Multi-objective linear optimization for strategic planning of shared autonomous vehicle operation and infrastructure design

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Background: Strategic and operational planning of SAV systems

Strategic planning of SAV systems

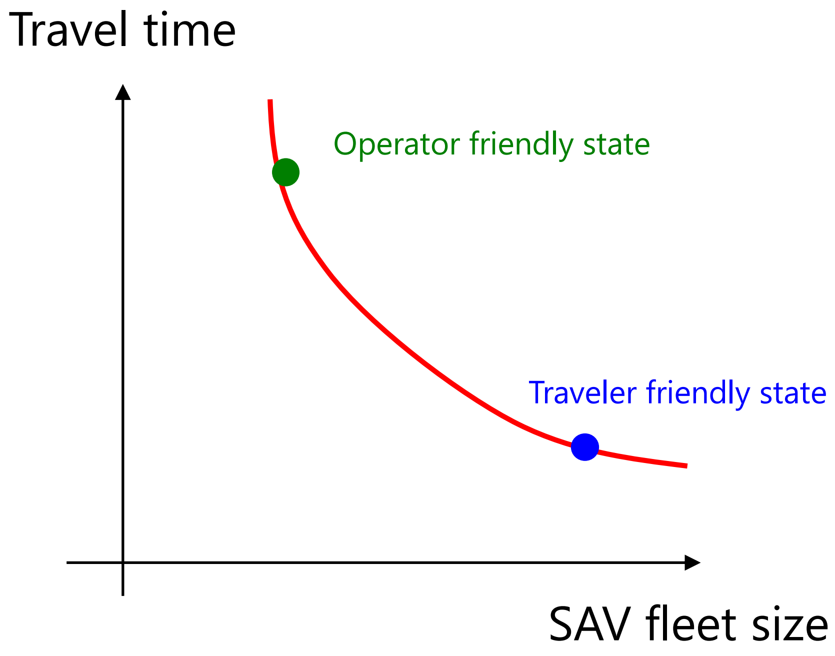
- Network design
- Parking slot allocation
- Fleet size

Operational planning of SAV systems

- SAV routing
- Passenger pickup/drop-off
- Ridesharing

Unified, tractable DTA framework for strategic optimization with explicit consideration to operation

Background: What is "optimal"?



- Trade-offs between objective values

Travel time	⟺	SAV fleet size
Traveler utility	⟺	Operator benefit
Profit-seeking operator	⟺	Public sector operator

- It is important to clarify the trade-off relations before implementing SAV systems

Multi-objective optimization to explicitly consider and derive trade-offs

Model: Key assumptions

- Dynamic OD matrix of travelers is available
- The only transportation mode is an SAV system

- Each SAV has passenger capacity
- Each road has traffic capacity
- Each node has storage capacity (queuing, parking)

Problem: Find the optimal SAV and passenger flow and infrastructure design that satisfy the traveler demand under the capacity constraints

Model: Multi-objective optimization problem

[SOSAV] $\min(T,\ D,\ N,\ C)$

subject to

$$\sum_{ij,s,t,k} t_{ij} y^{k,t}_{s,ij} = T$$

$$\sum_{ij,i\neq j} d_{ij} x^t_{ij} = D$$

$$\sum_i x^0_{0i} = N$$

$$\sum_{ij} c_{ij}(\mu_{ij} - \mu^{\min}_{ij}) + \sum_i c_i(\kappa_i - \kappa^{\min}_i) = C$$

definition of objective values

$$\sum_j x^{t-t_{ji}}_{ji} - \sum_j x^t_{ij} = 0 \qquad \forall i, t \in (0, t_{\max})$$

conservation law of SAVs

$$\sum_j y^{k,t-t_{ji}}_{s,ji} - \sum_j y^{k,t}_{s,ij} + y^{k,t}_{s,0i} - y^{k,t}_{s,i0} = 0 \qquad \forall i, s, k, t \in T_k$$

$$\sum_{s,k} y^{k,t}_{s,ij} \leq \rho x^t_{ij} \qquad \forall ij, i \neq j, t$$

conservation law of passengers

$$x^t_{ij} \leq \mu_{ij} \qquad \forall ij, i \neq j, t$$

link capacity

$$x^t_{ii} \leq \kappa_i \qquad \forall i, t$$

parking capacity

$$y^{k,k}_{s,0r} = M^k_{rs} \qquad \forall rs, k$$

$$\sum_{t\in T_k} y^{k,t}_{s,s0} = \sum_r M^k_{rs} \qquad \forall s, k$$

passengers' departure and arrival time

$$x^t_{ij} \geq 0 \qquad \forall ij, t$$

$$y^{k,t}_{s,ij} \geq 0 \qquad \forall ij, s, k, t \in T_k$$

$$x^0_{0i} \geq 0 \qquad \forall i$$

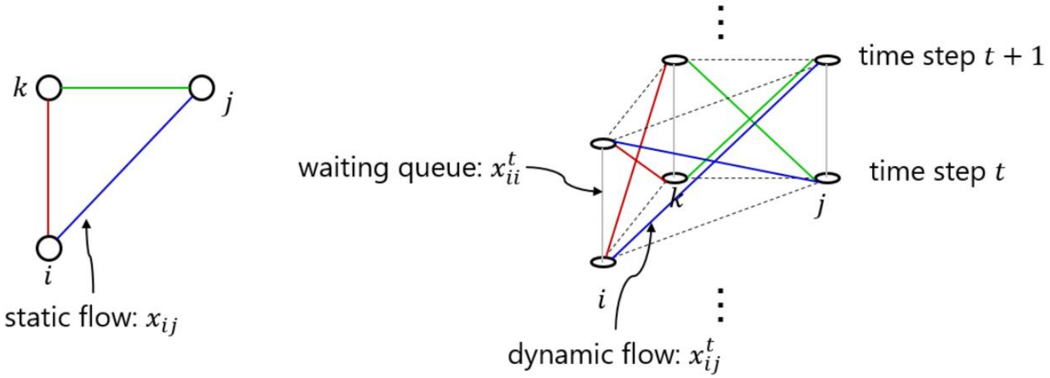
$$y^{k,t}_{s,s0} \geq 0 \qquad \forall s, t, k \in T_k$$

$$\mu^{\min}_{ij} \leq \mu_{ij} \leq \mu^{\max}_{ij} \qquad \forall ij$$

$$\kappa^{\min}_i \leq \kappa_i \leq \kappa^{\max}_i \qquad \forall i$$

- Objective functions:
  - Total travel time of passengers
  - Total distance traveled by SAVs
  - SAV fleet size
  - Total infrastructure (road, parking) cost
- Key decision variables:
  - Dynamic SAV flow
  - Dynamic passenger flow
  - SAV fleet size
  - Link capacity, parking capacity
- Multi-objective linear programming
- Solution = Pareto frontier

Model: Traffic features



$$\sum_j x_{ji}^{t-t_{ji}} - \sum_j x_{ij}^t = 0 \qquad \forall i, t \in (0, t_{\max})$$

conservation law of SAVs

$$\sum_j y_{s,ji}^{k,t-t_{ji}} - \sum_j y_{s,ij}^{k,t} + y_{s,0i}^{k,t} - y_{s,i0}^{k,t} = 0 \qquad \forall i, s, k, t \in T_k$$

$$\sum_{s,k} y_{s,ij}^{k,t} \le \rho x_{ij}^t \qquad \forall ij, i \neq j, t$$

conservation law of passengers

$$x_{ij}^t \le \mu_{ij} \qquad \forall ij, i \neq j, t$$

link capacity

$$x_{ii}^t \le \kappa_i \qquad \forall i, t$$

parking capacity

$$y_{s,0r}^{k,k} = M_{rs}^k \qquad \forall rs, k$$

$$\sum_{t \in T_k} y_{s,s0}^{k,t} = \sum_r M_{rs}^k \qquad \forall s, k$$

passengers' departure and arrival time

$$x_{ij}^t \ge 0 \qquad \forall ij, t$$

$$y_{s,ij}^{k,t} \ge 0 \qquad \forall ij, s, k, t \in T_k$$

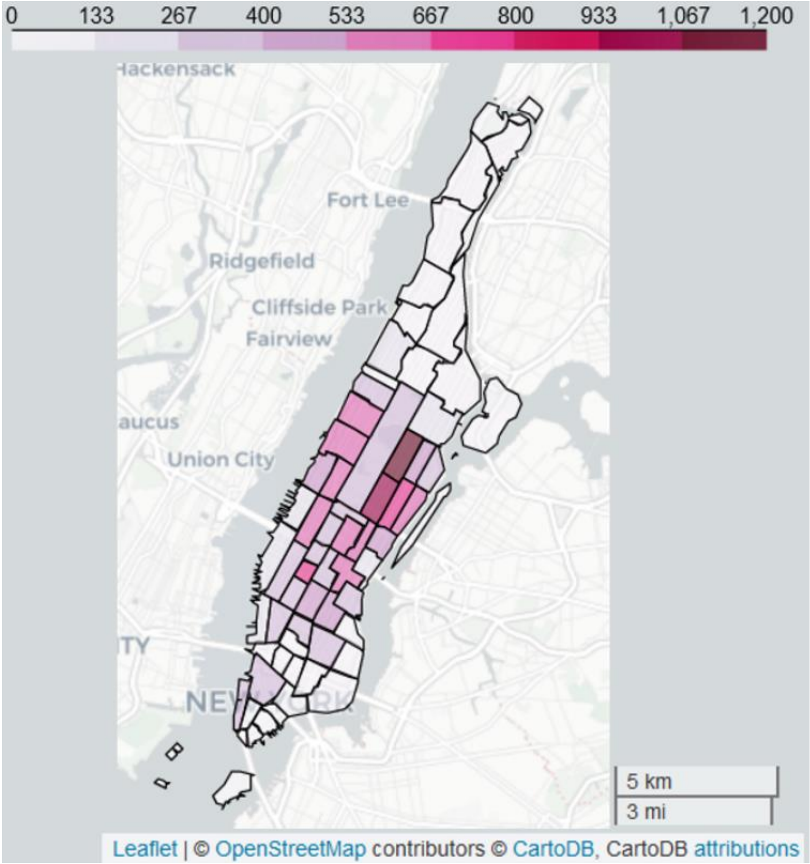
$$x_{0i}^0 \ge 0 \qquad \forall i$$

$$y_{s,s0}^{k,t} \ge 0 \qquad \forall s, t, k \in T_k$$

$$\mu_{ij}^{\min} \le \mu_{ij} \le \mu_{ij}^{\max} \qquad \forall ij$$

$$\kappa_i^{\min} \le \kappa_i \le \kappa_i^{\max} \qquad \forall i$$

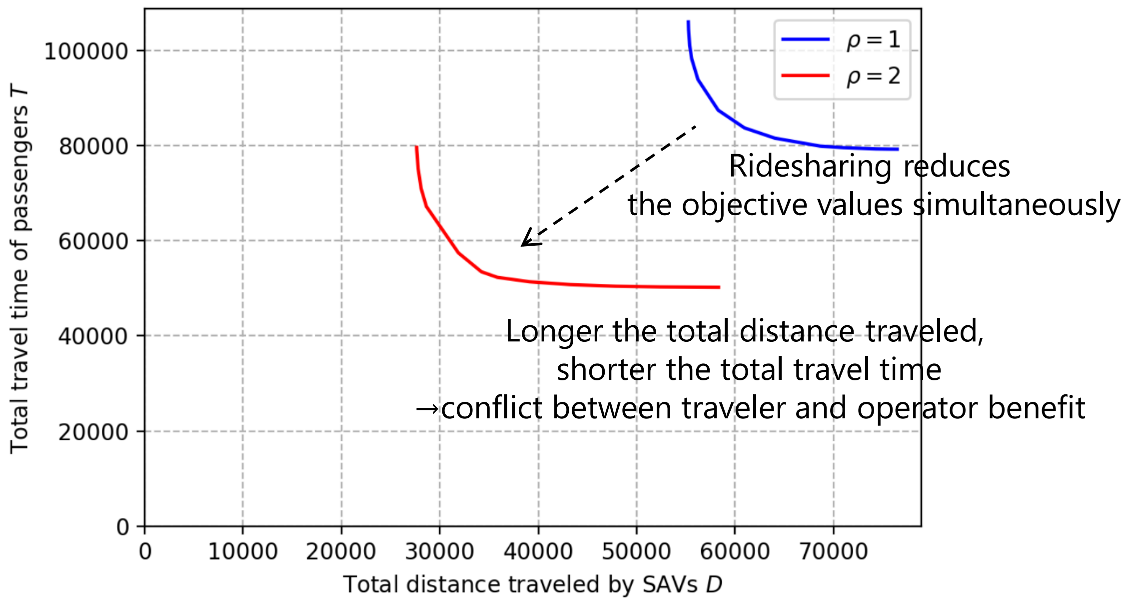
- DTA based on space-time network
- Consistent with standard DTA models
  - Conservation law of traffic
  - Free-flow speed, traffic capacity, jam density
- Important factors in SAV systems are captured
  - Traffic congestion
  - Empty vehicles' travel
  - Detour due to ridesharing
  - Waiting time of passengers

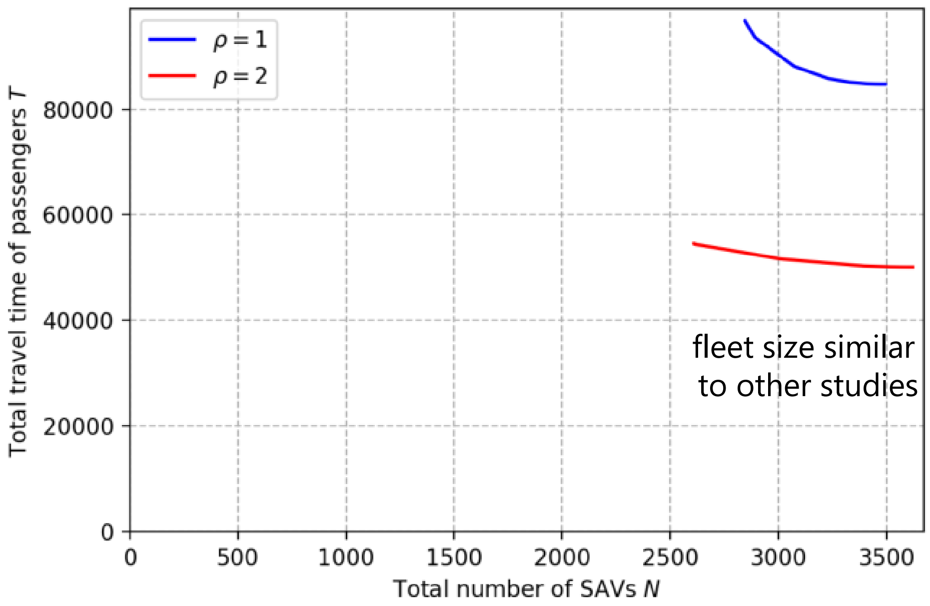


passenger demand

- NYC taxi data
  - 1 hour during morning peak
  - Total passenger demand: 17,998
- Derive optimal SAV system that serve this demand

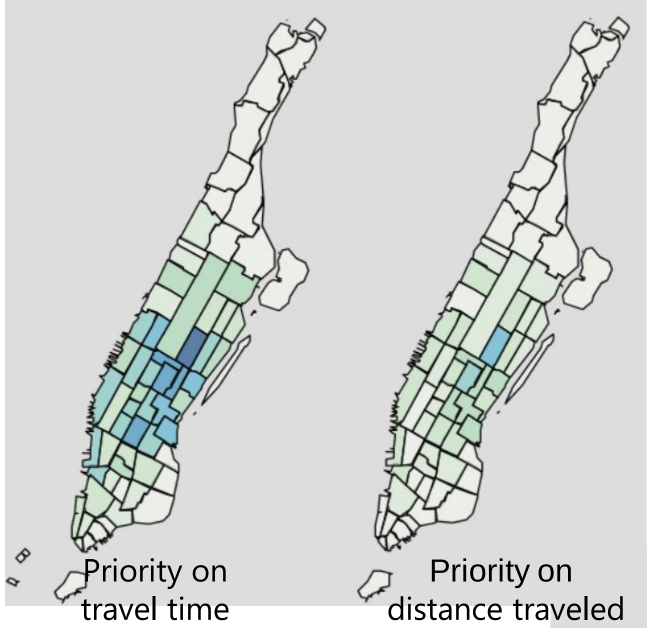
Numerical experiment



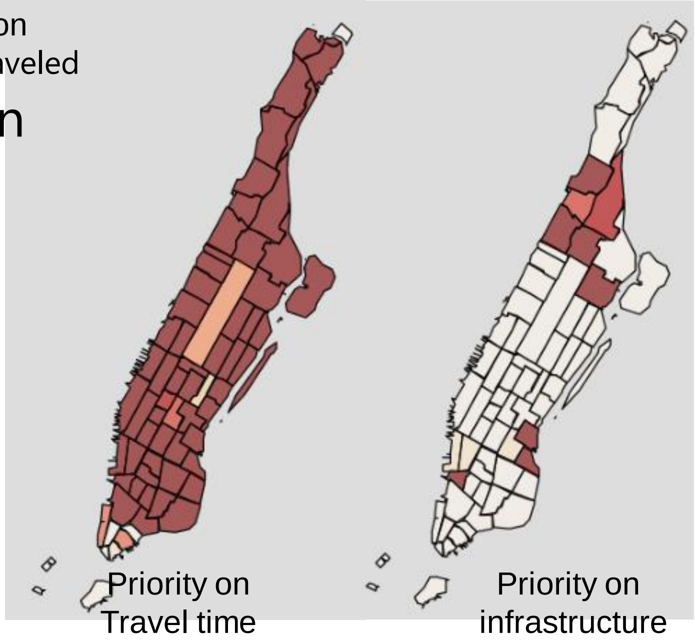


- Reasonable results
  - Trade-offs
  - Benefit of ridesharing
  - Operation patterns
- Consistent to some of the existing works based on detailed models

Numerical experiment



SAV flow distribution



Infrastructure requirement

- Reasonable results
  - Trade-offs
  - Benefit of ridesharing
  - Operation patterns
- Consistent to some of the existing works based on detailed models