Regulating Highly Automated Robot Ecologies:
Insights from Three User Studies

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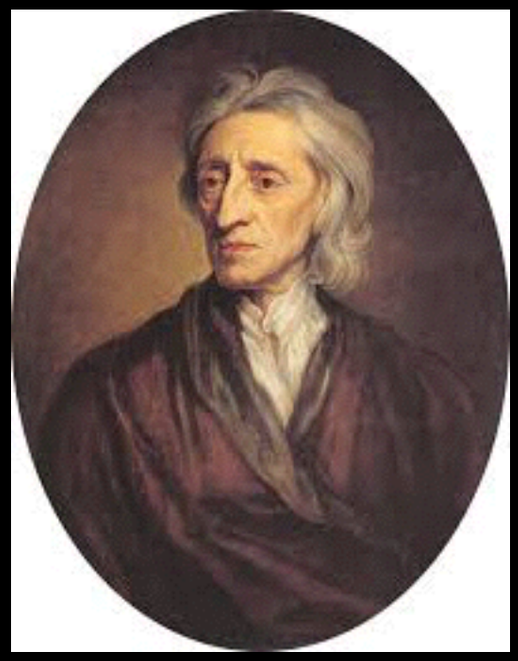
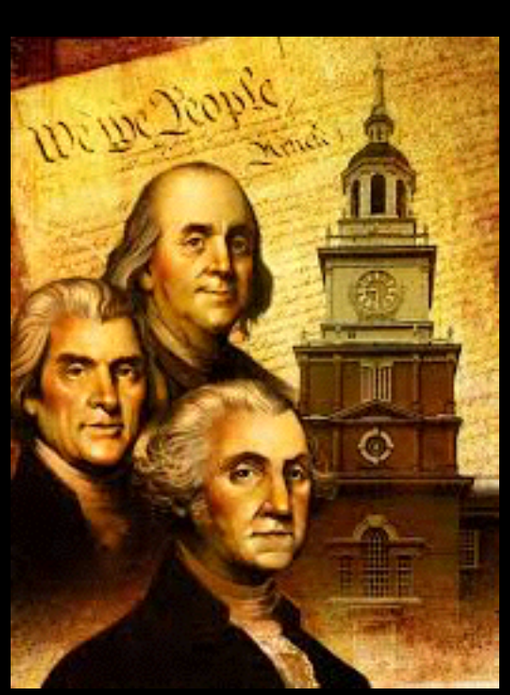
Iyad Rahwan (MIT)
Jacob W. Crandall (BYU)

Human Societies

- How do we achieve good human societies?





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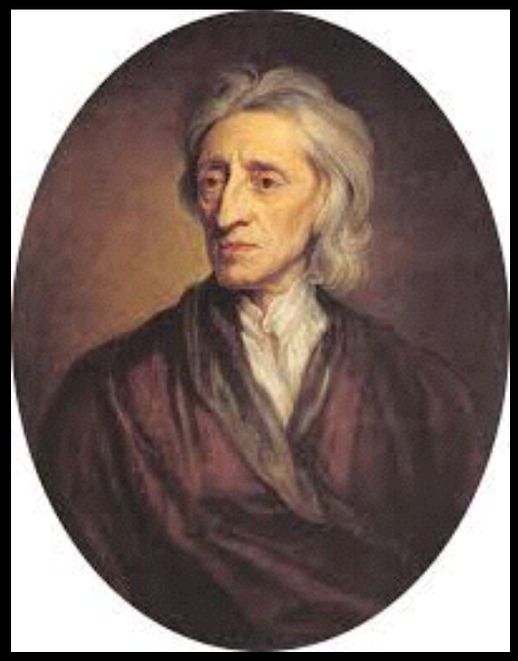
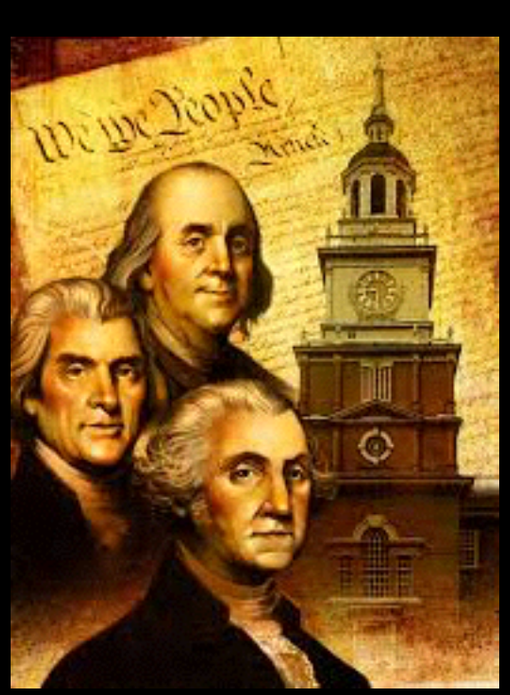
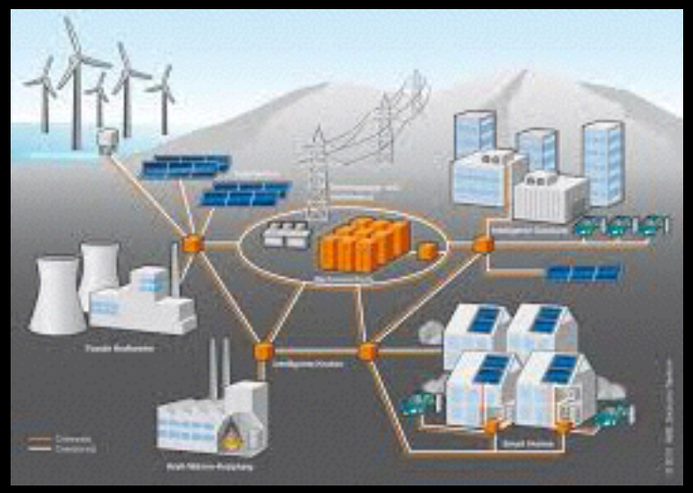




Strong central authority vs. strong individual rights

Societies of Robots?



Robotic buildings
connected via a smart grid

Self-driving cars

Financial Markets

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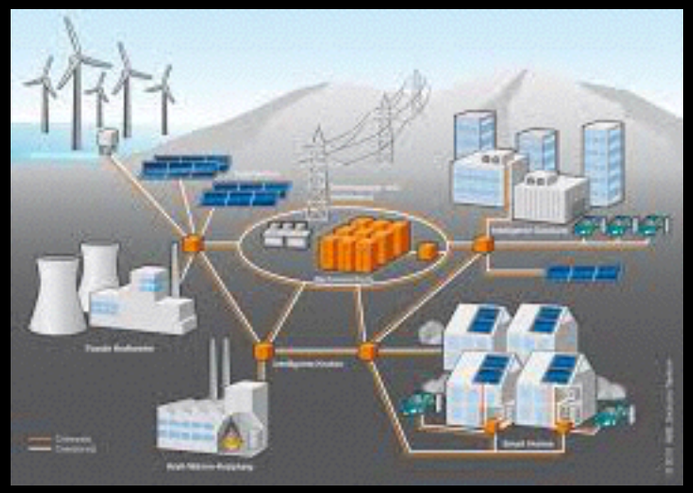

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Strong central authority vs. strong individual rights

Highly **A**utomated **R**obot **E**cologies

- Society of robots or systems
  - Robots are **independent** — owned by different stakeholders
  - Robots are **autonomous** (from the perspective of the regulator)

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How can such systems be “designed” to produce good societal outcomes?

HARE are like what?

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Supervisory control systems

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~~Supervisory control systems~~

Human Society

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Mechanism design problem

HARE are like what?

~~Supervisory control systems~~

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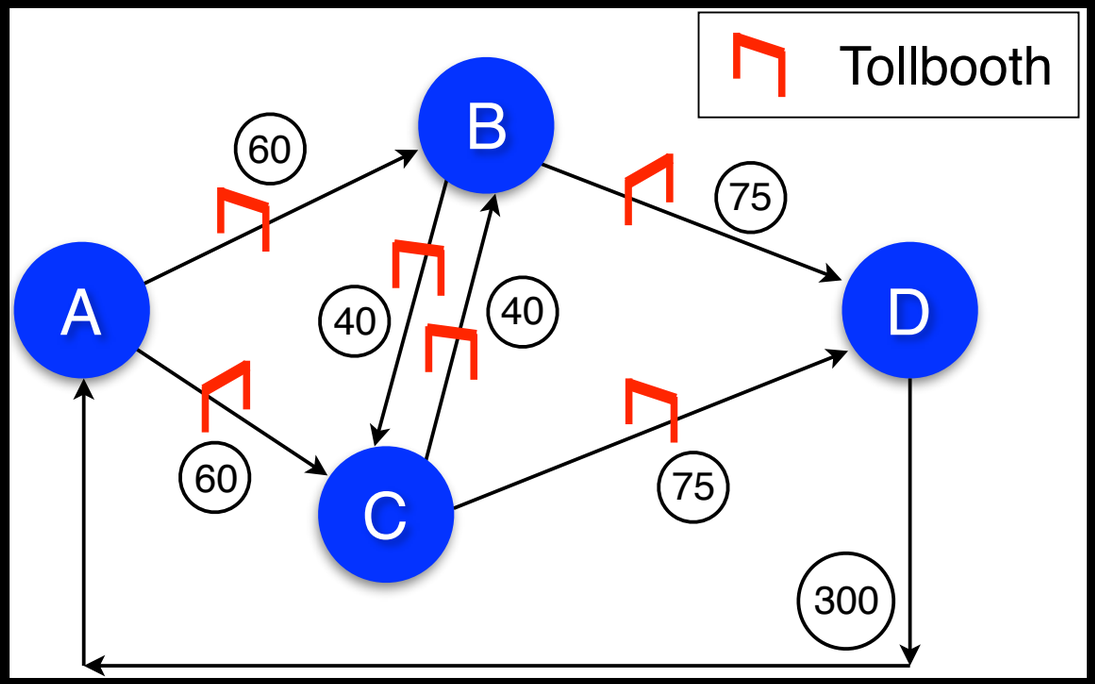
Challenge: Design efficient HARE

2 “design parameters”

- Regulatory power
- Robot autonomy (adaptability)

Example: Routing Game



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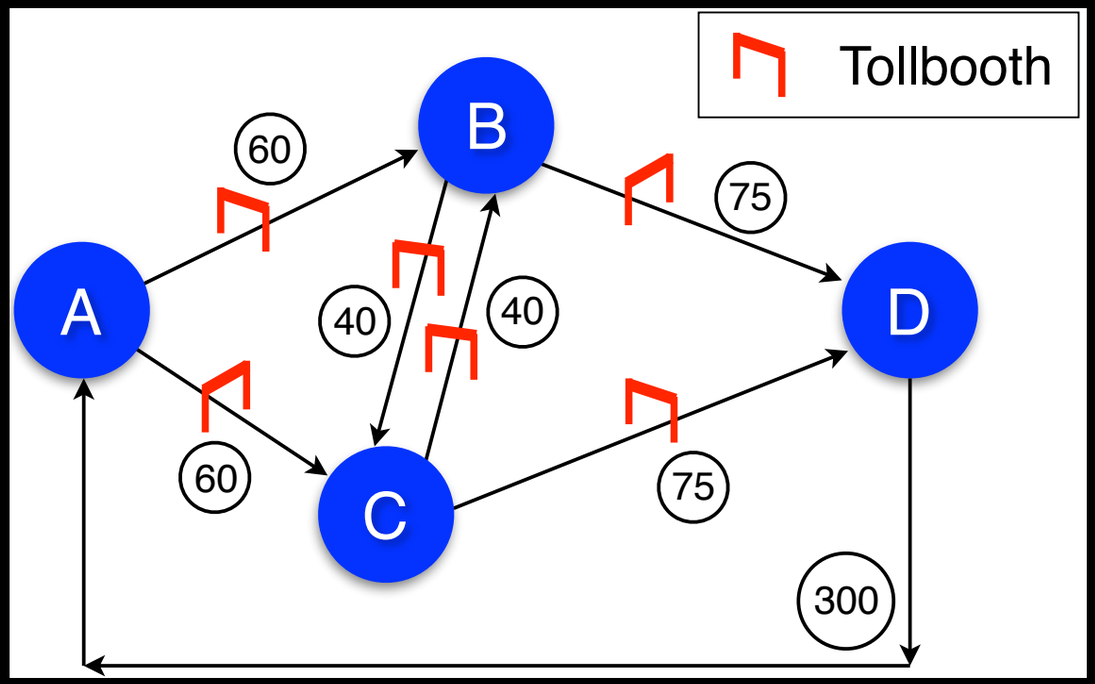

$$V_{ij} = f\,(N_{ij},\ C_{ij})$$

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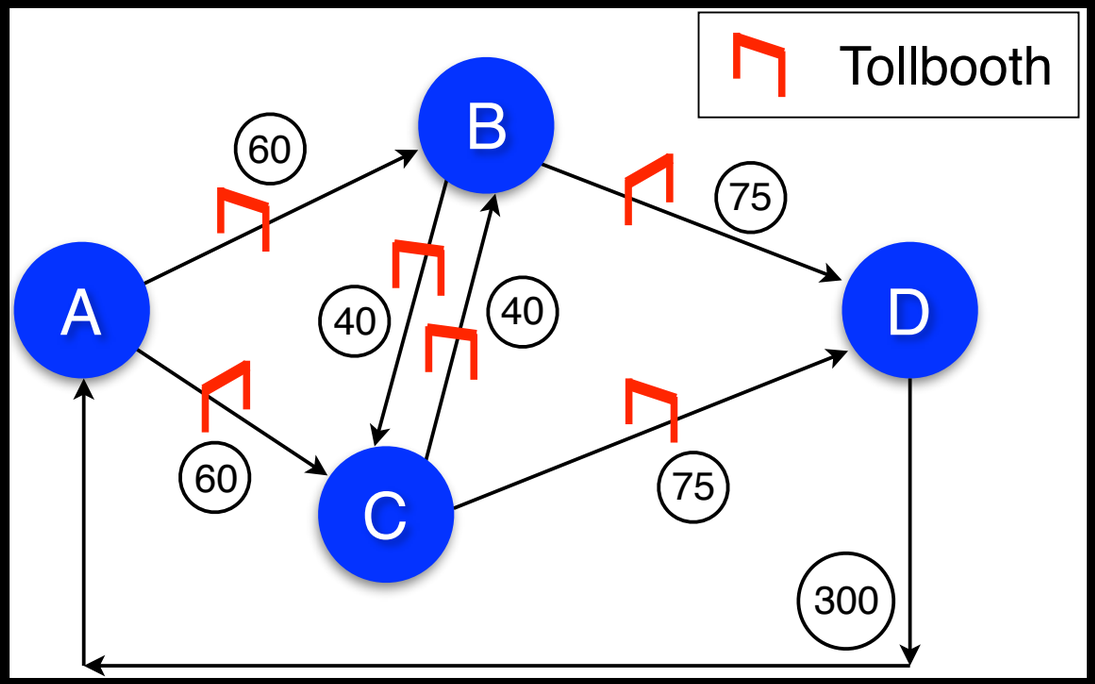

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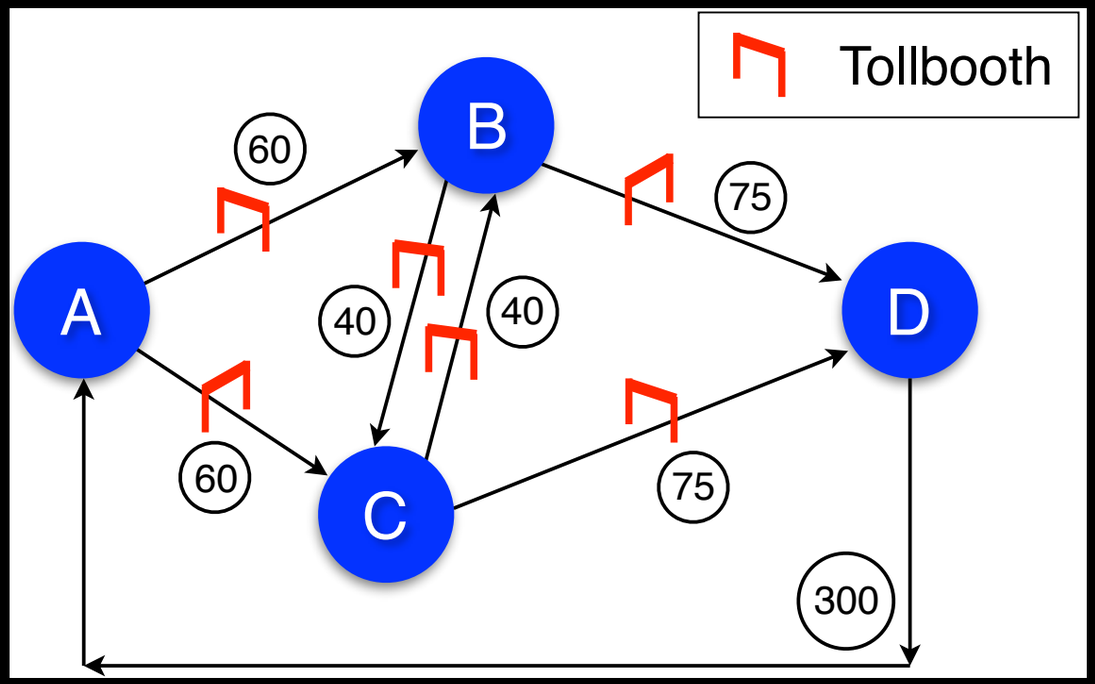

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# of vehicles on link i-j

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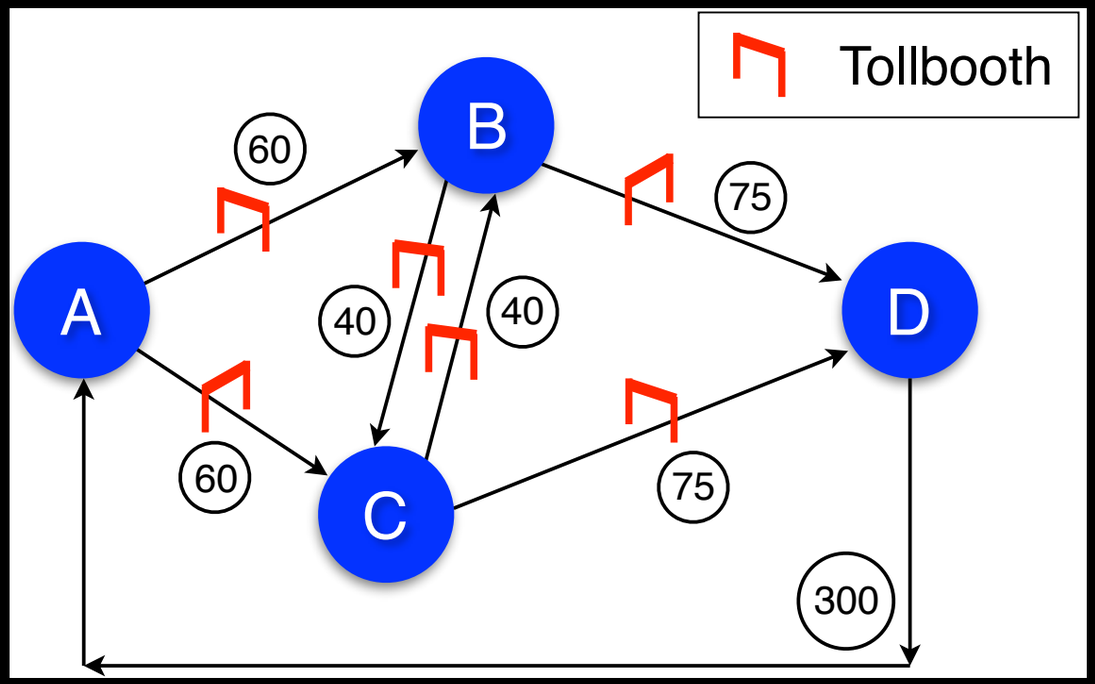

$$V_{ij} \propto \frac{1}{1 + e^{0.25(N_{ij} - C_{ij})}} + 0.1$$

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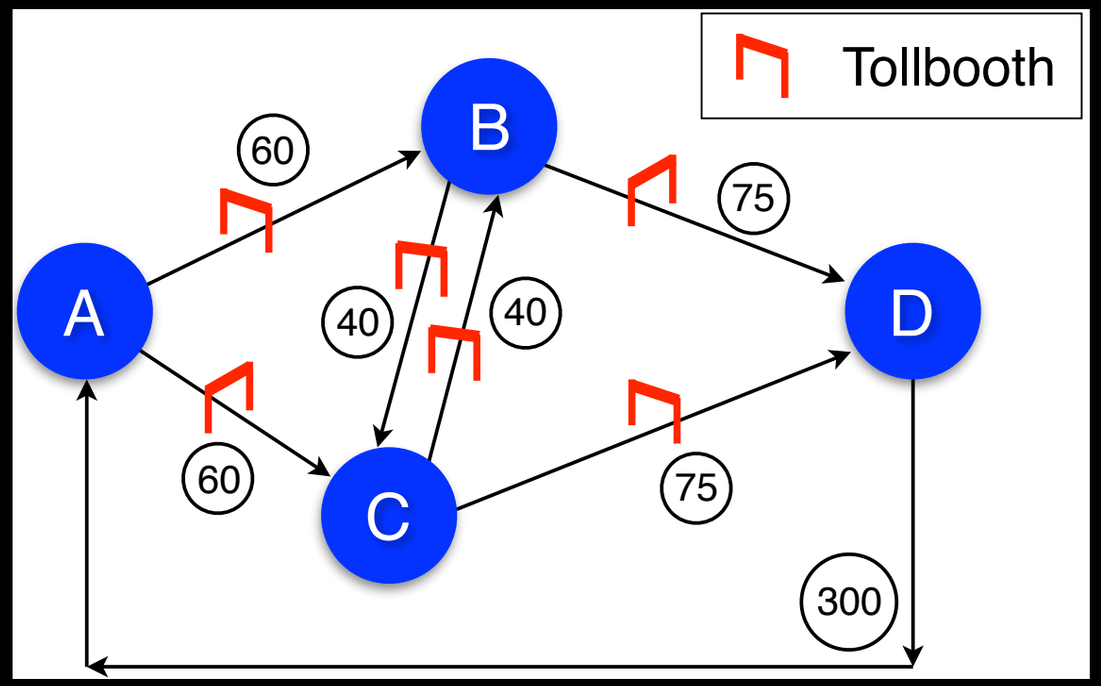

Regulator's Goal:
Maximize throughput
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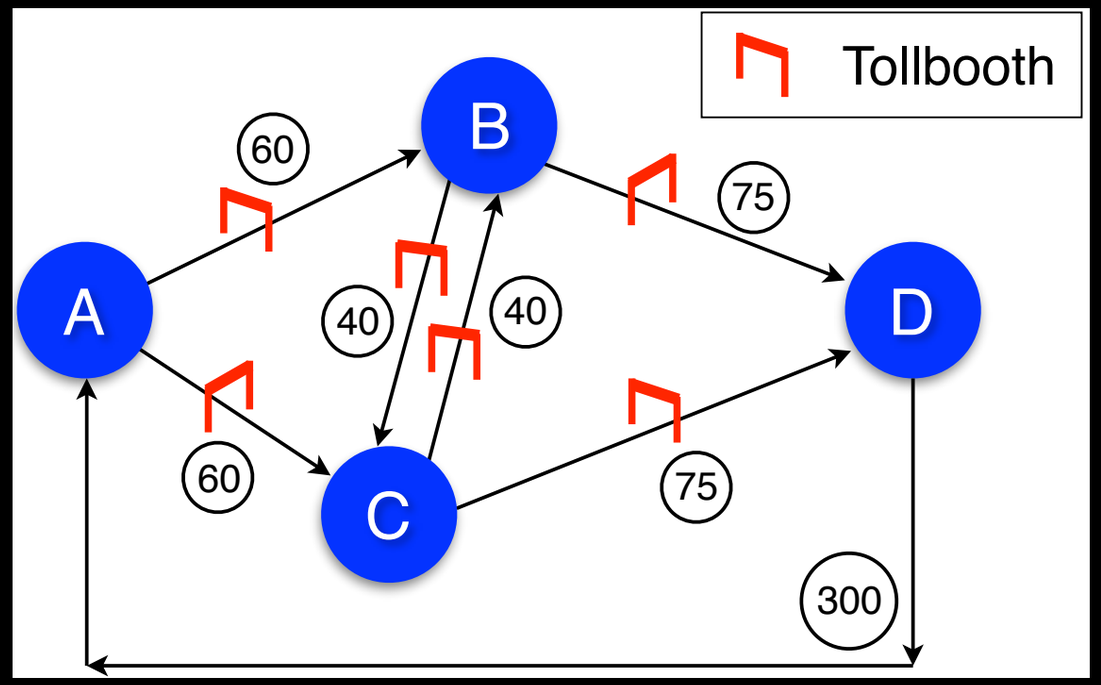


Regulator's Goal:
Maximize throughput through node D

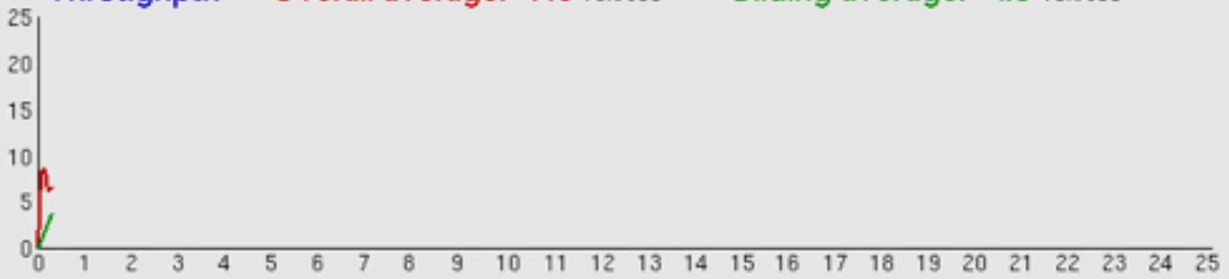
Needs to remove traffic congestion

$$V_{ij} \propto \frac{1}{1 + e^{0.25(N_{ij} - C_{ij})}} + 0.1$$

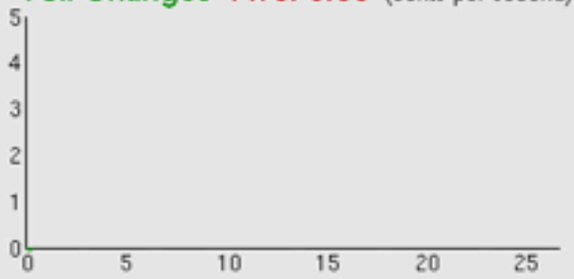
Jiao Tong

00:21

Throughput Overall average: 7.0 veh/sec Sliding average: 4.9 veh/sec



Toll Changes Ave: 0.00 (cents per second)



High Scores

1.	005	14.93
2.	Bill	14.71
3.	07	13.49
4.	08	13.37
5.	017	13.33

Your Score: $ 6.95 / sec

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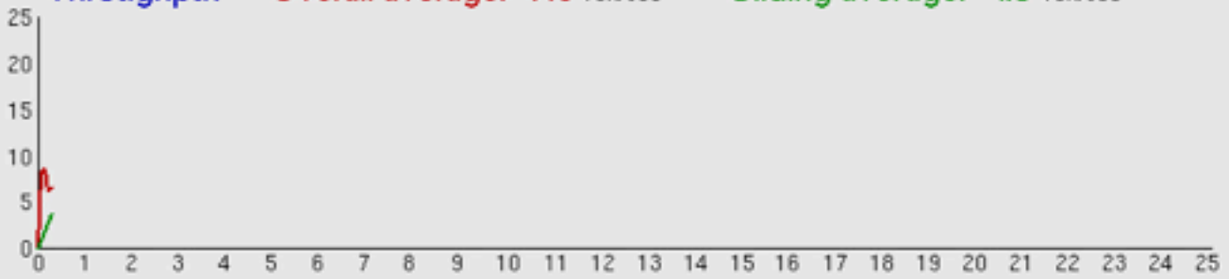

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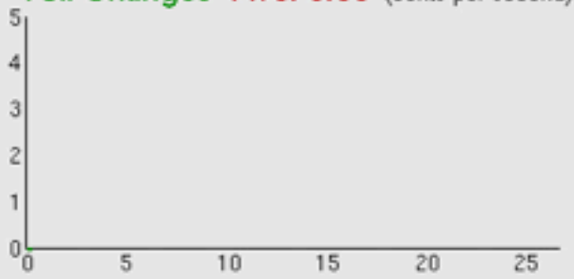

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Value of getting to node *g*

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Robot Autonomy (2 levels)

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Value of getting to node *g*

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Toll Cost

Robot Autonomy (2 levels)

- **Simple** — Estimate $c_t(i,g)$ assuming no congestion

Robot Behaviors

$$u(i,g) = v(g) - c_t(i,g) - c_\$(i,g)$$

Value of getting to node *g*

Travel Cost

Toll Cost

Robot Autonomy (2 levels)

- **Simple** — Estimate $c_t(i,g)$ assuming no congestion
- **Adaptive** — Estimate $c_t(i,g)$ using reinforcement learning

Regulatory Power

Regulator's ability to change tolls

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3 levels

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- **None** — Regulator can do nothing

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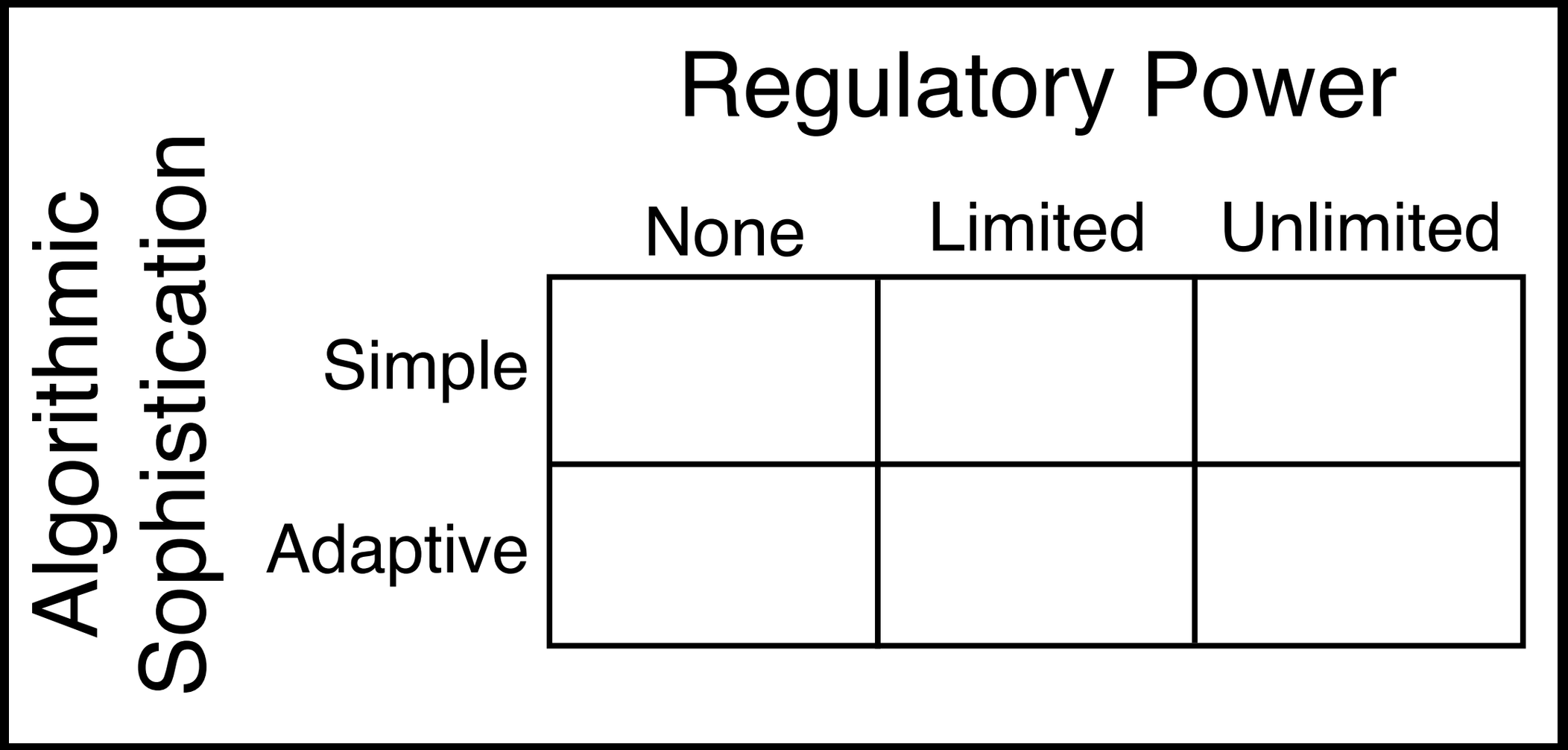
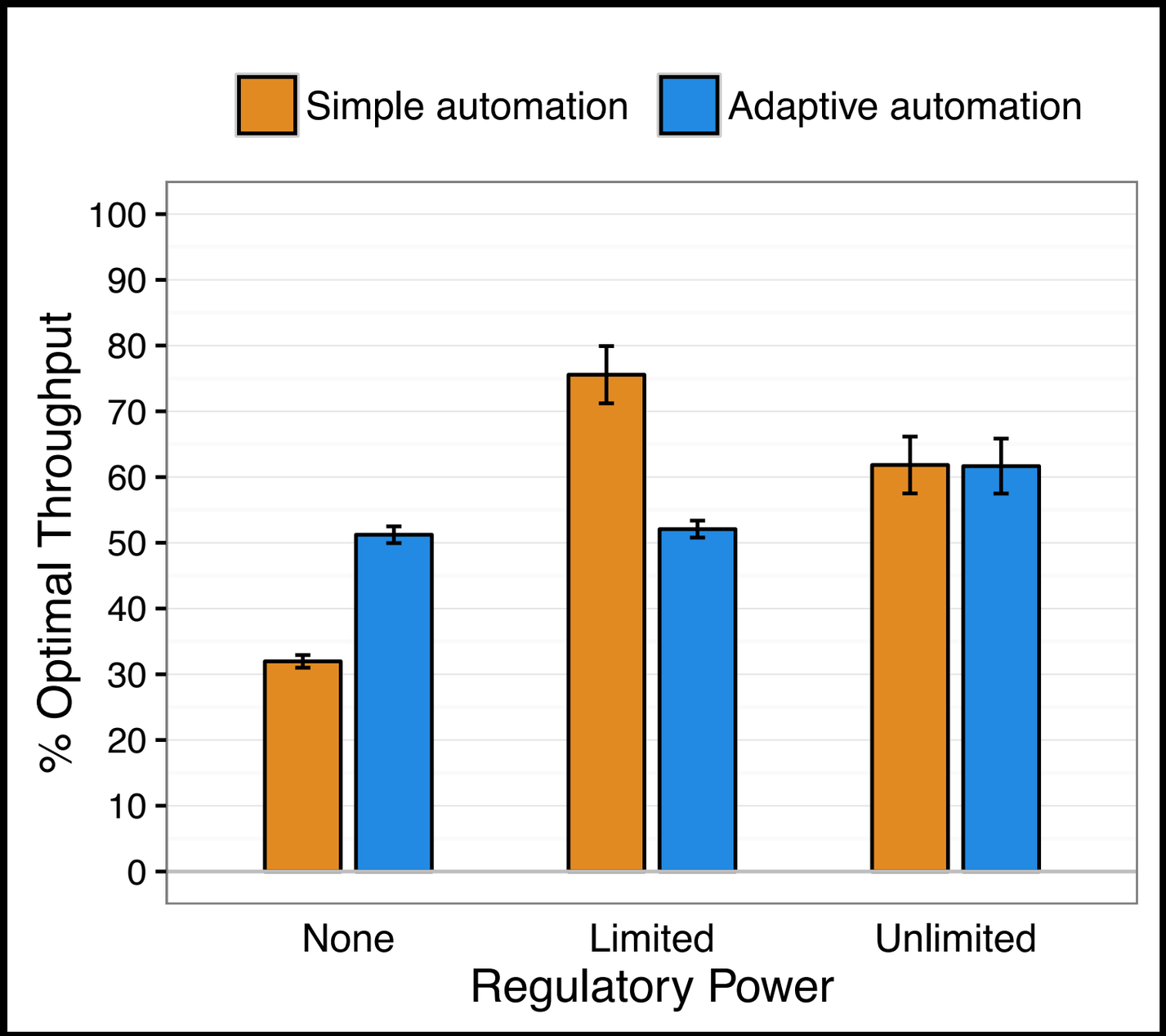
- **Unlimited** — Regulator can make unlimited toll changes

Experimental Setup



Which one will be best?

Outcome


Simple automation
Adaptive automation
% Optimal Throughput
100
90
80
70
60
50
40
30
20
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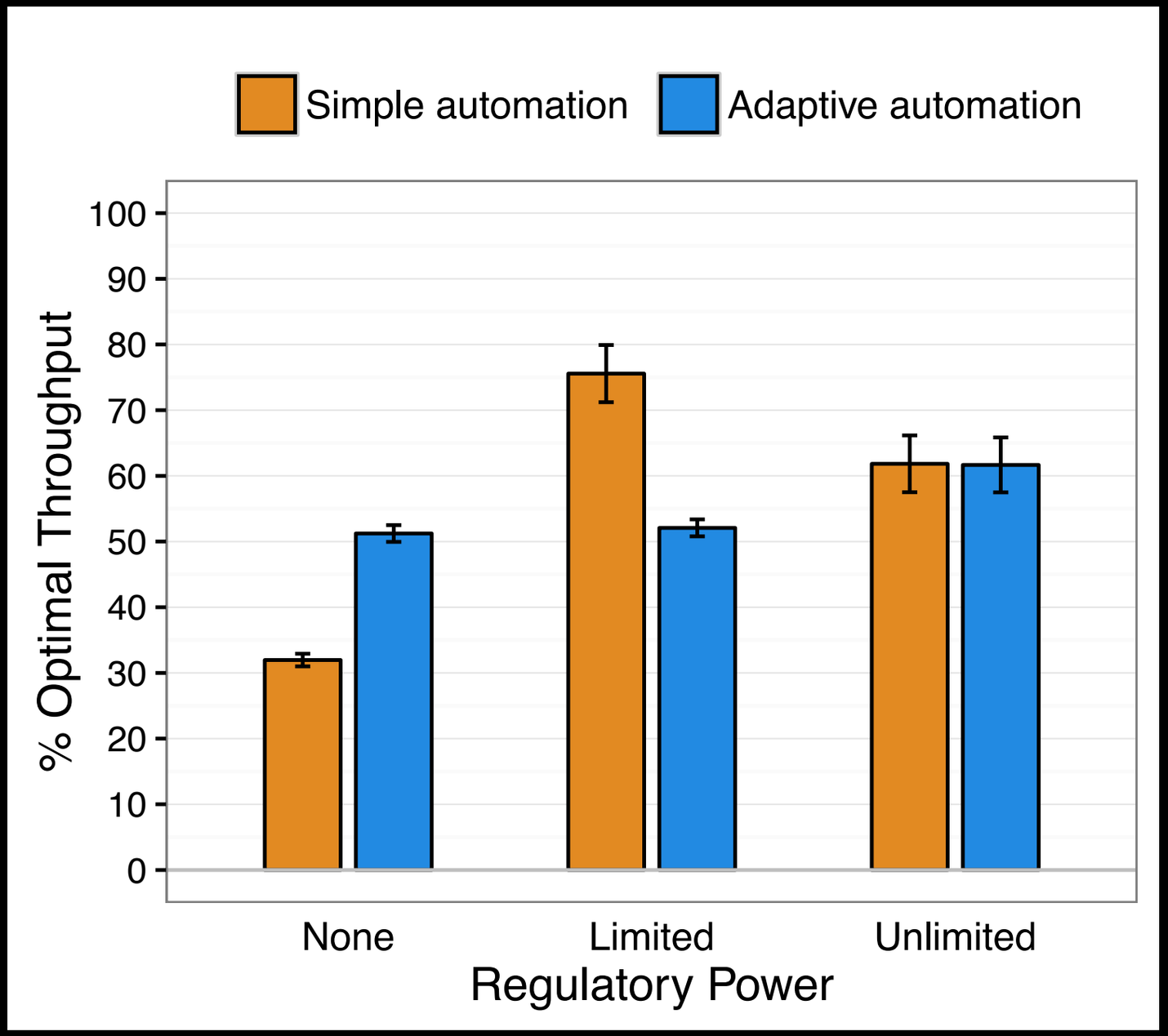
None
Limited
Unlimited
Regulatory Power

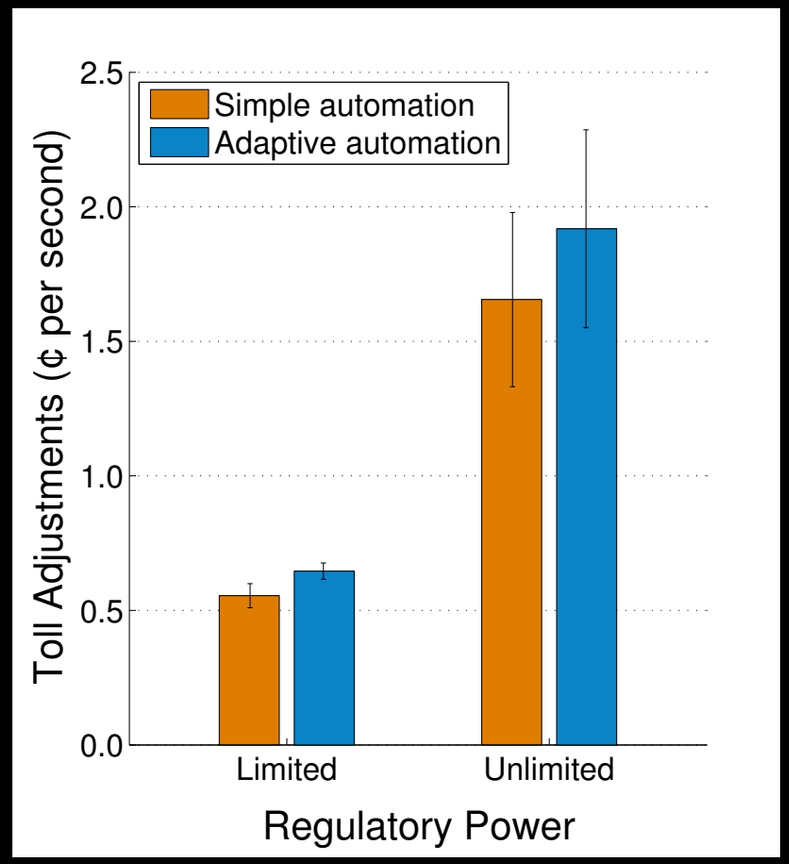
Outcome

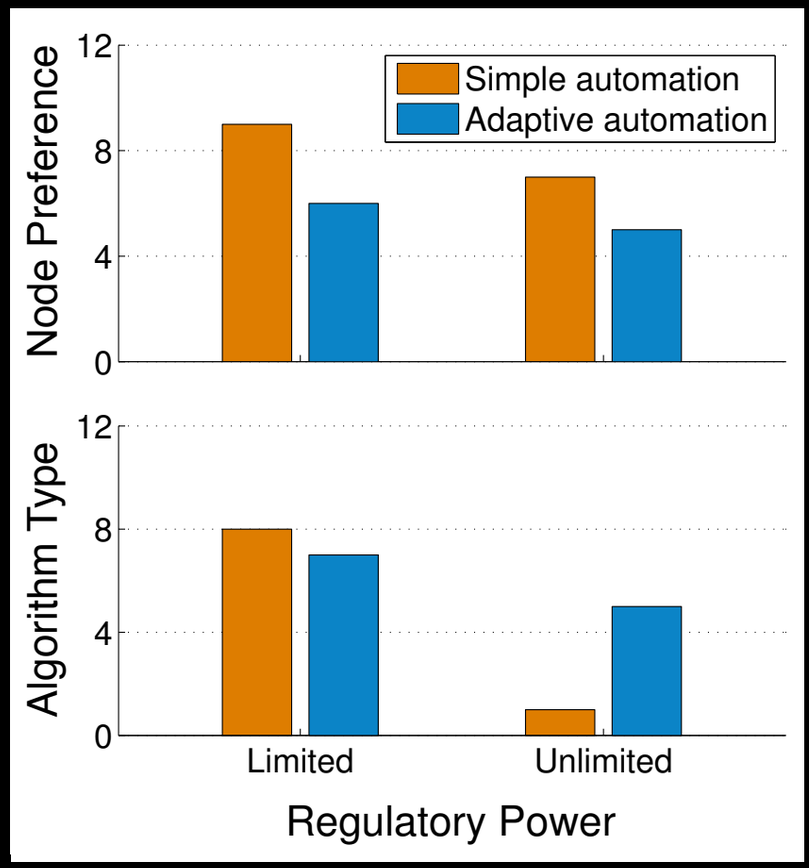


Algorithmic Sophistication

	Regulatory Power: None	Limited	Unlimited
Simple	6	1	T2
Adaptive	T4	T4	T2

Why Simple-Unlimited?





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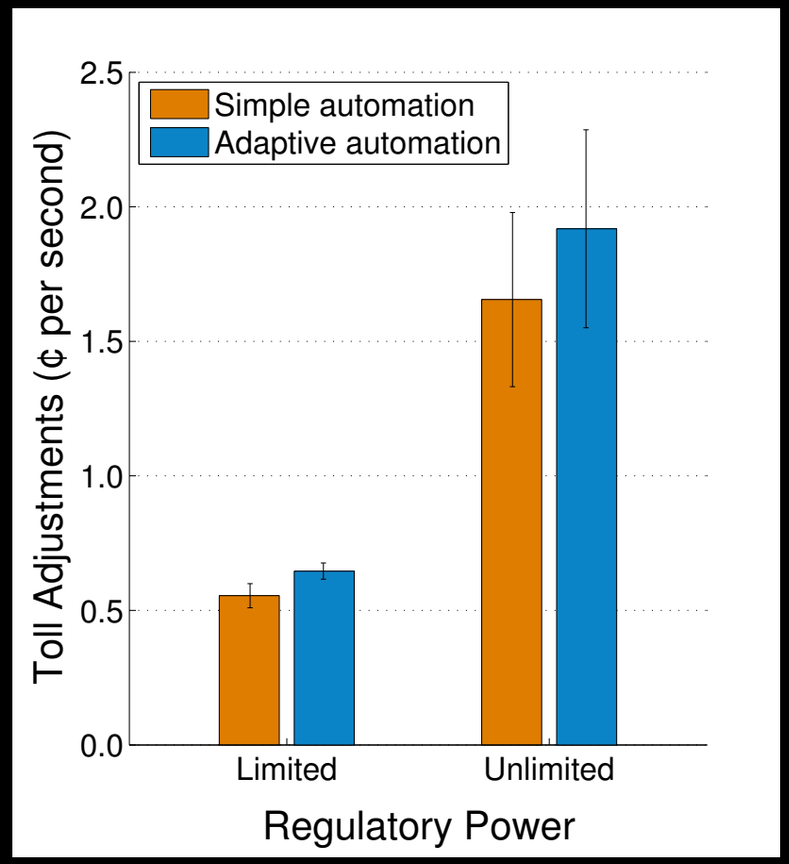

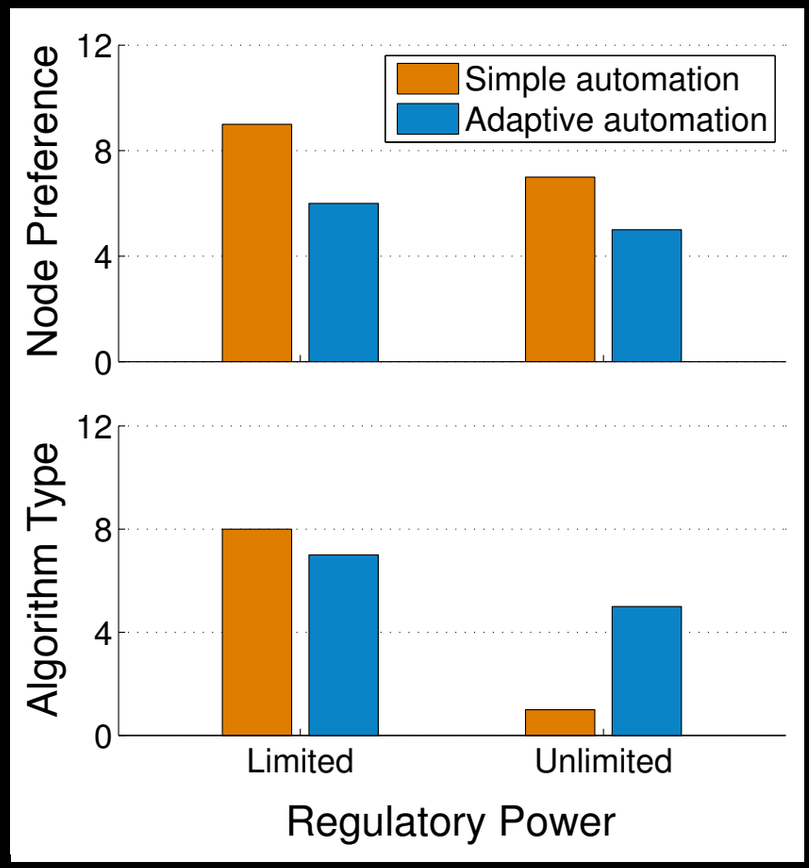

Given Unlimited Power,
Regulators used power
they didn't need

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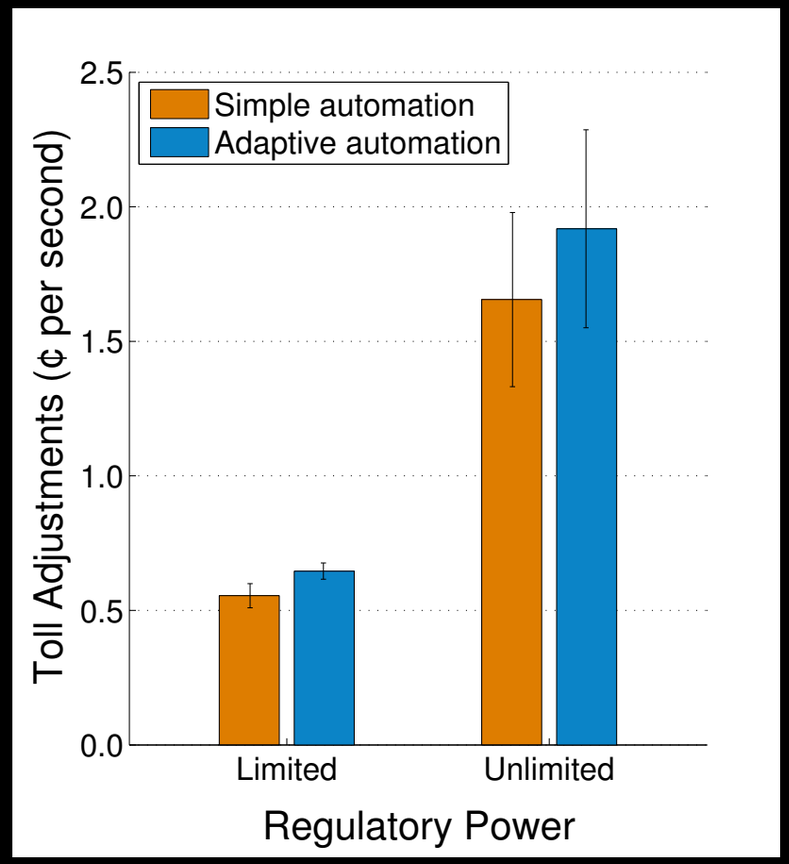

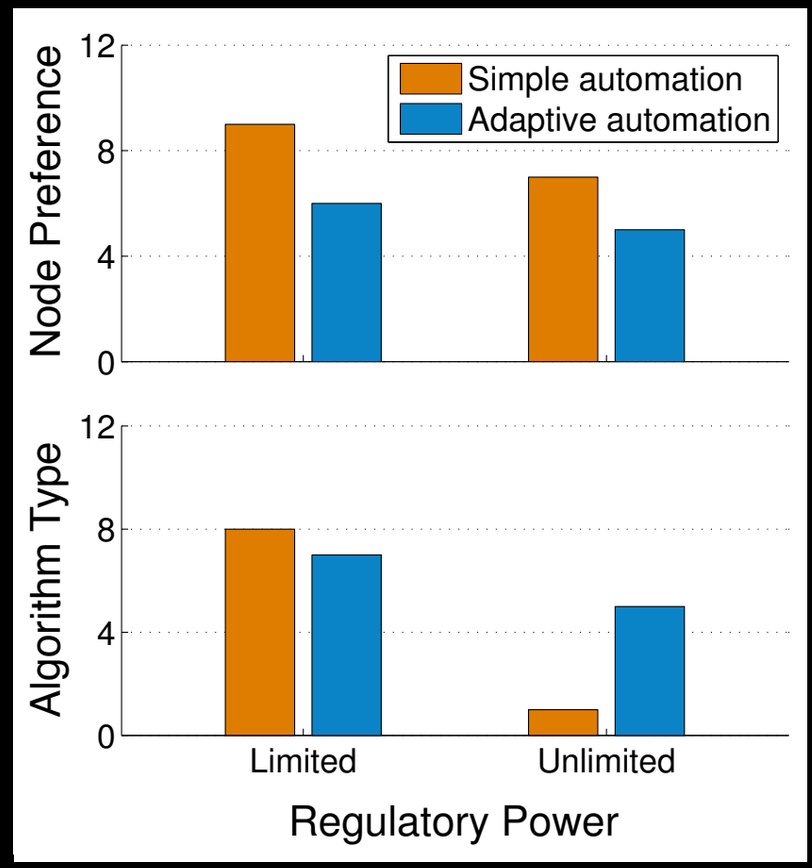

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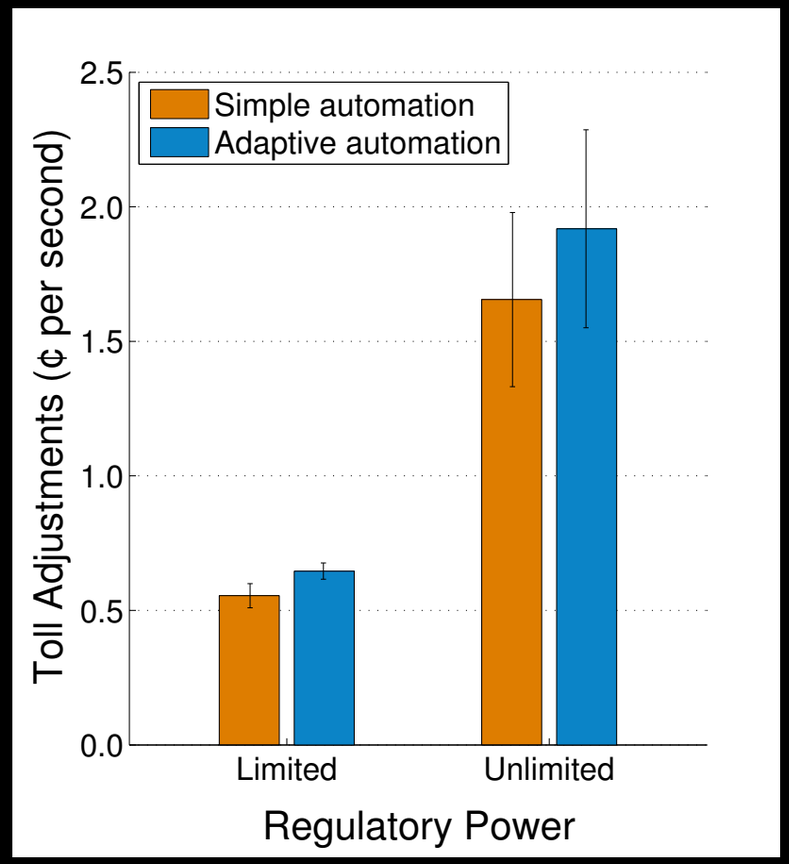
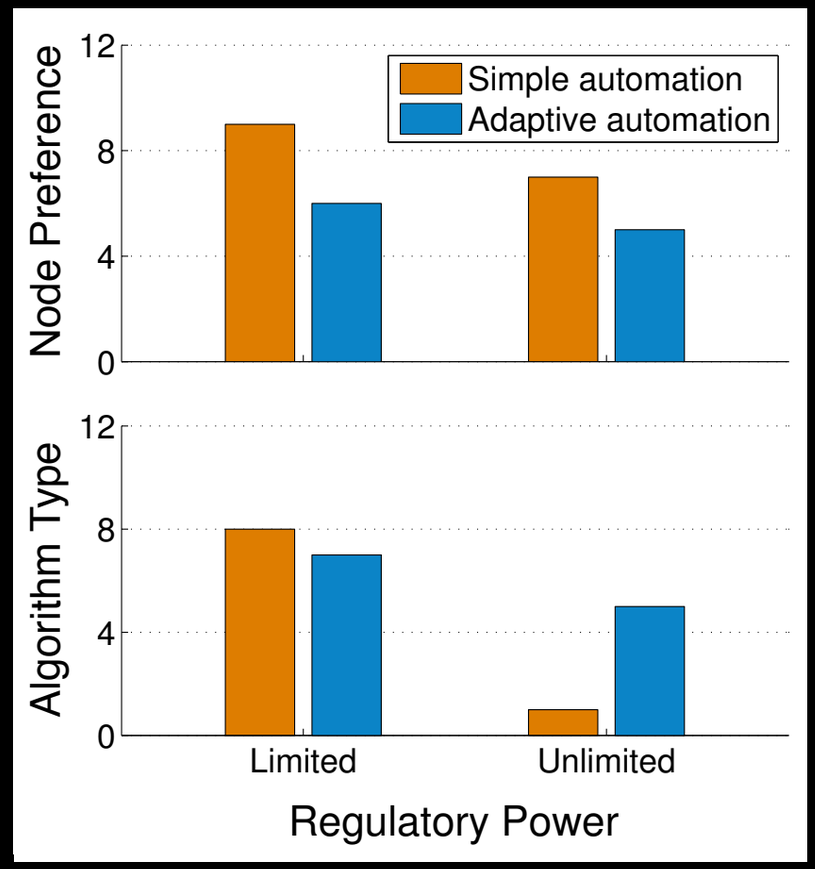
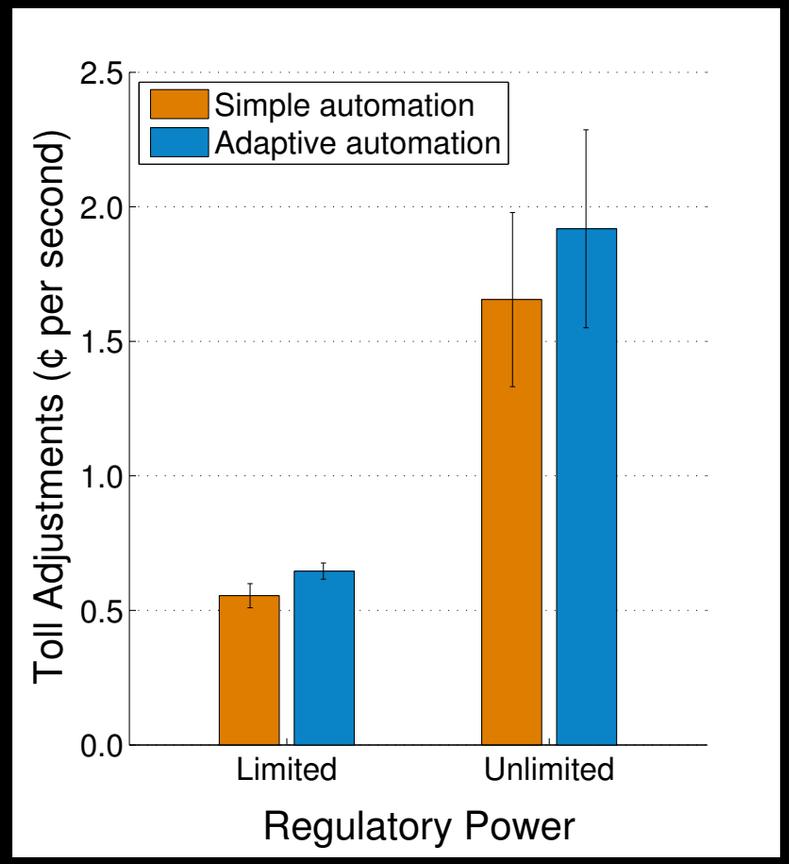


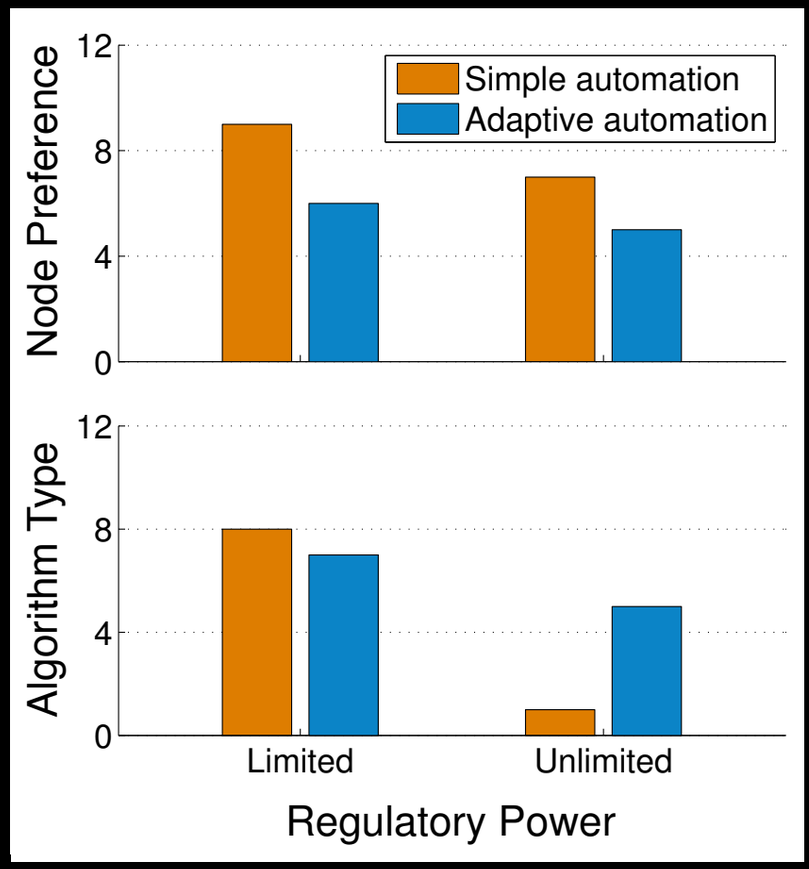


Given Unlimited Power, Regulators used power they didn't need

Regulators had poorer models of robot behavior

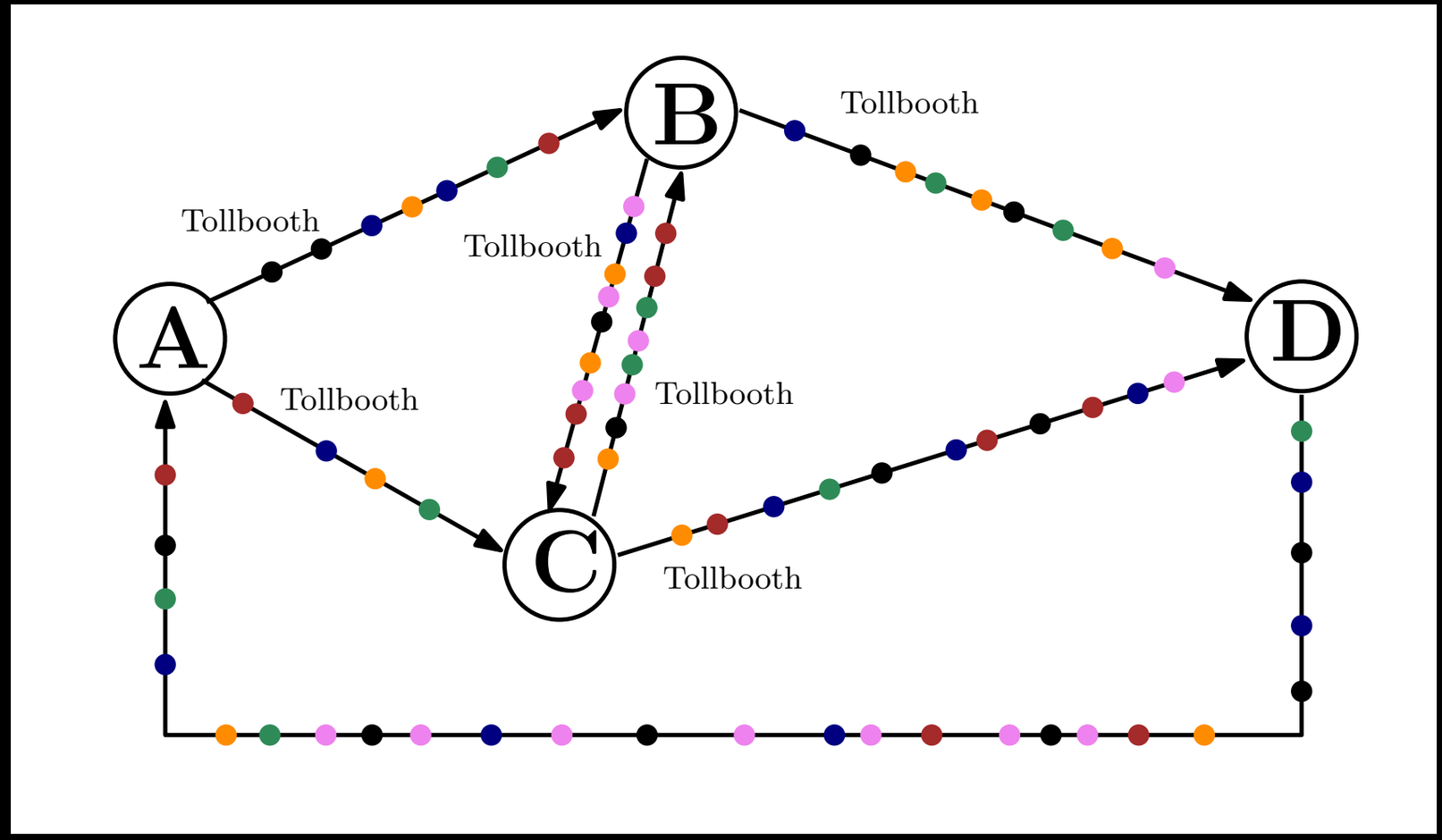
Why Simple-Unlimited?





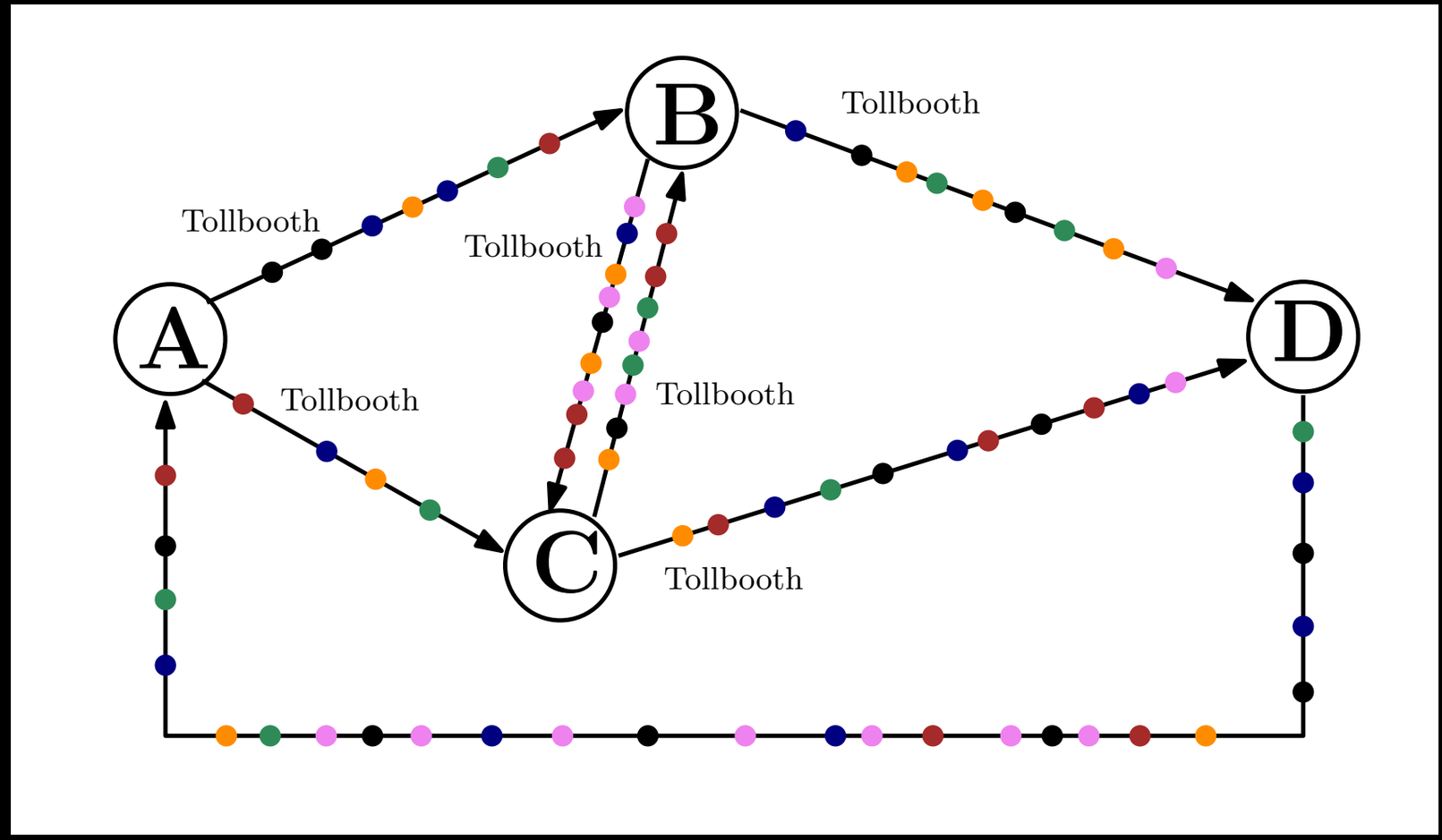
Simple automation was easier to model

Automated Help



Automated Help

- Predict when the congestion will occur



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- Predict when the congestion will occur
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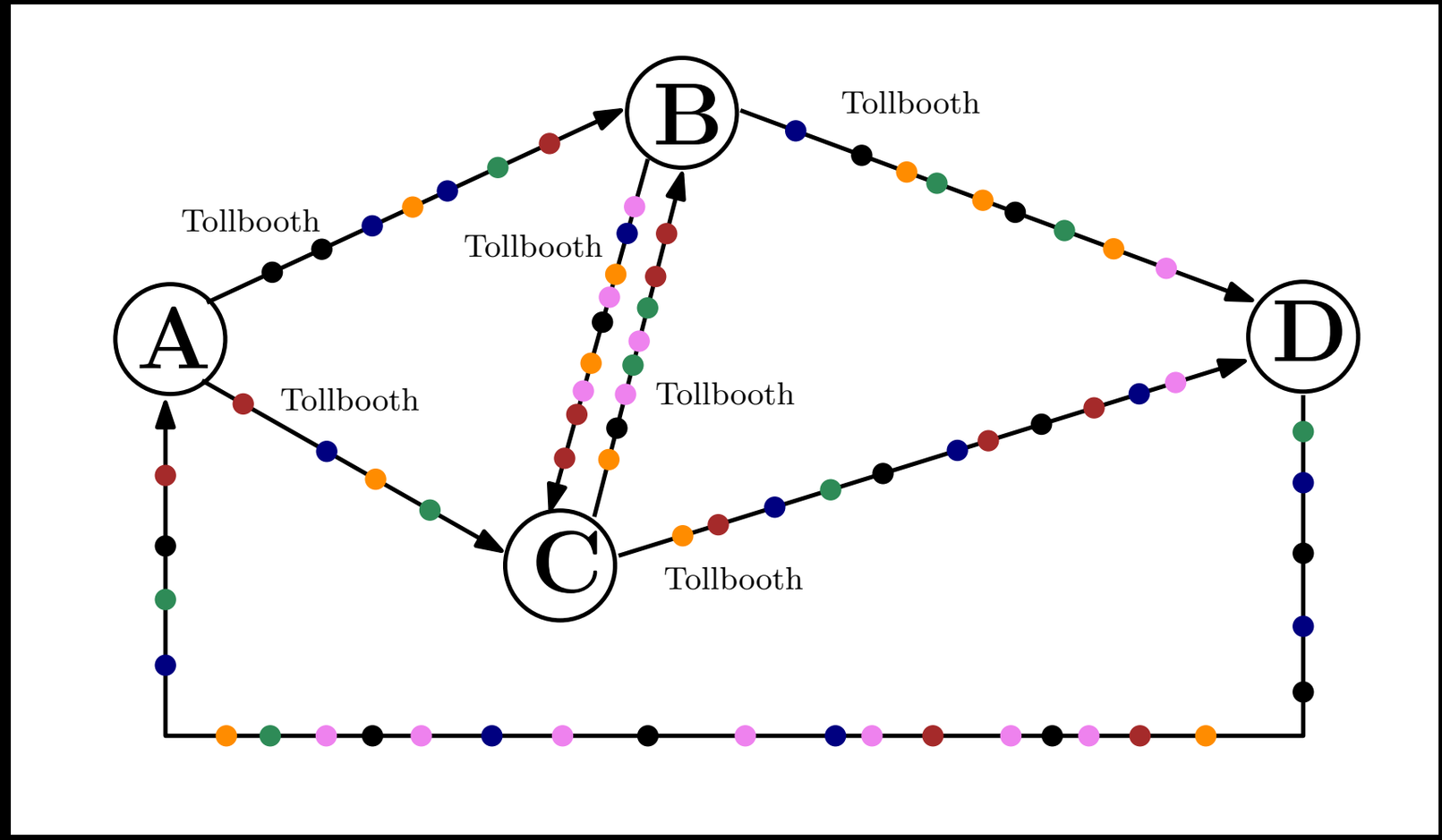

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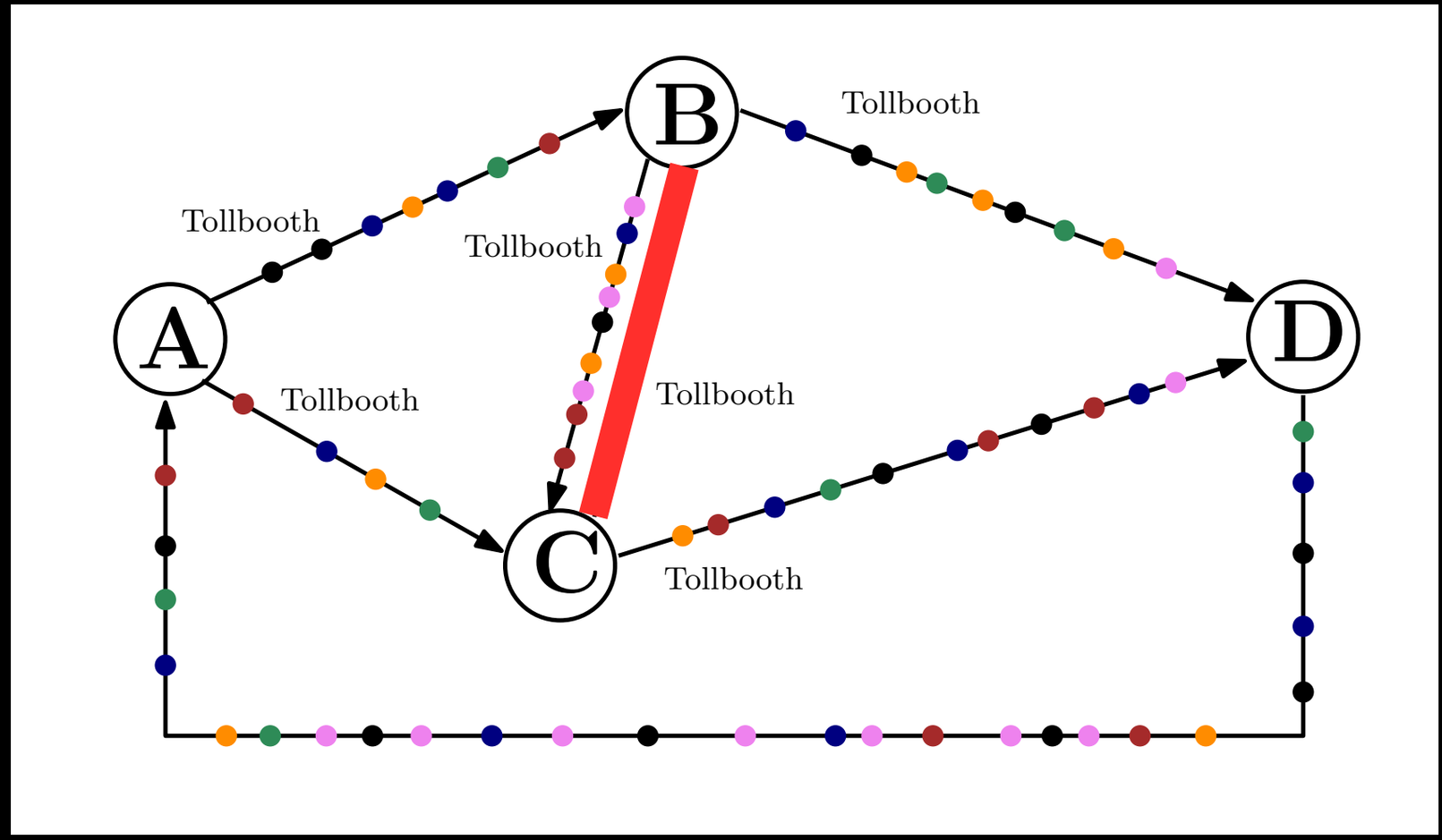
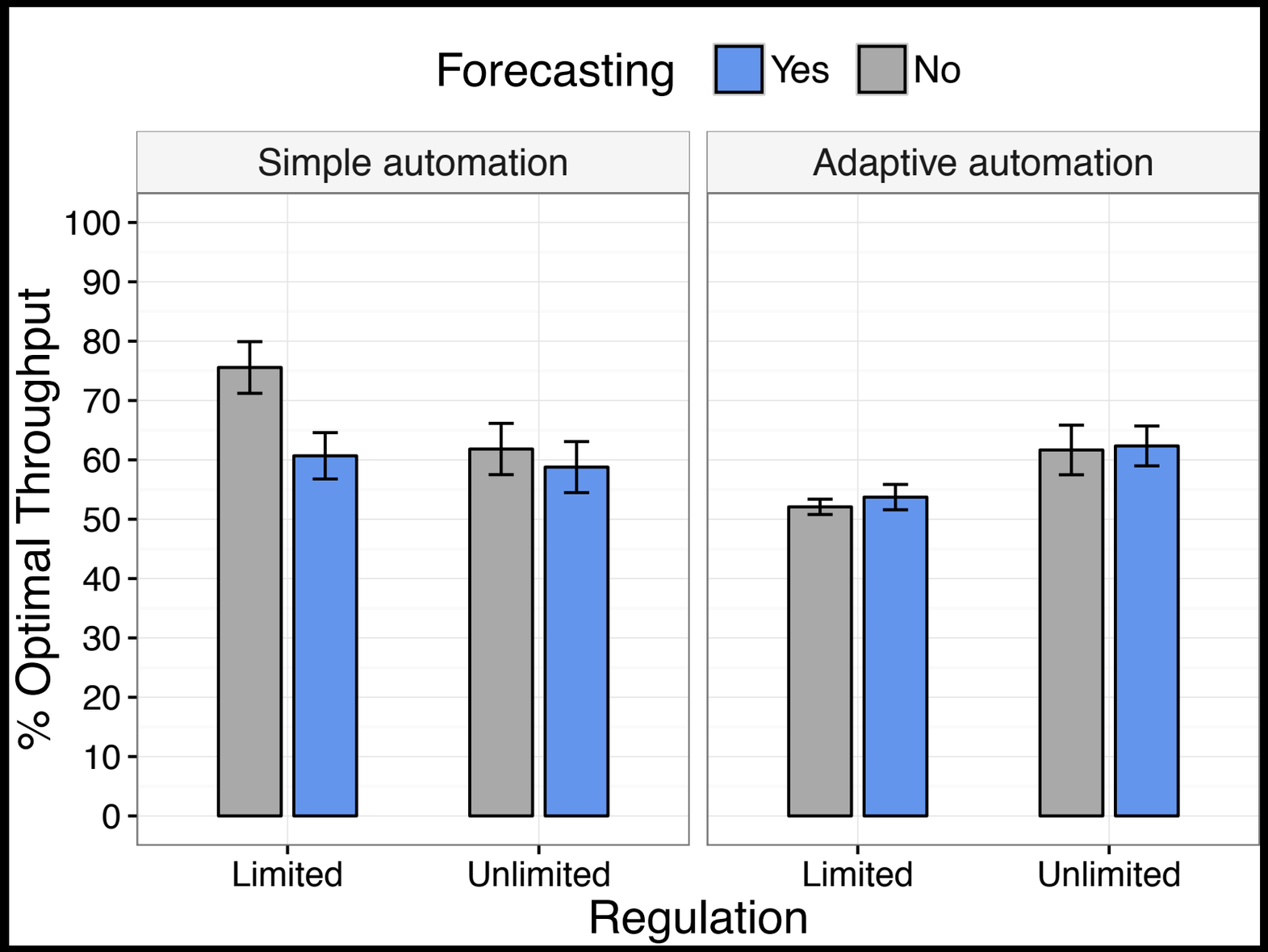


Outcome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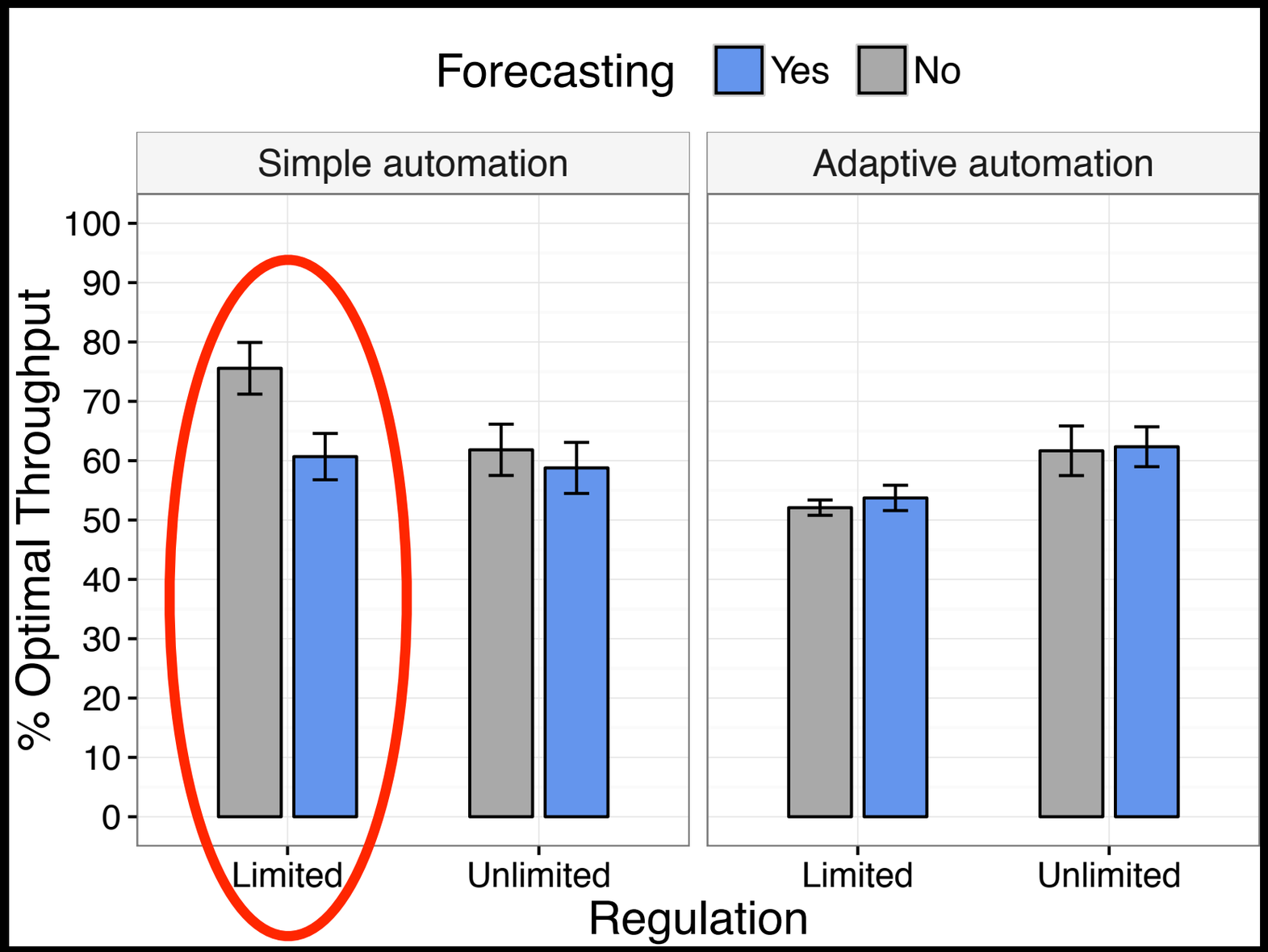
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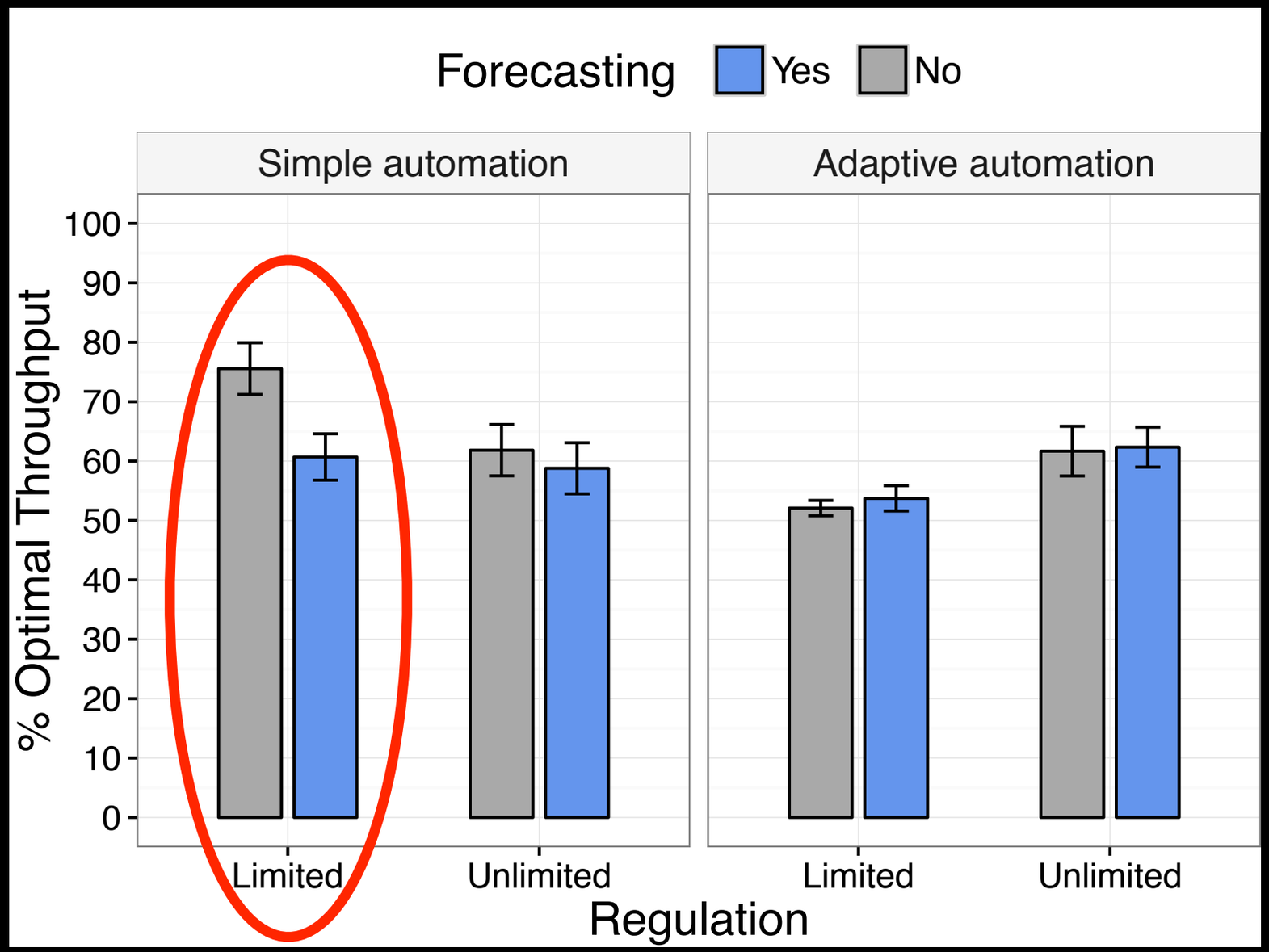
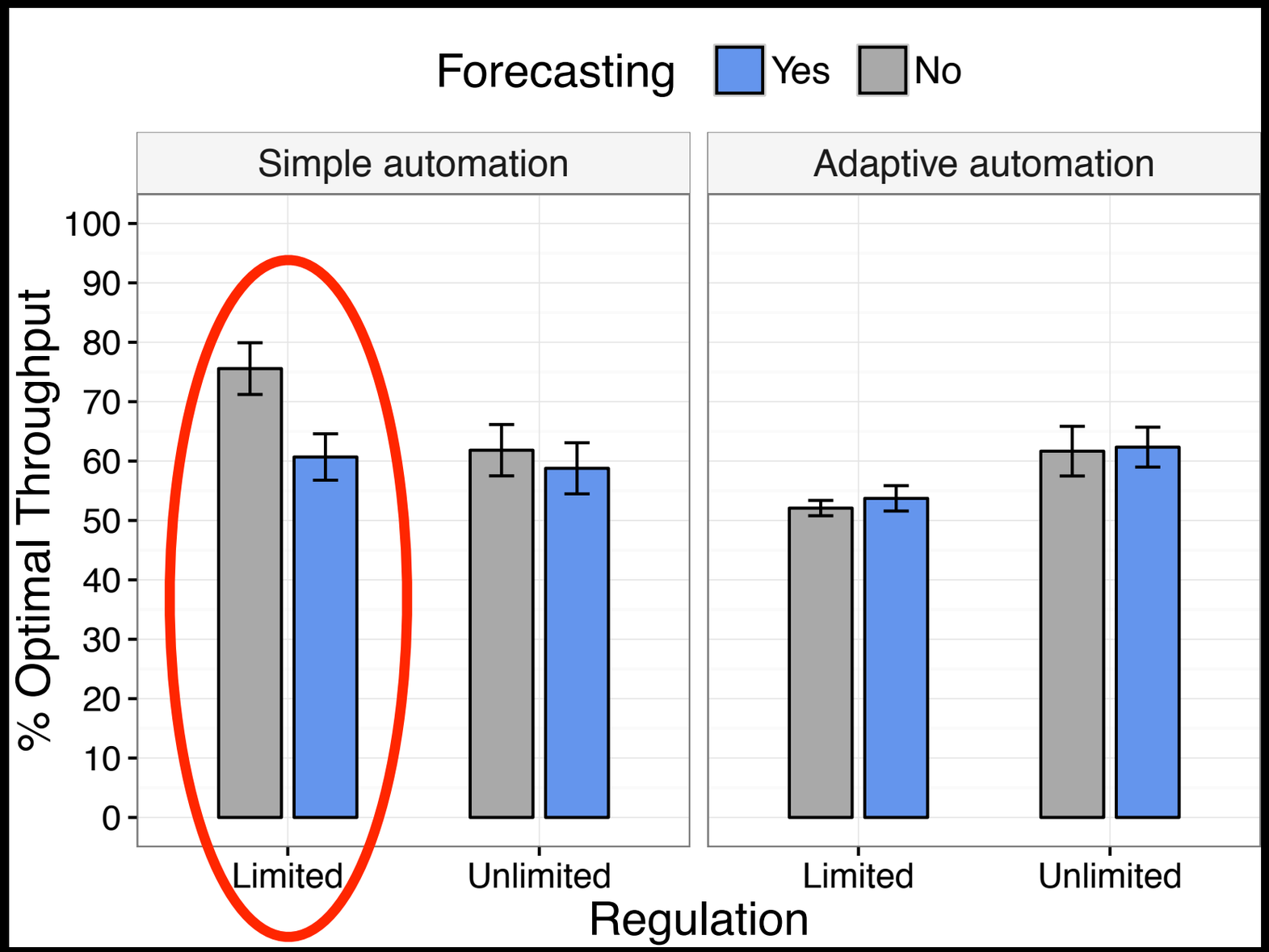


Decision support made Simple-Limited worse!

Outcome



Decision support made Simple-Limited worse!

Why? Regulators had a poorer model of the cars.

Toward a General Theory

3 “Forces”:

- Adaptive robots -> Regulator must spend more time modeling
- Adaptive robots -> Regulators need more regulatory power
- More regulator power -> Decreased time modeling robots

Conclusions and Future Work

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- Data points that suggest less is more

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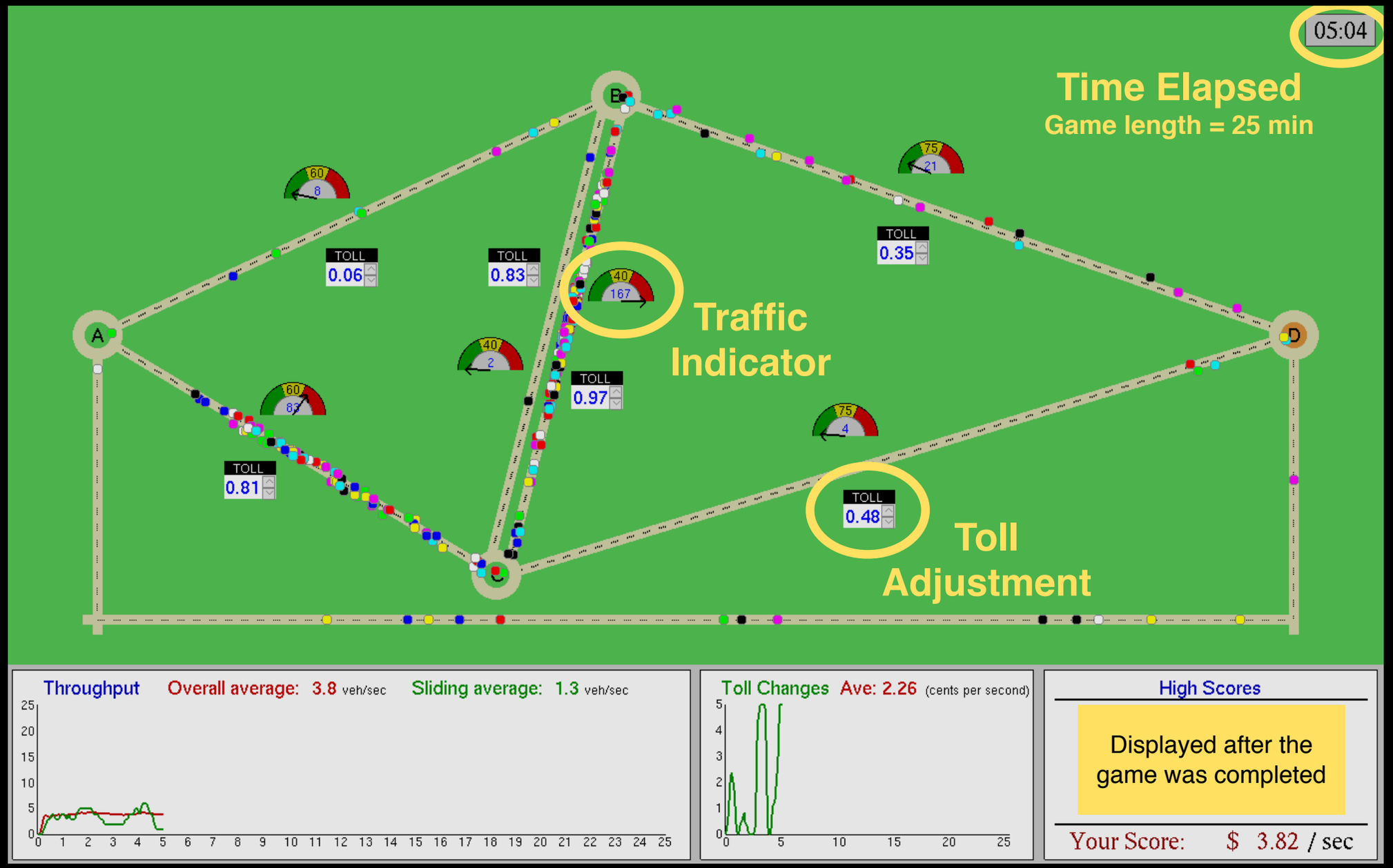
- Data points that suggest less is more
  - Limited regulator power with simple robots produced the best results
- Just outliers? Or part of a general trend?
- Can we find a way to do more with more?

Extras



High Scores

Displayed after the game was completed

Your Score: $ 3.82 / sec