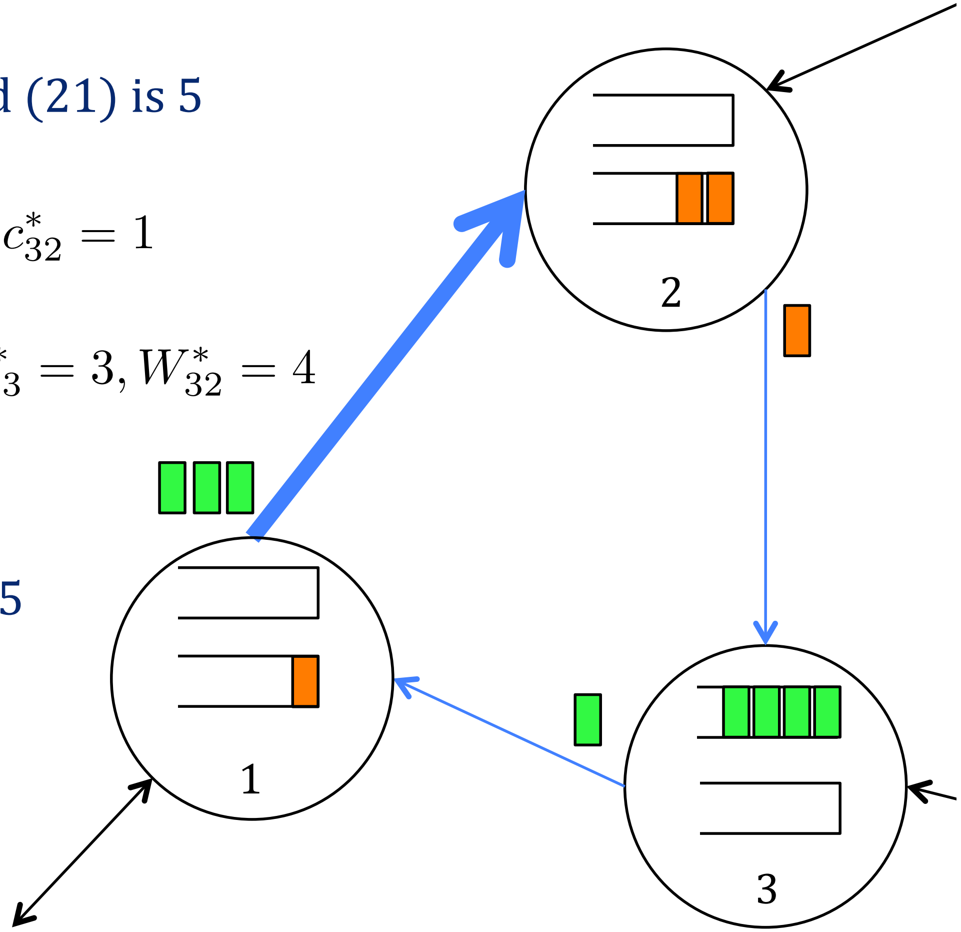

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- Optimal control: *clockwise*
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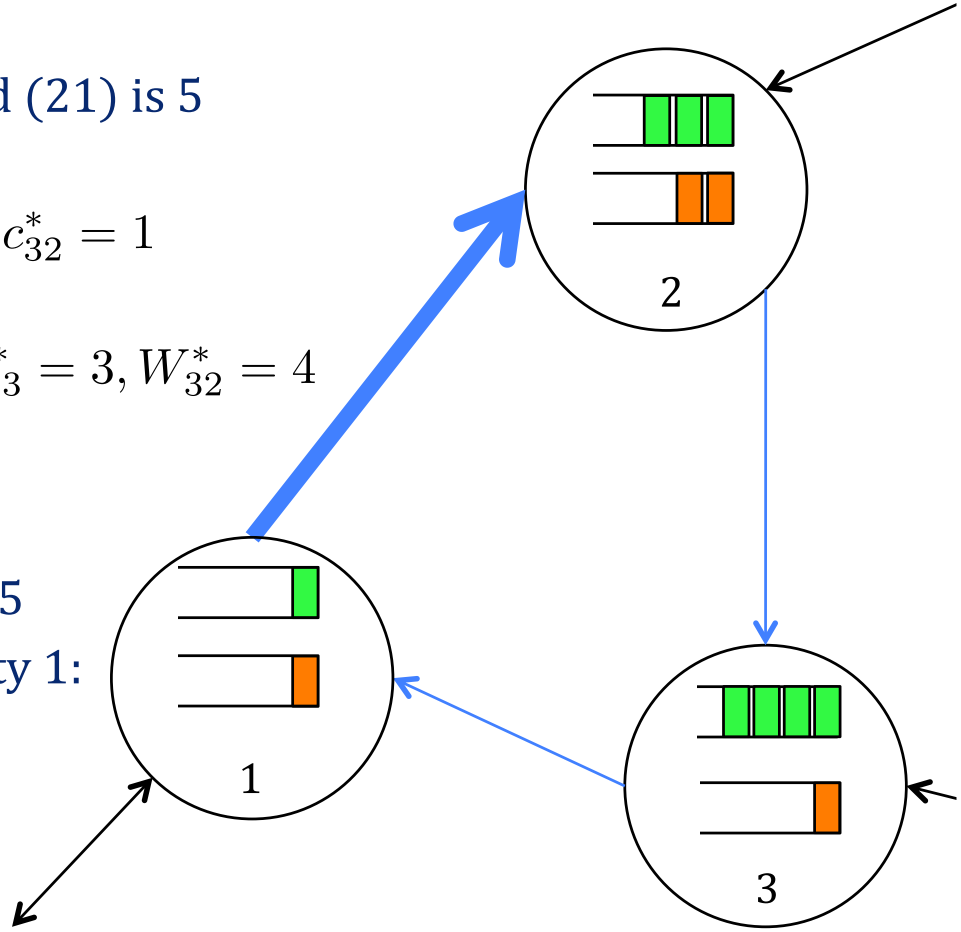
- If node 2 is destination for commodity 1: green queue will be empty again



Outline

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- From communication networks to transportation networks
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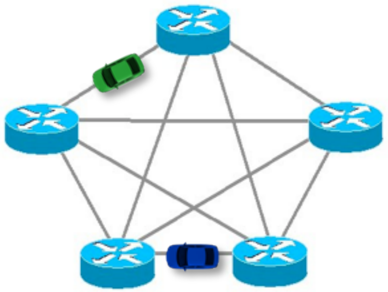
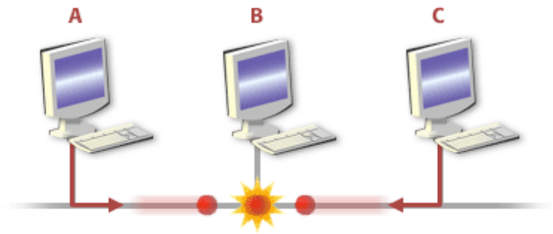
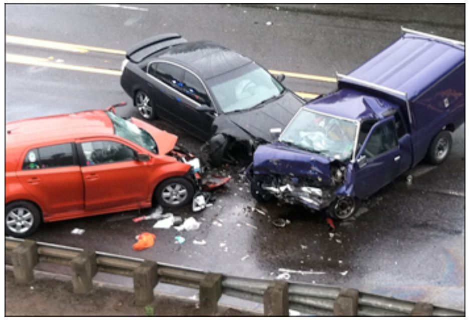
From communication to transport networks

- *Communication:* packets, buffers, links, rates, schedules, routes
- *Transport:* vehicles, roads, junction lanes, flow, junctions phases, routes







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- J. Gregoire, E. Frazzoli, A. Fortelle, T. Wongpiromsarn. "Back-pressure traffic signal control with unknown routing rates." In *the 19th World Congress of the International Federation of Automatic Control (IFAC)*, 2014.
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- J. Van Kampen, "Route Guidance and Signal Control Based on the Back-Pressure Algorithm", PhD. Thesis, Delft University, 2015.

Detailed comparison

	Wireless	Transport
Control actions	hard global problem	easy local problems ☺
Buffers are ordered	no	yes: cars cannot be reordered ☹
Separate buffer for each commodity	yes	no: all commodities are mixed ☹
Transmission rates	Based on information theory / communication theory	Based on phase duration + LWR with fundamental diagram
Queue state	known exactly	estimated through sensors (cameras, loop detectors)
Buffers are infinite	approximately yes	definitely no ☹

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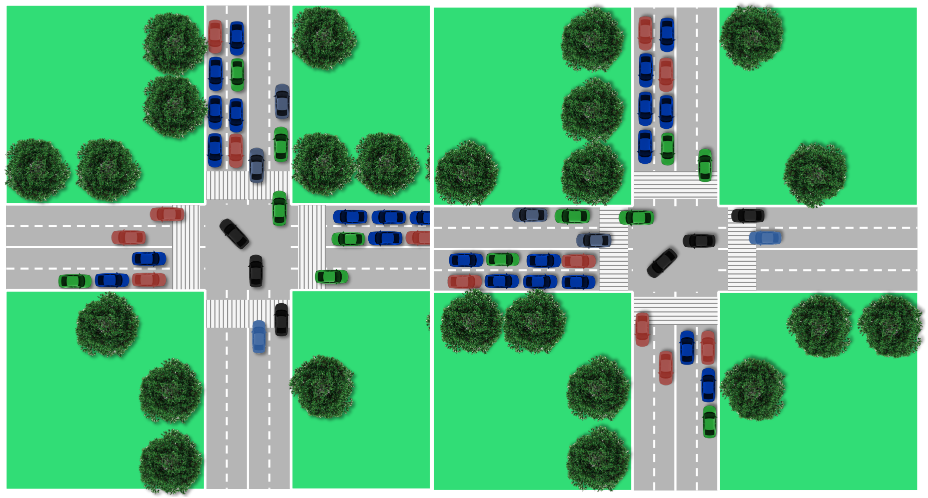
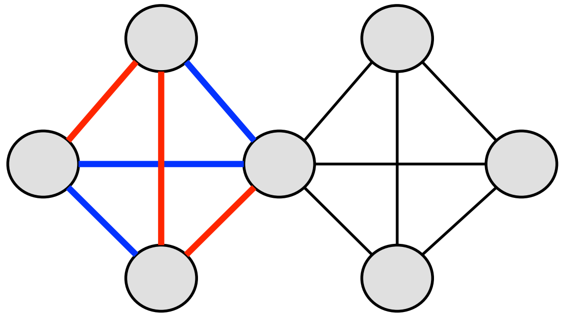
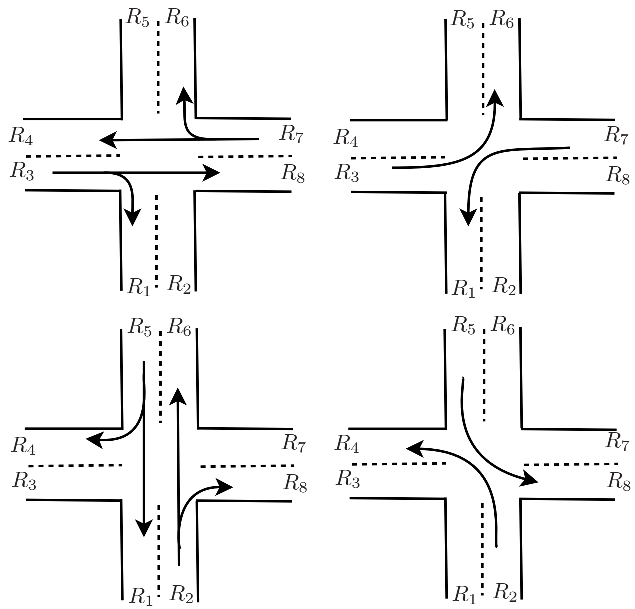
Control actions do not need to be coordinated







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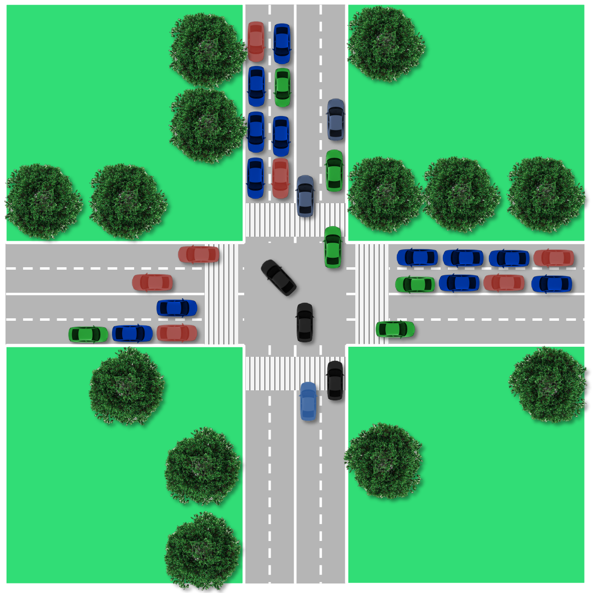
Real queues and logical queues must be decoupled

- Can be ignored by backpressure (so no routing)
- Or can be modeled through shadow queues* (so adaptive routing)
- Routing requires *explicit* information from vehicles



*E. Athanasopoulou, L. X. Bui, T. Ji, R. Srikant, and A. Stolyar, "Back-pressure-based packet-by-packet adaptive routing in communication networks," *IEEE/ACM Transactions on Networking,* vol. 21, no. 1, pp. 244–257, Feb. 2013.

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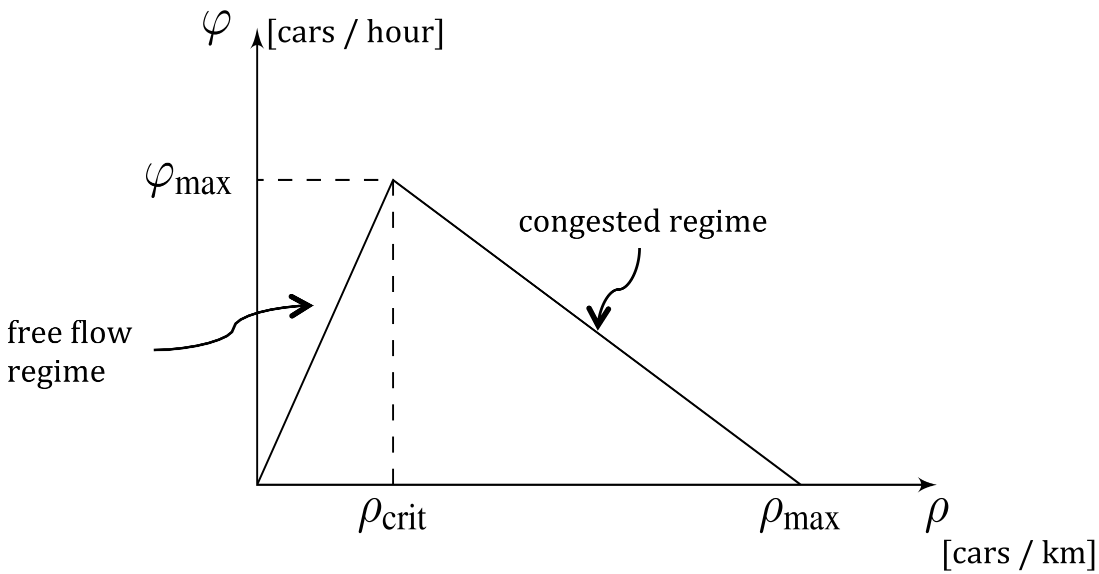
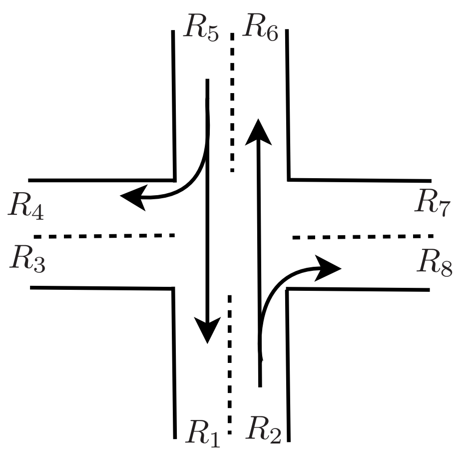
Computing the pressure and control

- Rate: vehicles that can leave a lane during green light
- Queue size: number of cars on lane (free flow + congested)
- Does not consider TWR or fundamental diagram
- Turns out to not be critical for performance





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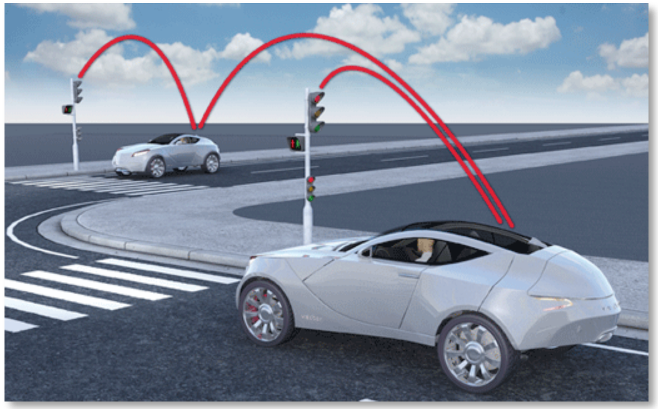
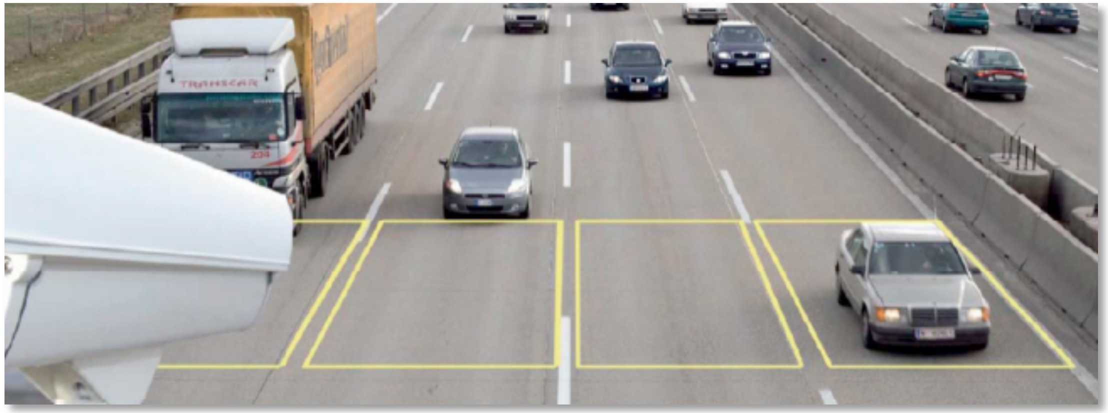
Different sources of uncertainty

- People may not follow decisions/suggestions
- Queues based on sensor data may be incorrect



floating car data



cameras, loop detectors

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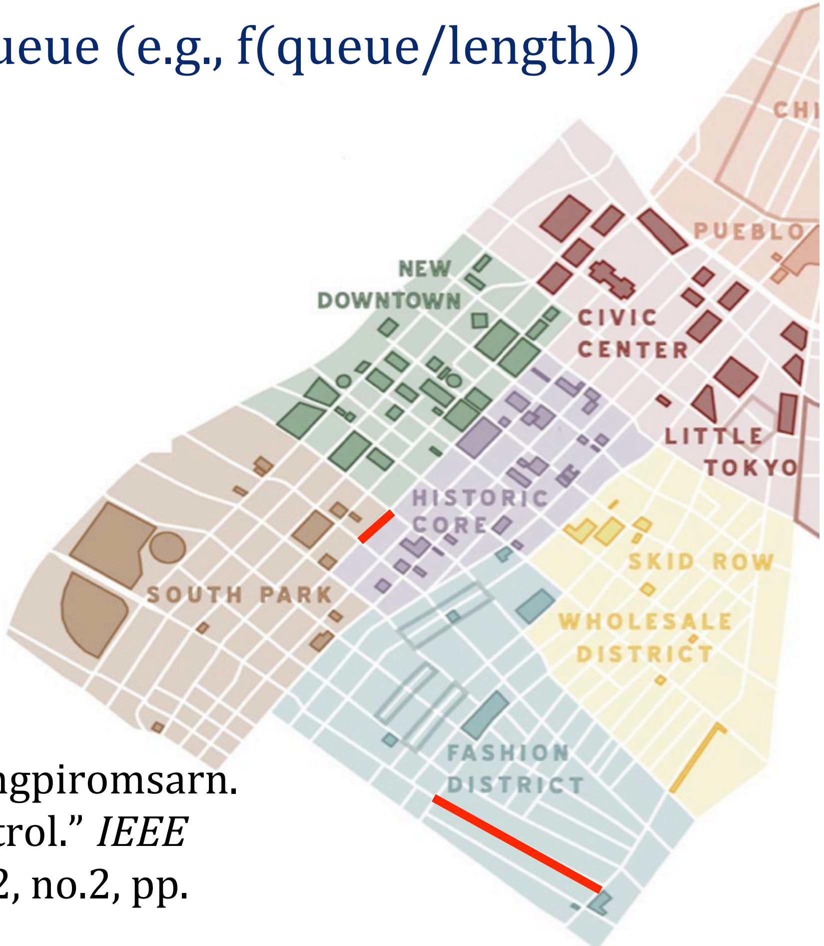
Roads are buffers

- Roads are finite (especially short ones), leading to non-work conserving behavior and gridlock
- Use admission control or normalized queue (e.g., f(queue/length)) with fairness constraint



J. Gregoire, E. Frazzoli, A. de La Fortelle and T. Wongpiromsarn. "Capacity-Aware Back-Pressure Traffic Signal Control." *IEEE Transactions on Control of Network Systems* , vol.2, no.2, pp. 164-173, June 2015

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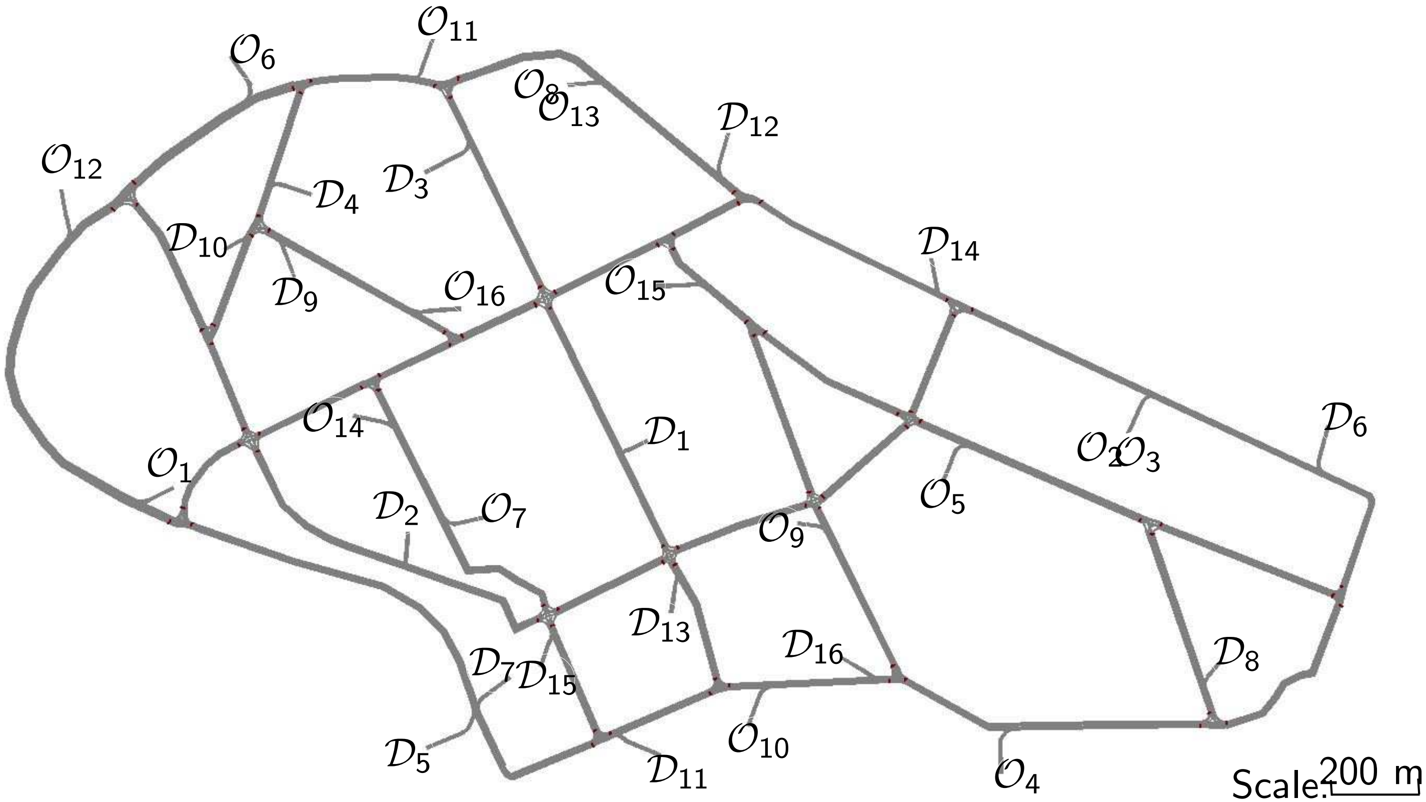
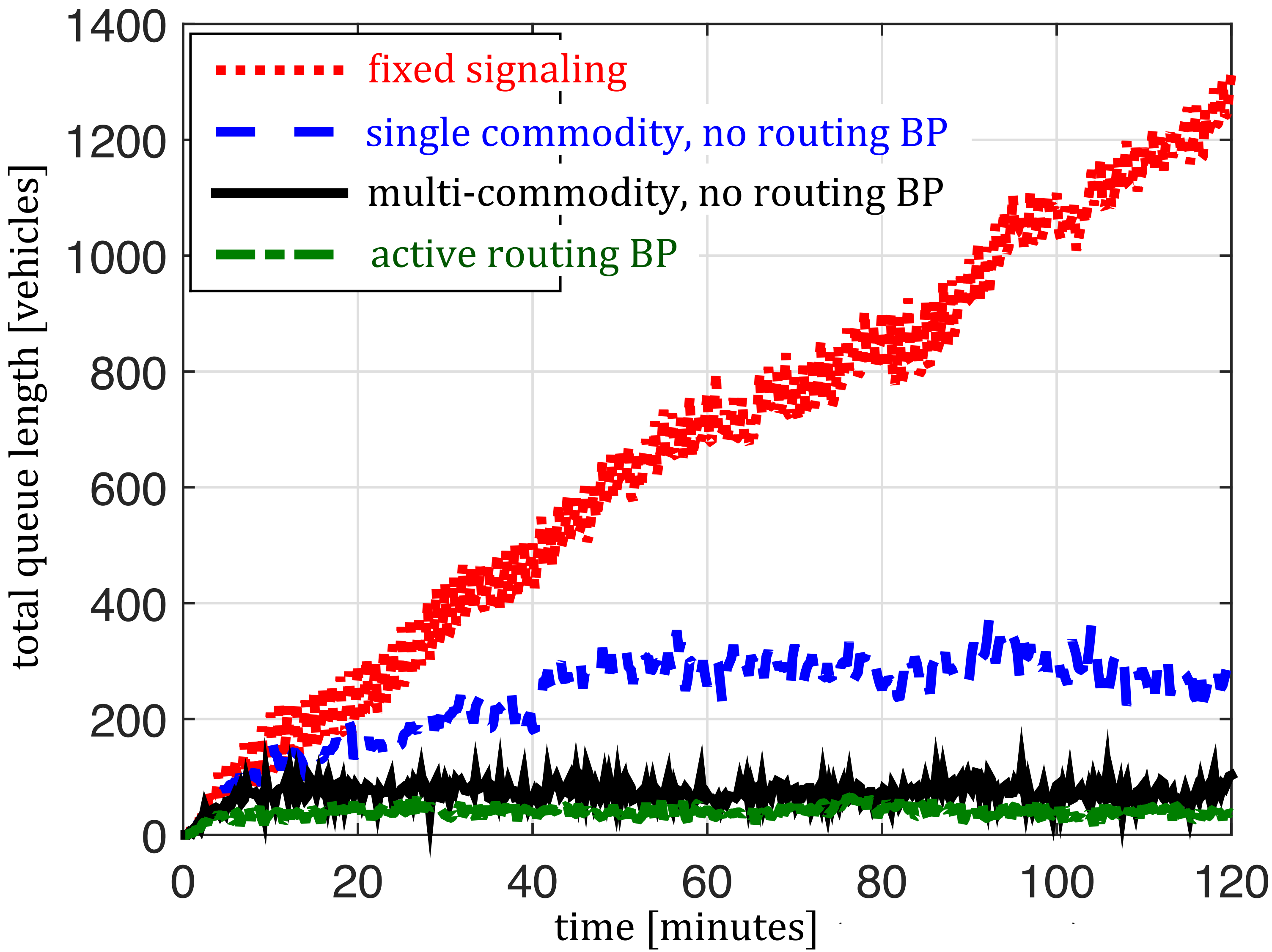
Scenario: Stockholm network

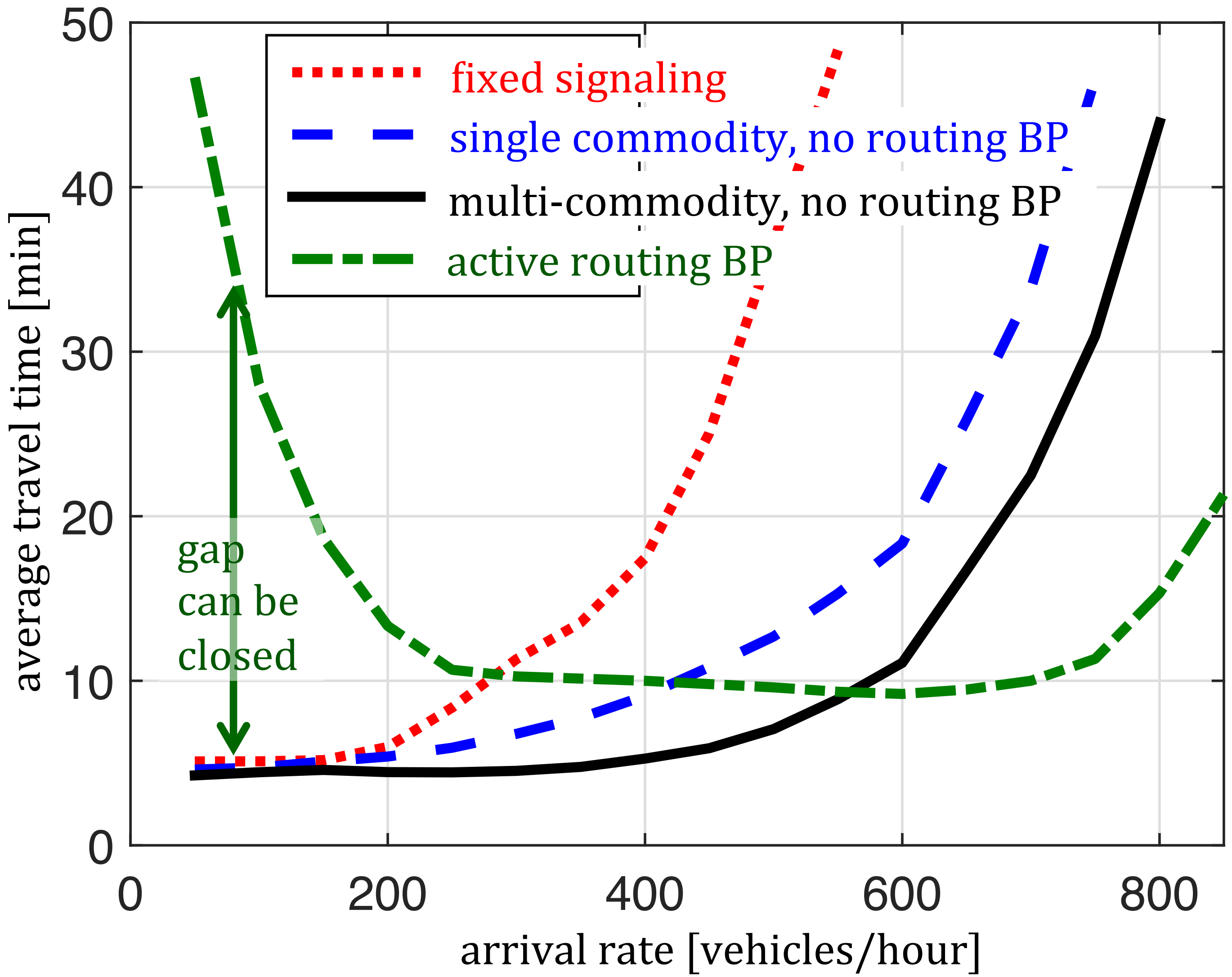


- **Parameters:** 24 intersections, 84 links, 16 flows (origin destination pairs), max speed 70 kph, signal phase lasts 15 sec. Simulation using PTV VISSIM.
- **Methods:** fixed, single-commodity BP with fixed routing, multi-commodity BP with fixed routing, multi-commodity BP active routing

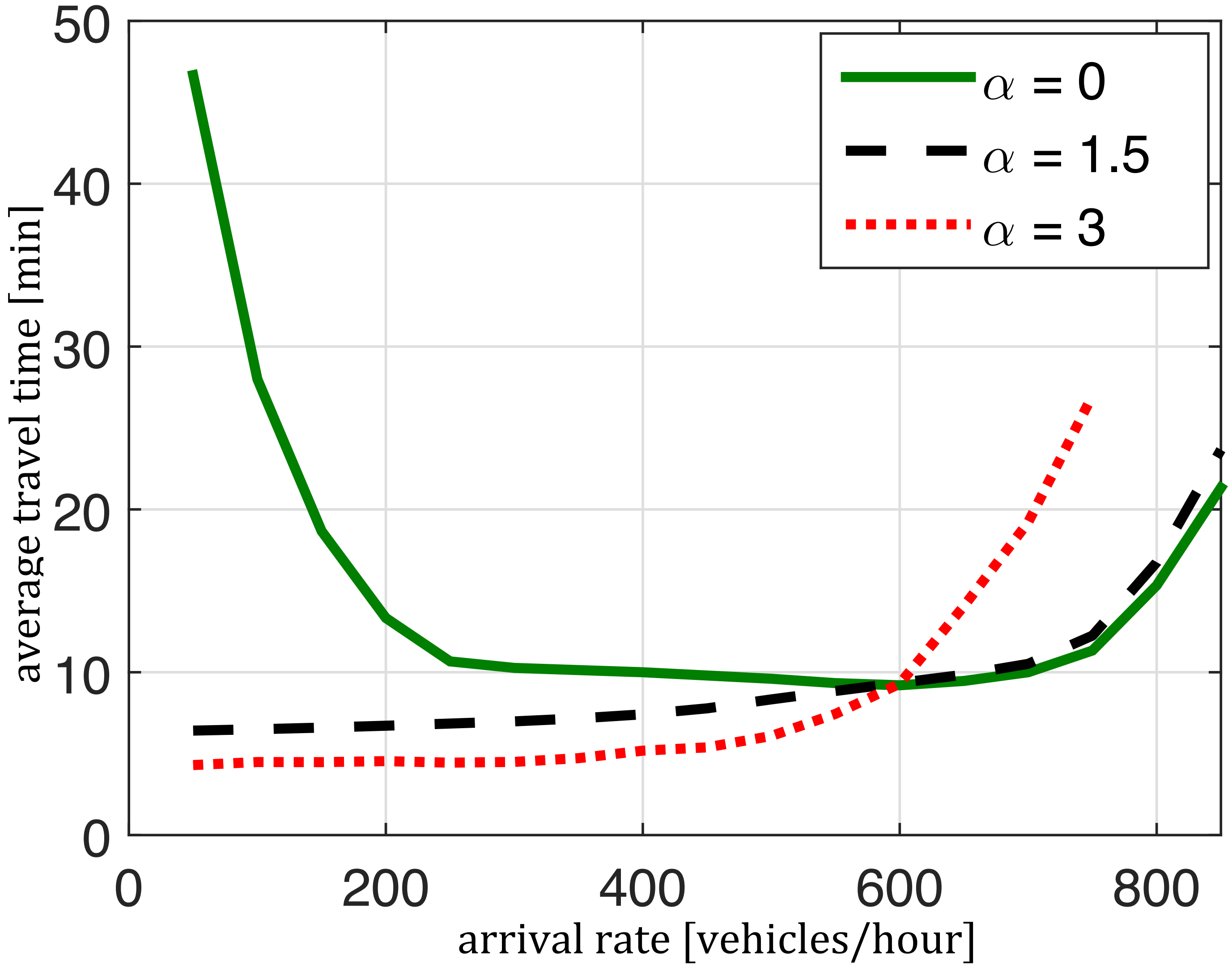
Backpressure stabilizes queues (@ 350 veh/hour arrival)



Adaptive routing can lead to excessive delays



Backpressure delays can be mitigated in many ways



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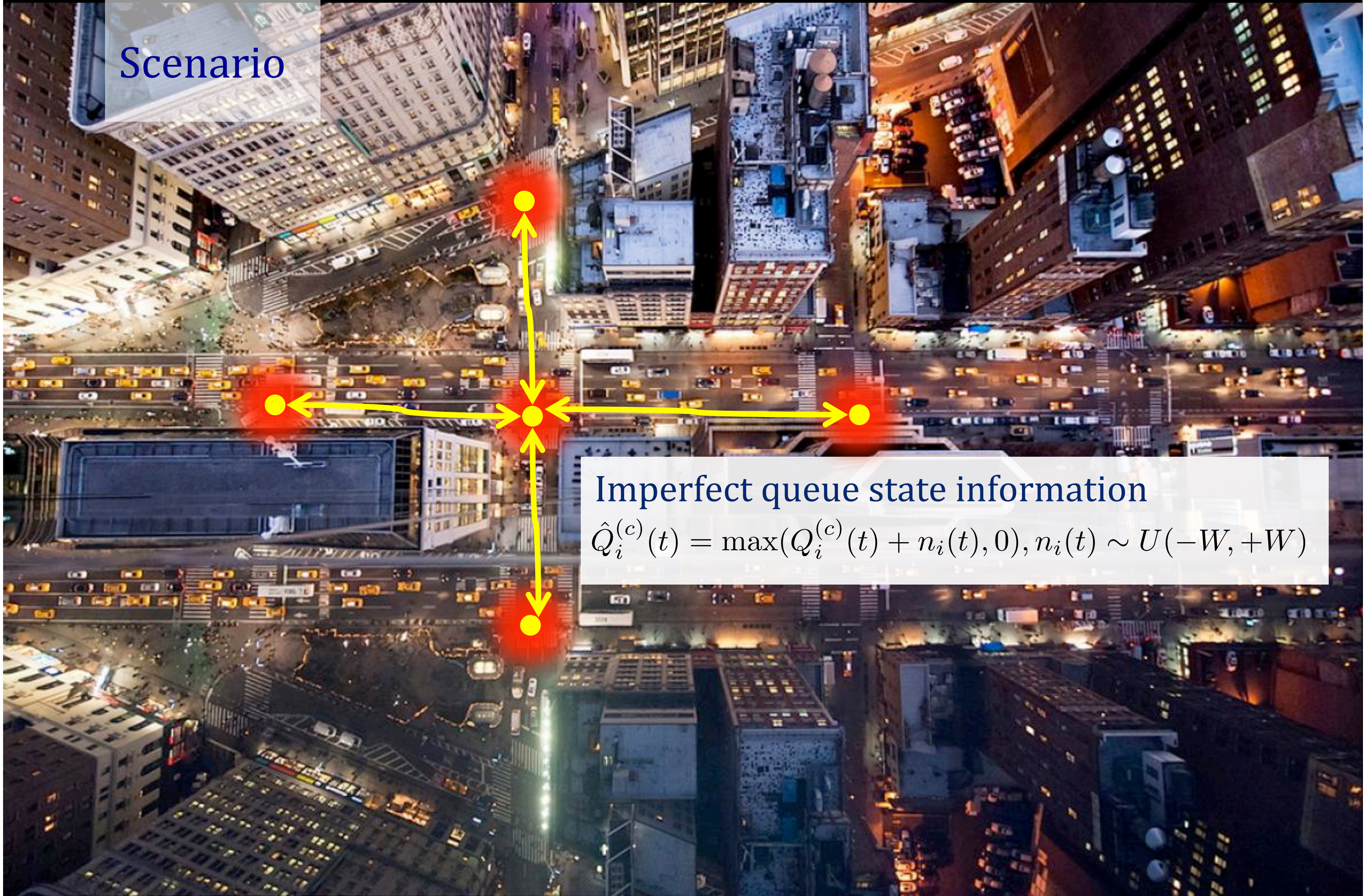
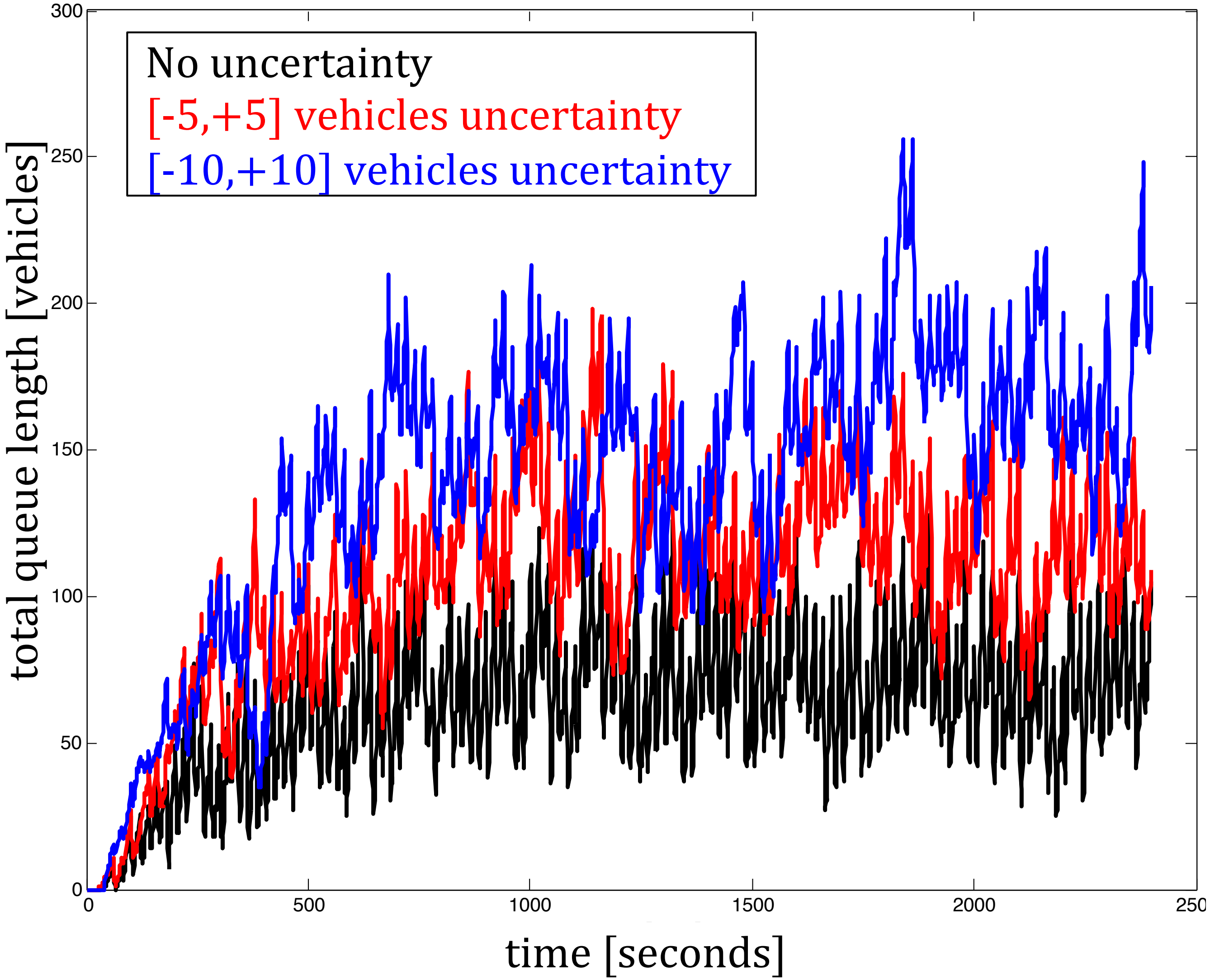


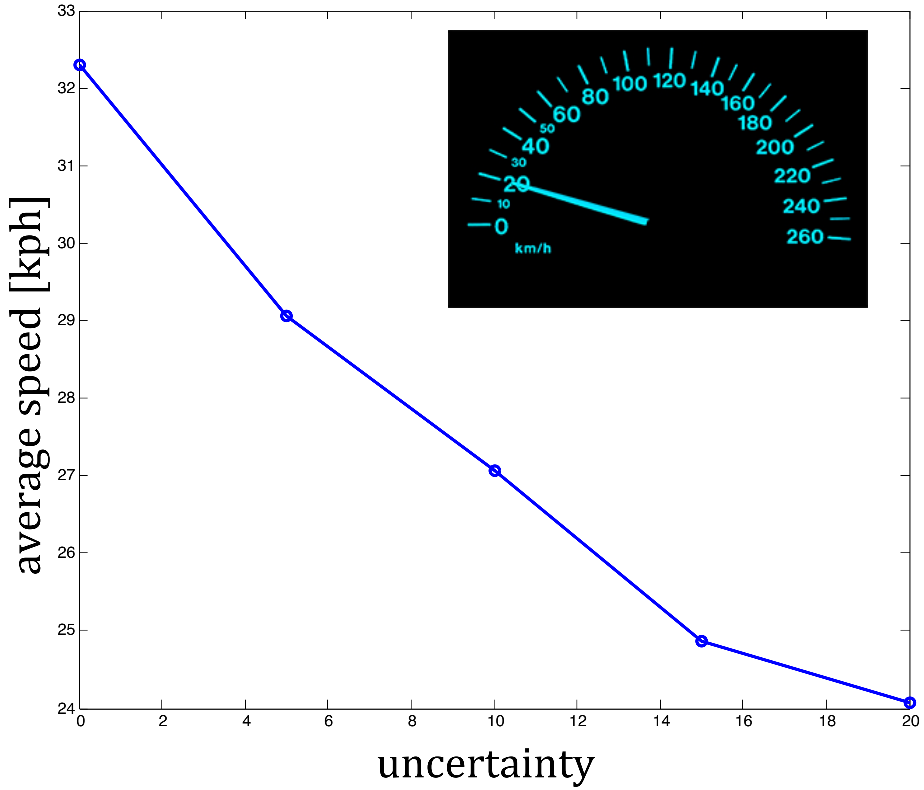
Imperfect queue state information

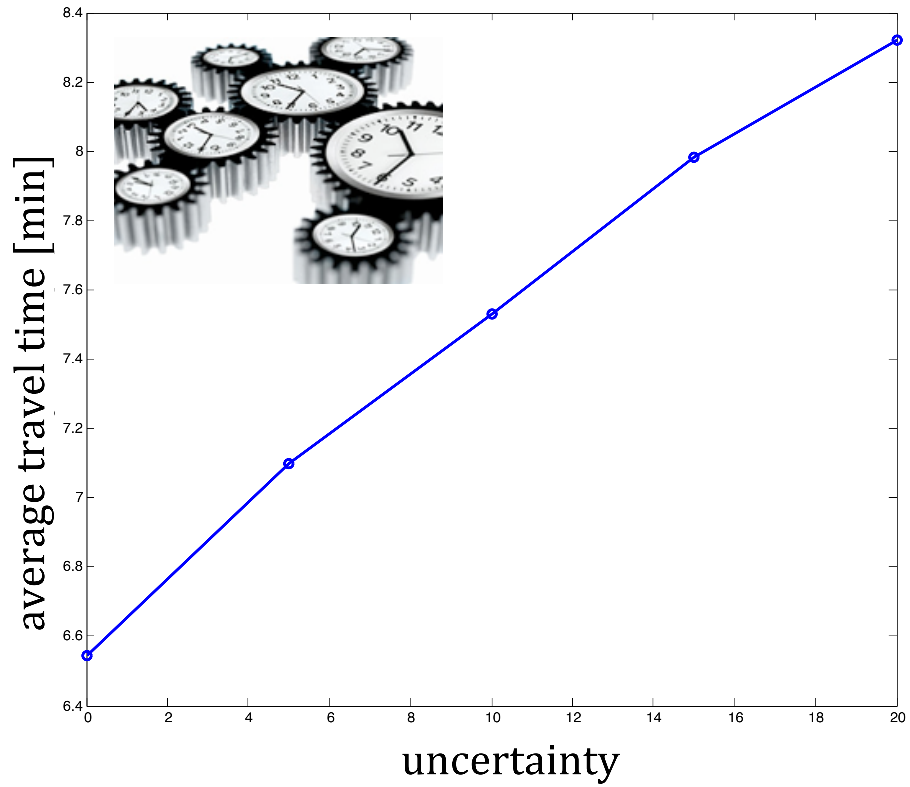
$$\hat{Q}_i^{(c)}(t) = \max(Q_i^{(c)}(t) + n_i(t), 0), n_i(t) \sim U(-W, +W)$$

Noisy queue information leads to longer queues



Noisy queue information leads to reduced speed, longer travel time





- Filtering would help to reduce uncertainty
- What are suitable models for uncertainty?

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Future work

- Backpressure operates only on queues, ignores fundamental diagram. Can we address this?
- How much queue uncertainty is tolerable? Relation to real sensors?
- Performance in the presence of adversarial cars, trying to game the system?

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Conclusions

- Scheduling and routing of vehicles can alleviate traffic problems
- Backpressure-style algorithms have rich history in communication networks
- Many changes needed in vehicular context, but algorithms appear robust against model mismatch and uncertainty
- Impact of traffic sensing is important and not fully understood
- Connection with road flow dynamics is unclear