Toward Understanding the Impact of User Participation in Autonomous Ridesharing Systems

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Traffic and Turkey

A Thanksgiving dinner

Traffic on the 405 Freeway in Los Angeles on 11/21/2018

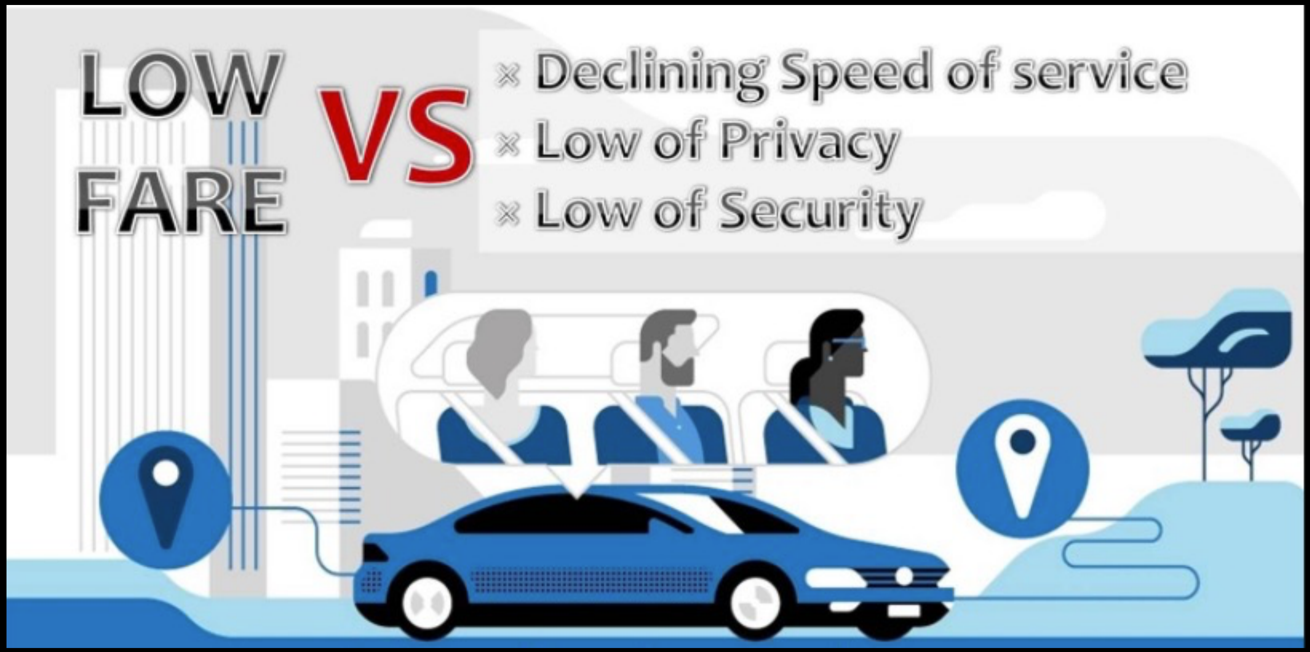
Photo credit: NYT, NBC

Benefits of Ridesharing

Challenge: human factor

- User participation: tradeoffs

  -Privacy (Aivodji et al. 2016)
  -Quality of service (Shen and Lopes, 2015)
  -Reputation and trust (Furuhata 2013)



- Selfish behavior vs public good

  -Price of anarchy can be quite high
  (Shen et al. 2017; Youn et al. 2008)

Cost when passengers' behavior follow worst user equilibria

$$PoA = \frac{\max_{s \in Equil} Cost(s)}{\min_{s \in S} Cost(s)}$$

Cost when system achieves optimal efficiency

Photo credit: NYT, KABC-TV

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Photo credit: Business Insider

Outline

- Ridesharing
- Method: Simulation Framework
- Data and Experimental Design
- Results
- Conclusion and future work

Ridesharing

- Trip-Vehicle Assignment
- Modeling User Participation

Trip-Vehicle Assignment

- Heuristic algorithms do not scale
  - Branch-and-cut: up to 32 users (Cordeau 2006)
  - Annealing meta-heuristic algorithm: 100 users (Braekers et al. 2014)
  - Dynamic programming and large neighborhood search: up to 144 users (Ritzinger et al. 2016)

Trip-Vehicle Assignment

- Graph-theoretic approaches:
    - Shareability Networks: static, up to three passengers per vehicle (Santi et al. 2014)
    - An anytime algorithm: dynamic, high capacity, up to ten passengers per vehicle (Alonso-Mora et al. 2017)

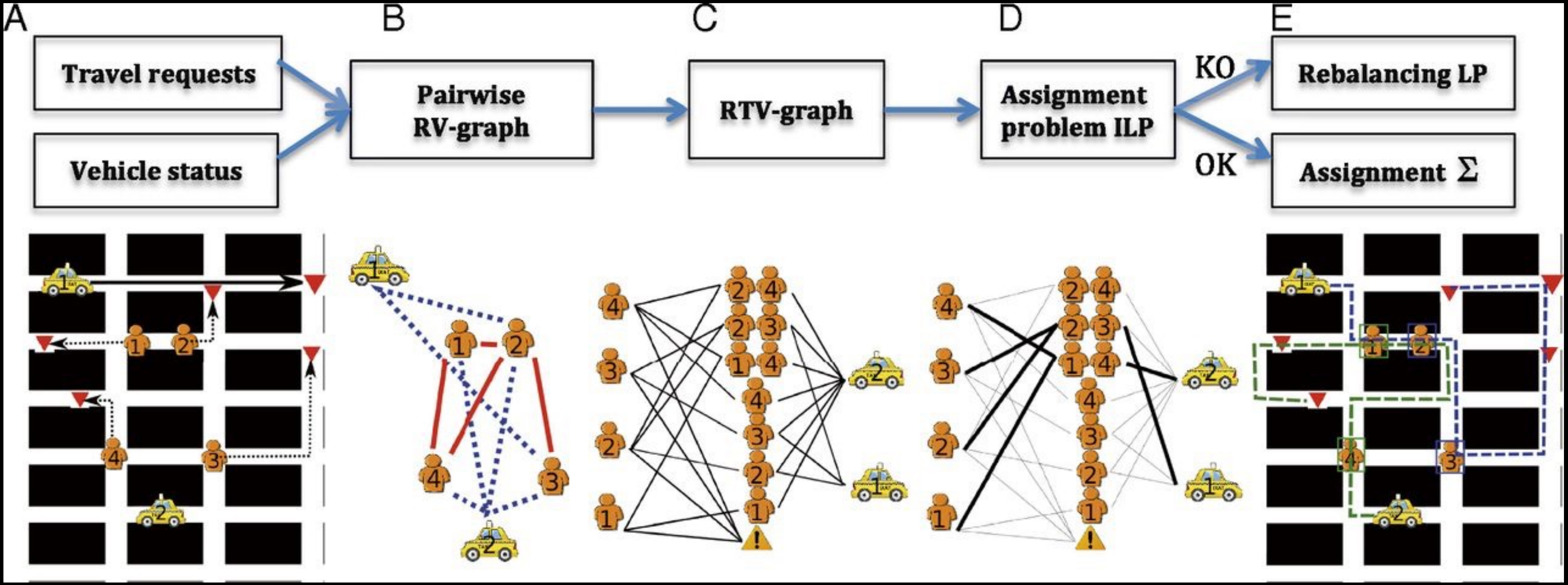


Photo credit; Alonso-Mora et al. 2017

Modeling User Participation

- Traditional approaches

  -Well defined games with complete information, e.g., selfish routing (Roughgarden 2005), finite congestion game (Christodoulou and Koutsoupias, 2005)

  -Assume that agents' utilities are determined by a unified function or drawn from a known probability distribution (Shen,Lopes and Crandall, 2016; Zhao et al. 2014)

- Our approach

  - Different (varying) levels of user participation

  - Detailed simulation based on real-world data

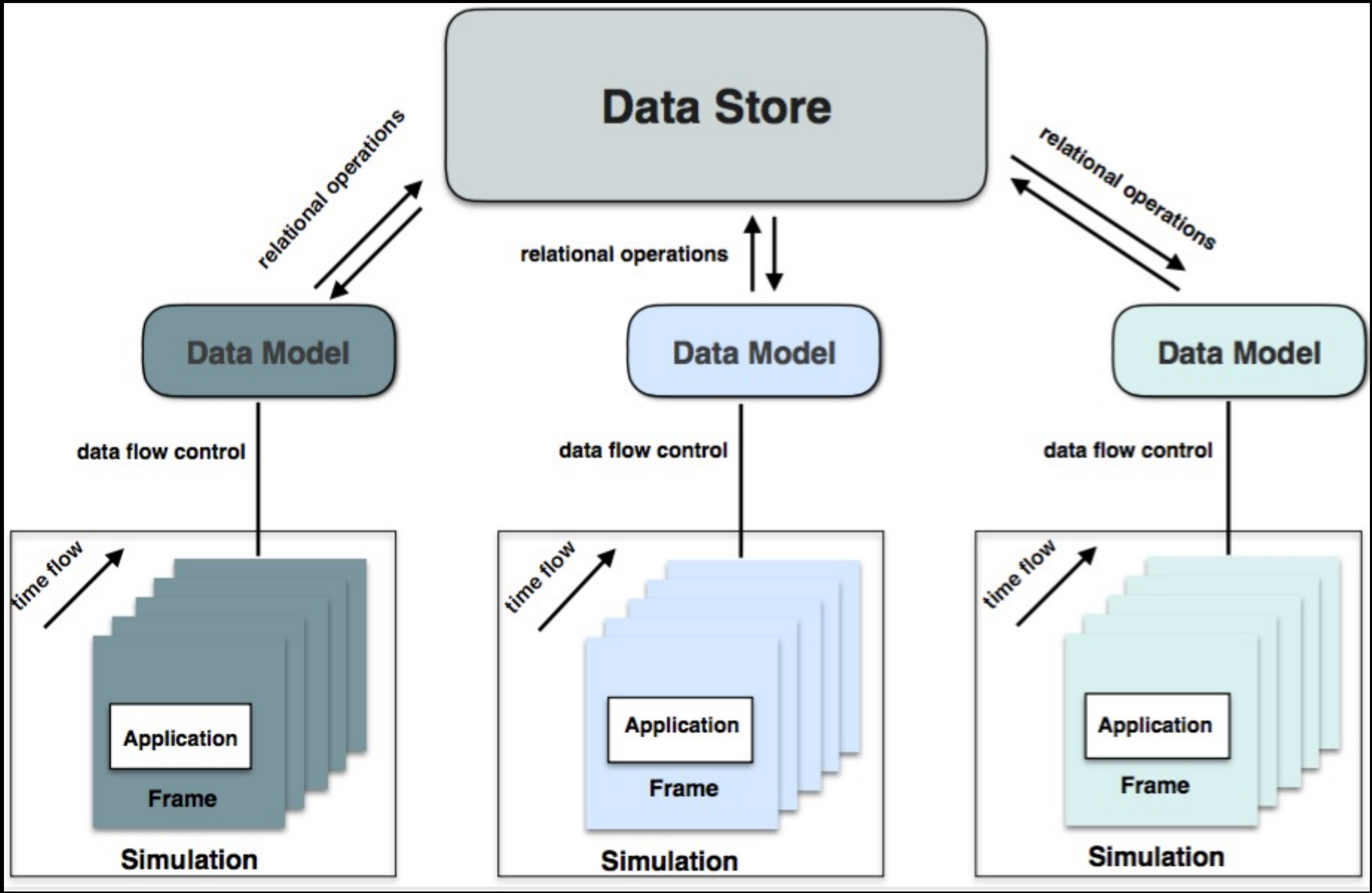
Research Questions

- How do the levels of user participation influence the performance of autonomous ridesharing systems?

- To what extent passengers' uncoordinated behavior on ridesharing participation diminishes the efficiency of autonomous ridesharing systems?

Reducing Simulation Complexity

- Spacetime (Lopes et al. 2017)

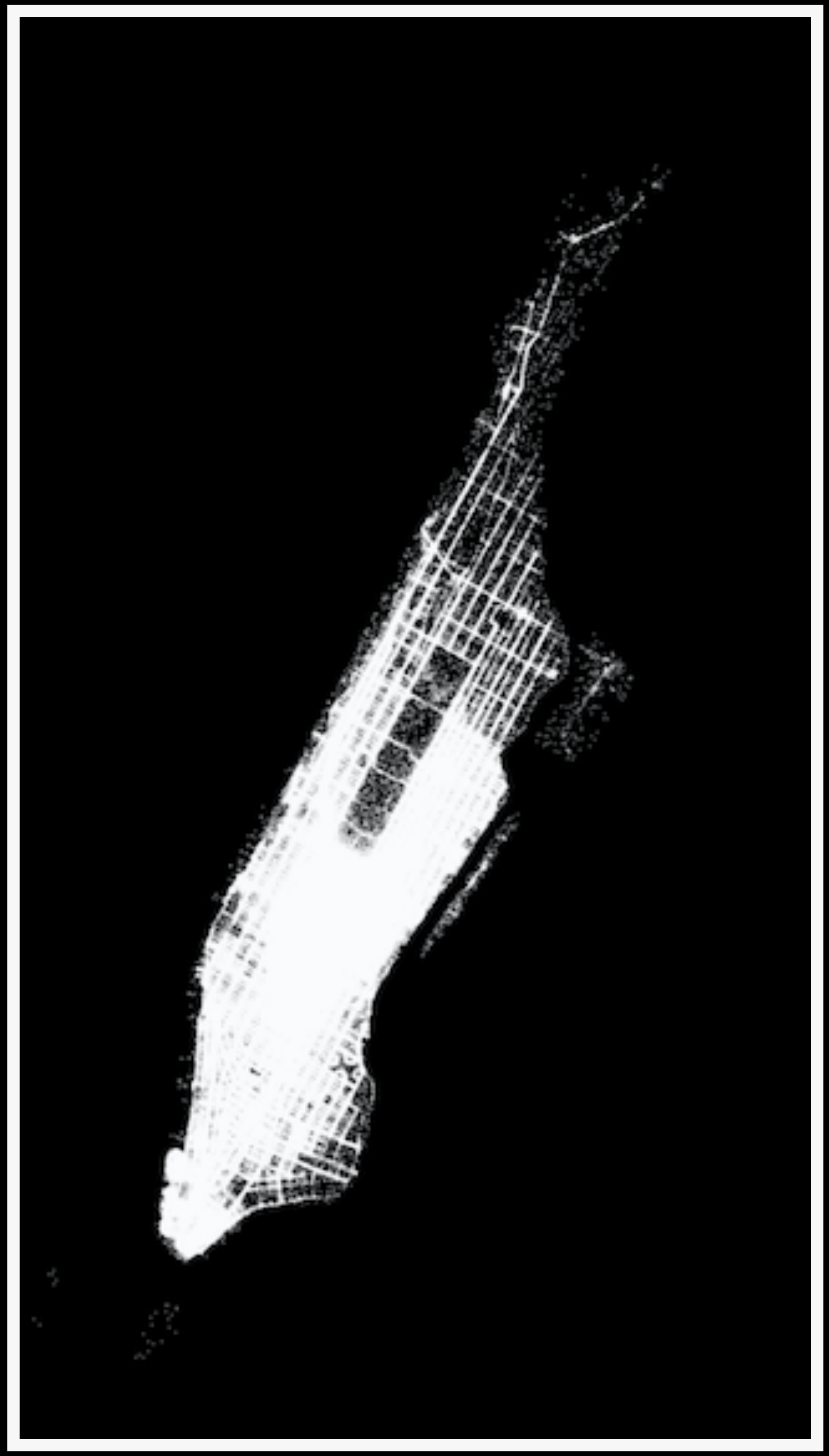


SpaceTime for Autonomous Ridesharing Systems (STARS)

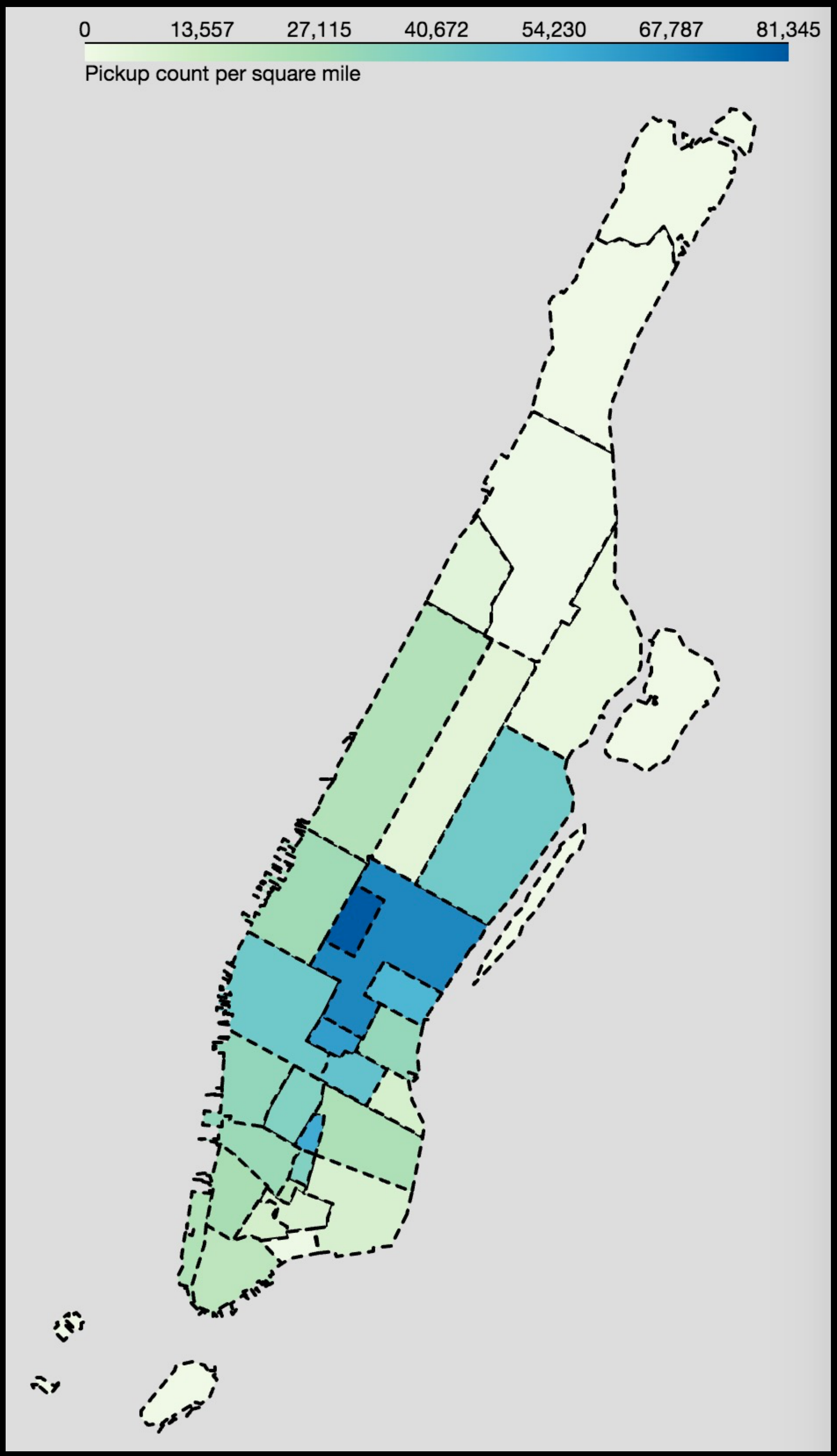
- Anytime algorithm for trip-vehicle assignment
- Spacetime for a modular design
- A data-driven approach for simulating city-scale ridesharing systems

Data

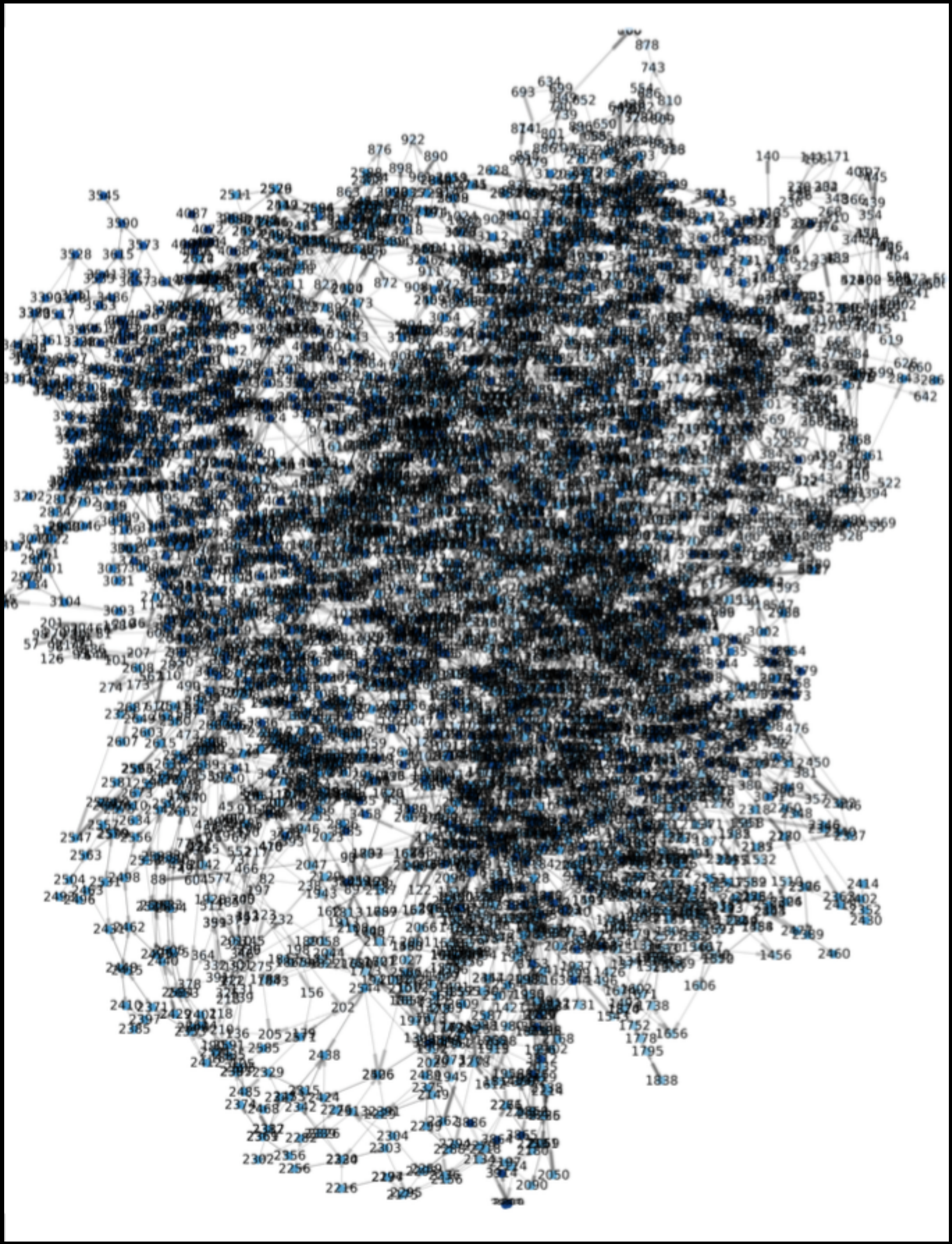
- A typical week (June 6th - June 12th, 2011) in Manhattan
- 3,014,628 trips ranging from 391,246 (Sat.) to 465,331(Mon.) per day
- Each trip: pickup datetime, drop-off datetime, passenger count, pickup longitude, pickup latitude, drop-off longitude, and drop-off latitude
- Road network: Manhattan (extracted from OpenStreetMap)



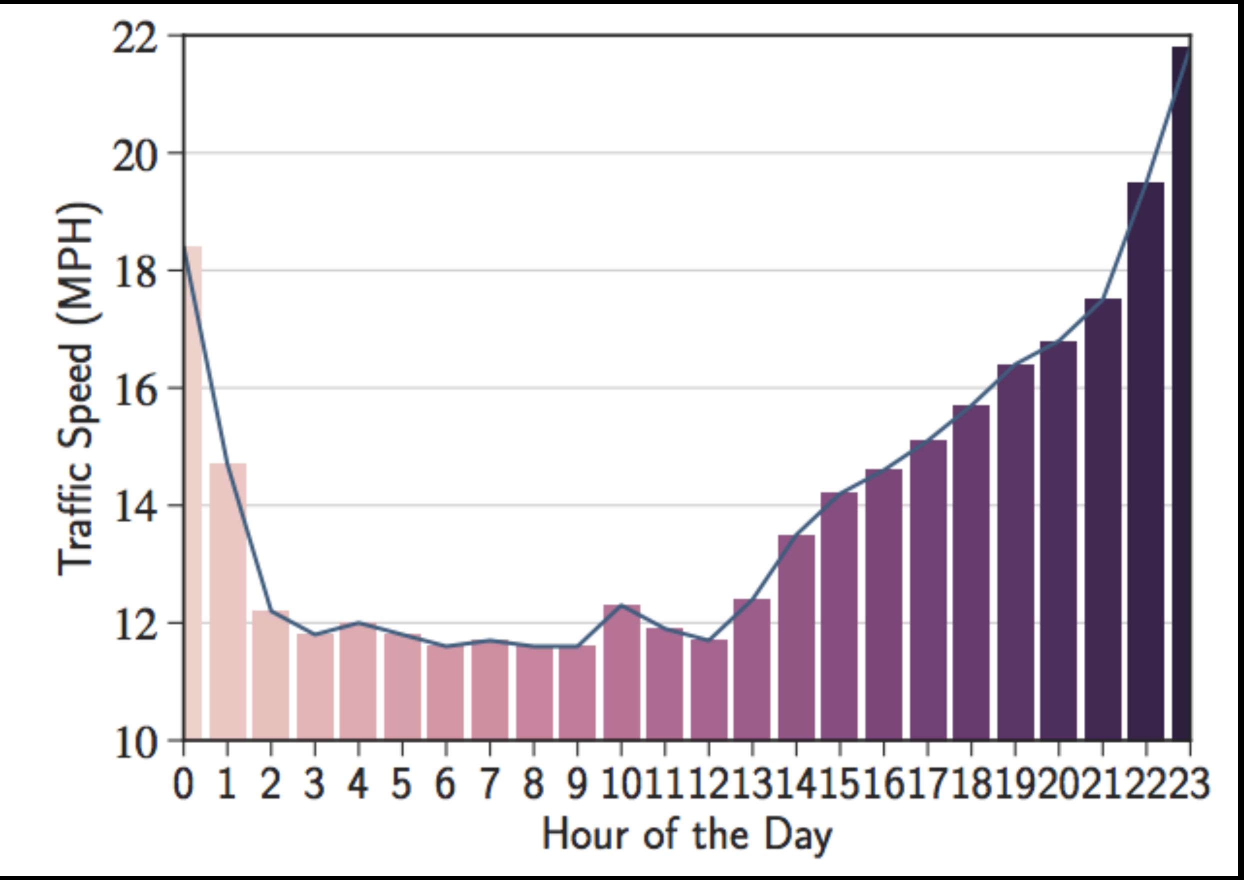
Request distribution of Manhattan (06/08/2011)



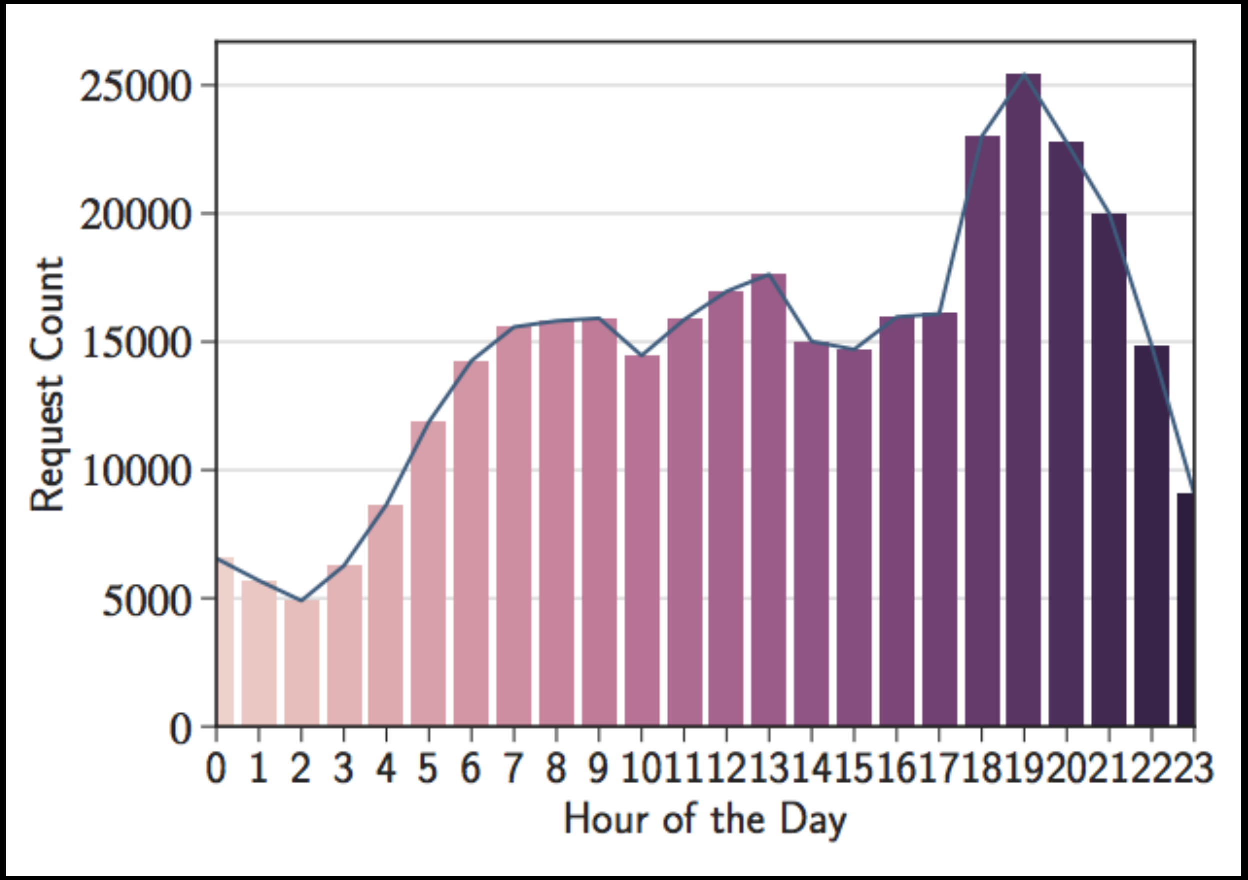
Request density by neighborhood of Manhattan (06/08/2011)



Road graph of Manhattan (4,092 nodes, 9,453 edges)



Average traffic speed (MPH) for each hour of a typical day (Wednesday, 06/08, 2011)



Count of requests for each hour of a typical day (Wednesday, 06/08, 2011)

Independent Variables

- Varying the levels (0%, 10%, …, 100%) of user participation for different systems
    - Size of vehicle fleet: 1000, 2000, 3000, 4000
    - Vehicle capacity: 1, 2, 4, 6, 8, 10
    - Maximum waiting time (min): 2, 4, 6, 8
- Varying request density and traffic conditions (fleet = 3000, capacity = 4, max. waiting = 6)
    - Density: half of the demand, normal demand, double of the demand
    - travel time estimate: 12:00 (lowest speed), 19:00 (highest speed), mean daily travel time estimate (average speed)

Dependent Variables

- Total cost

$$C(p) = \sum_{r \in R_o} \delta_r + \sum_{r \in R_d} c_d$$

Sum of travel delay for all serviced requests

Sum of cost for all the denied requests

- Price of anarchy

$$PoA = \frac{\max_{p \in P_{sue}} C(p)}{\min_{p \in P} C(p)}$$

the total cost when passengers' decisions on participation are under the worst user equilibria

the total cost when the system achieves optimal efficiency

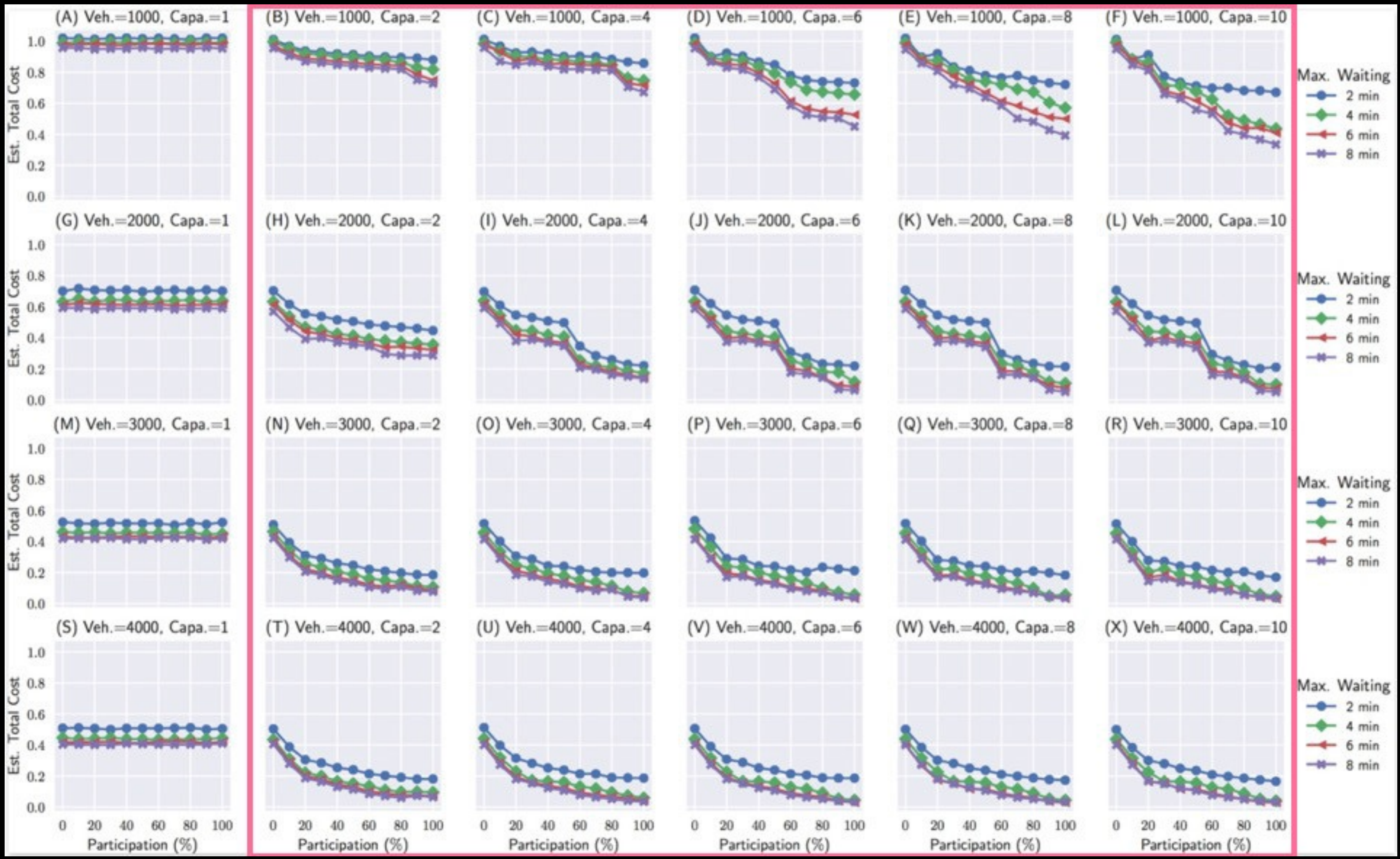
Simulation setup

- Hardware
  - 24-core 3.0 GHz
  - 128GB RAM
- Solver
  - Gurobi academic version 7.0.2
- Accelerating simulation: 0.1 (discounting factor)
- Number of simulations: 1,122
- Five weeks

Performance improves as participation increases

- Observation 1: User participation typically improves the performance of autonomous ridesharing systems, but the degree of improvement generally slows down as user participation increases to a high level.

Total Cost


(A) Veh.=1000, Capa.=1
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(C) Veh.=1000, Capa.=4
(D) Veh.=1000, Capa.=6
(E) Veh.=1000, Capa.=8
(F) Veh.=1000, Capa.=10
(G) Veh.=2000, Capa.=1
(H) Veh.=2000, Capa.=2
(I) Veh.=2000, Capa.=4
(J) Veh.=2000, Capa.=6
(K) Veh.=2000, Capa.=8
(L) Veh.=2000, Capa.=10
(M) Veh.=3000, Capa.=1
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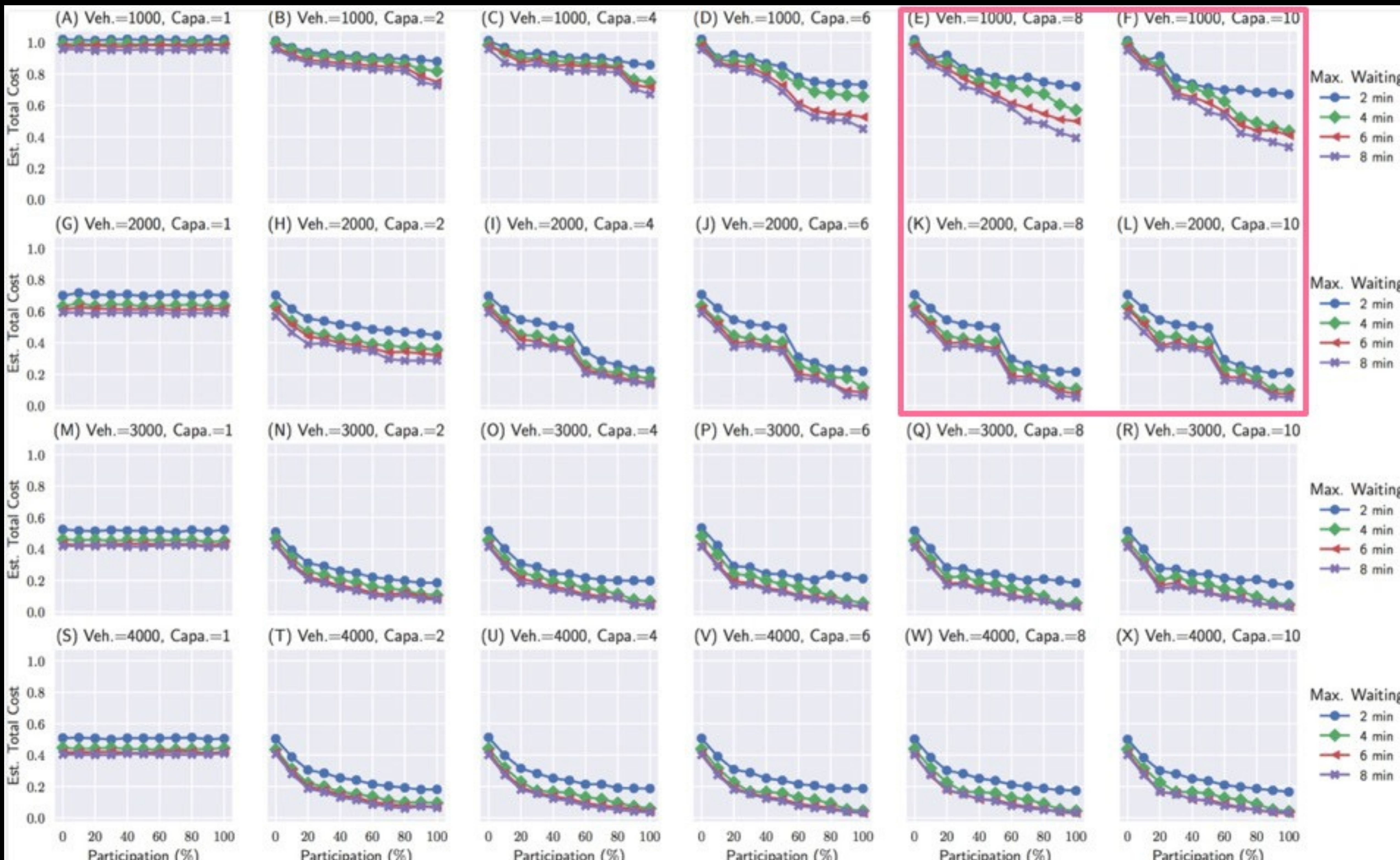
(Q) Veh.=3000, Capa.=8
(R) Veh.=3000, Capa.=10
(S) Veh.=4000, Capa.=1
(T) Veh.=4000, Capa.=2
(U) Veh.=4000, Capa.=4
(V) Veh.=4000, Capa.=6
(W) Veh.=4000, Capa.=8
(X) Veh.=4000, Capa.=10
Est. Total Cost
Participation (%)
Max. Waiting
2 min
4 min
6 min
8 min

Greater impact when equipped with small fleets of high-capacity vehicles

- Observation 2: User participation typically has a greater impact on the performance of autonomous ridesharing systems with small fleets of high-capacity vehicles.

Total Cost



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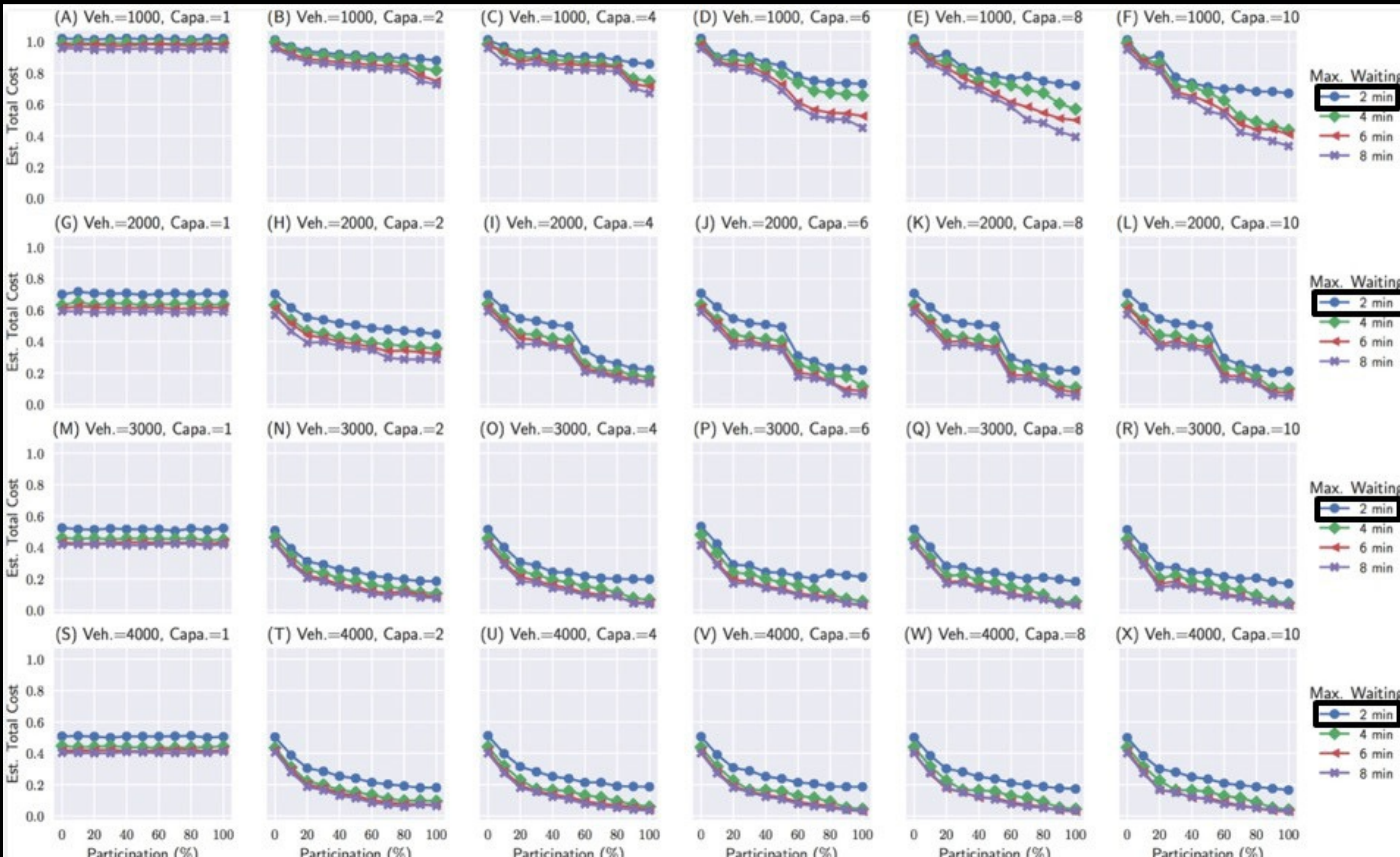
(W) Veh.=4000, Capa.=8
(X) Veh.=4000, Capa.=10
Est. Total Cost
Participation (%)
Max. Waiting
2 min
4 min
6 min
8 min

Smaller impact for systems with a short maximum waiting time

- Observation 3: User participation typically has a smaller impact on the performance of autonomous ridesharing systems with a short period of maximum waiting time allowed.

Total Cost



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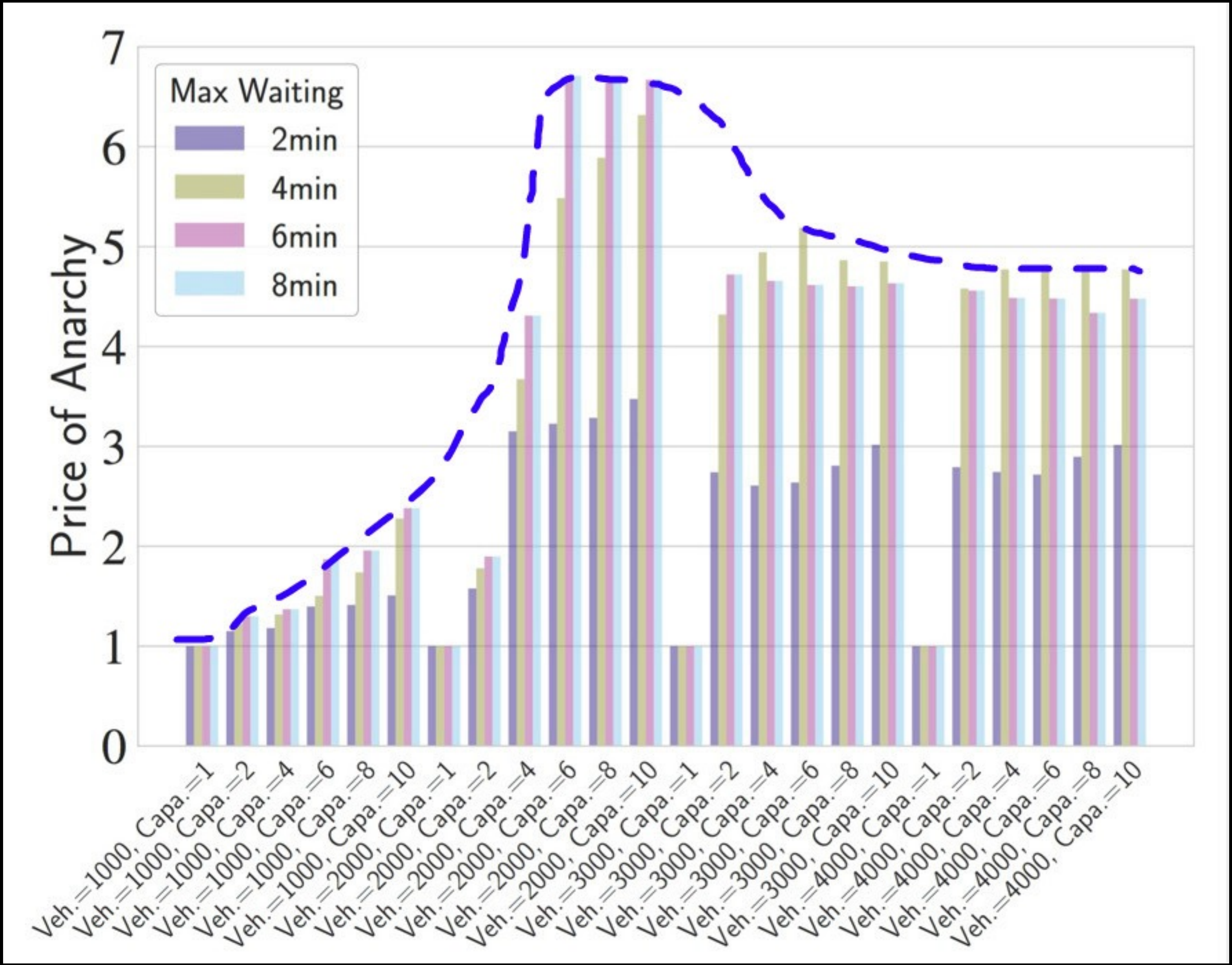
(U) Veh.=4000, Capa.=4
(V) Veh.=4000, Capa.=6
(W) Veh.=4000, Capa.=8
(X) Veh.=4000, Capa.=10
Est. Total Cost
Participation (%)
Max. Waiting
2 min
4 min
6 min
8 min

Price of anarchy increases and then decreases as fleet size increases

- Observation 4: As the fleet size increases, the price of anarchy due to users' uncoordinated choices on participation typically first increases and then decreases.



Max Waiting
2min
4min
6min
8min
Price of Anarchy
0
1
2
3
4
5
6
7
Veh.=1000, Capa.=1
Veh.=1000, Capa.=2
Veh.=1000, Capa.=4
Veh.=1000, Capa.=6
Veh.=1000, Capa.=8
Veh.=1000, Capa.=10
Veh.=2000, Capa.=1
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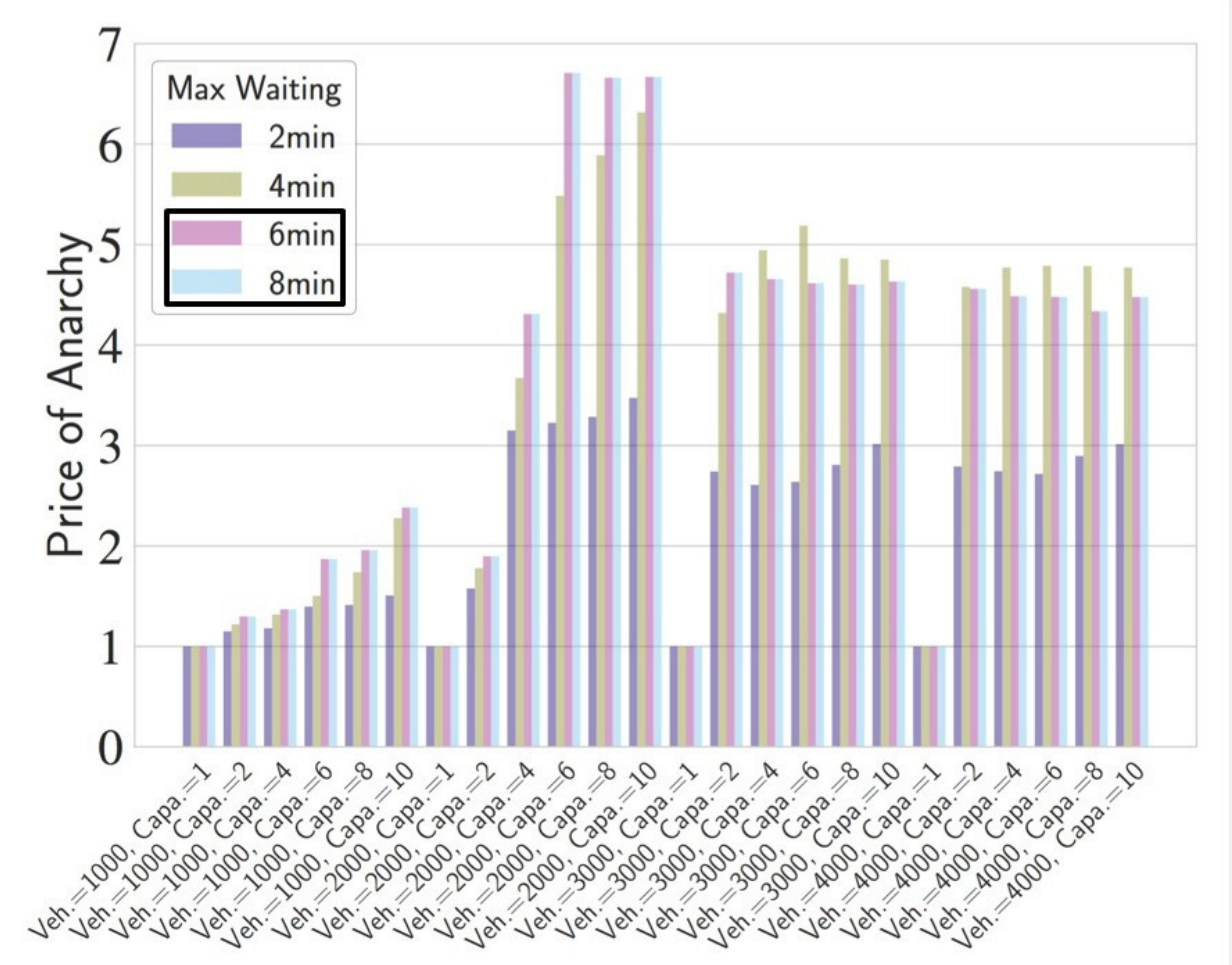
Veh.=4000, Capa.=4
Veh.=4000, Capa.=6
Veh.=4000, Capa.=8
Veh.=4000, Capa.=10

Price of anarchy keeps steady for systems with long maximum waiting time

- Observation 5: The price of anarchy due to users' uncoordinated choices on participation typically keeps steady when the maximum waiting time is sufficiently long.


Max Waiting
2min
4min
6min
8min
Price of Anarchy
0
1
2
3
4
5
6
7
Veh.=1000, Capa.=1
Veh.=1000, Capa.=2
Veh.=1000, Capa.=4
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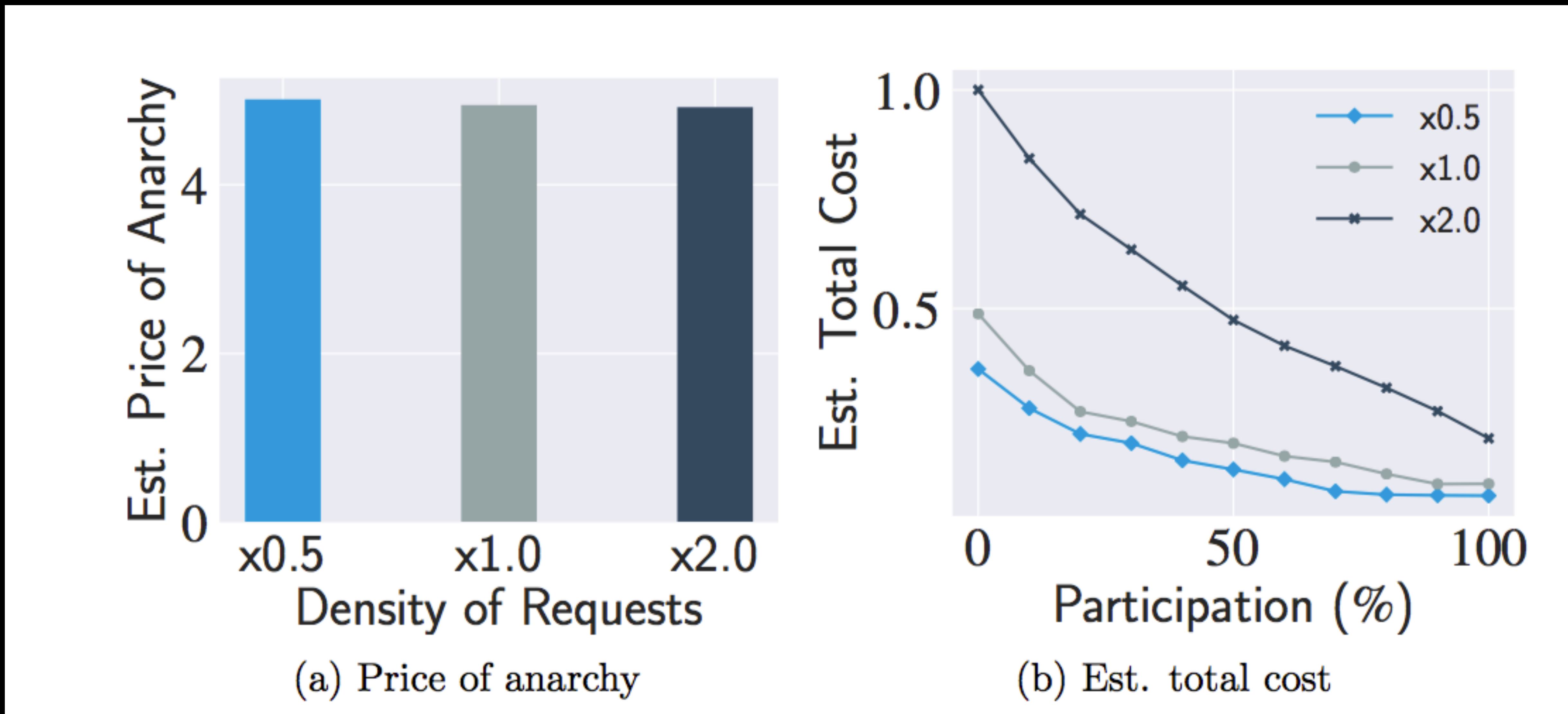
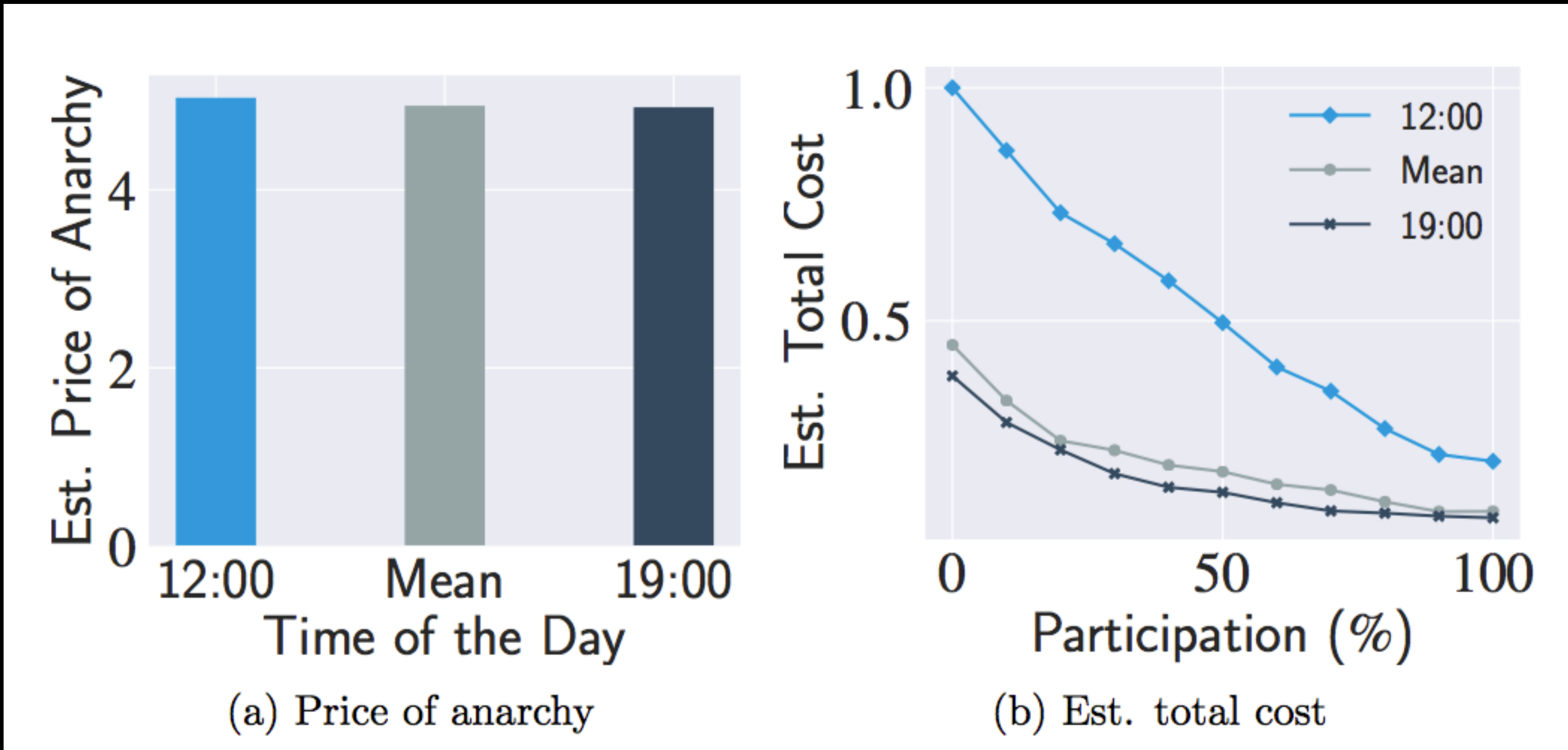
Veh.=4000, Capa.=2
Veh.=4000, Capa.=4
Veh.=4000, Capa.=6
Veh.=4000, Capa.=8
Veh.=4000, Capa.=10

Request density or traffic condition has litter impact on price of anarchy

- Observation 6: Request density or traffic condition typically has little impact on the price of anarchy, although the system efficiency generally increases when the request density reduces or the traffic condition improves.



A comparison of the price of anarchy and efficiency on a ridesharing system (fleet size = 3000, capacity = 4, and maximum waiting time = 6 mins) by varying request density



A comparison of the price of anarchy and efficiency on a ridesharing system (fleet size = 3000, capacity = 4, and maximum waiting time = 6 mins) by varying the time of the day used for travel time estimate.

Discussion

- What are the implications?
    - sweet spots exist
    - tradeoffs are needed
- Will the observations generalize?
    - not known yet

Conclusion

- Research question:
  - How and to what extent user participation influences the efficiency of autonomous ridesharing systems?
- Contributions:
  - Spacetime for Autonomous Ridesharing Systems
  - An extensive empirical study
- Take-aways:
  - Specific configurations of ridesharing systems can be identified to counter the effect of passengers' uncoordinated behavior regarding participation on the system efficiency
  - To achieve desired outcomes, stakeholders should make tradeoffs between system efficiency and price of anarchy based on realistic simulations with real-world data.

Future work

- Can we generalize the findings in other road networks?
- How to incentivize user participation?
- What if some parts of the ridesharing networks fail?

Autonomous Mobility on Demand Systems

Photo credit: Vox