AUTONOMOUS MOBILITY-ON-DEMAND SYSTEMS AND THE BUILT ENVIRONMENT: MODELS AND LARGE-SCALE COORDINATION ALGORITHMS
Self-driving vehicles

2005 → 2017
Self-driving vehicles

- Safety (Economic cost) $242B
- Safety (Societal harm) $594B
- Productivity $1.315T
- Congestion $160B
- Health $15B
- Carsharing $402B

References:
1 [Blincoe et al., NHTSA Report, 2015]
2 [Schrank et al., Texas A&M Transportation Institute, 2015]
3 [Levy et al., Environmental Health, 2010]
4 [Spieser, Treleaven, Zhang, Frazzoli, Morton, Pavone, Road Vehicle Automation, 2014]
Self-driving vehicles

- **Safety (Economic cost)**: $242B
- **Safety (Societal harm)**: $594B
- **Productivity**: $1.315T
- **Congestion**: $160B
- **Health**: $15B
- **Carsharing**: $402B

---

1. Blincoe et al., NHTSA Report, 2015
2. Schrank et al., Texas A&M Transportation Institute, 2015
3. Levy et al., Environmental Health, 2010
4. Spieser, Treleaven, Zhang, Frazzoli, Morton, Pavone, Road Vehicle Automation, 2014
Fleets of self-driving vehicles

Productivity $1.315T

Safety (Societal harm) $594B

Safety (Economic cost) $242B

Congestion $160B

Health $15B

Carsharing $402B

1 [Blincoe et al., NHTSA Report, 2015]
2 [Schrank et al., Texas A&M Transportation Institute, 2015]
3 [Levy et al., Environmental Health, 2010]
4 [Spieser, Treleaven, Zhang, Frazzoli, Morton, Pavone, Road Vehicle Automation, 2014]
Autonomous Mobility-on-Demand

Vehicle Autonomy

+ Car Sharing

Impact on the built environment?
AMoD systems and the built environment

• Congestion
  “… the additional empty repositioning trips made by [shared autonomous vehicles] increased congestion and travel times and a significant number of [shared autonomous vehicles] were needed to provide effective service.”
  [Levin et al. 2016]

  “Robocars present one risk of increased congestion, because they allow vehicles to move while empty. … Empty vehicles can increase congestion.”
  – Brad Templeton

• The electric power network
  “Depending on the scenario, price may increase by only 1.2–2.7 percent (in WECC – RMP/ANM) or, for evening recharging at 6 kW, by as much as 141 percent (in FRCC), 196 percent (in WECC-CA) and 297 percent (in SERC). In contrast to what was suggested by other research, the model predicts increases in electricity prices for almost all regions.”
  [Hadley and Tsvetkova 2009]

  “V2G could stabilize large-scale (one-half of US electricity) wind power with 3% of the fleet dedicated to regulation for wind, plus 8–38% of the fleet providing operating reserves or storage for wind.”
  [Kempton and Tomic 2005]
Problem statement

• Propose models that capture the interaction between AMoD systems and the built environment, with particular attention to traffic congestion and the electric power network.

• Propose control algorithms that optimize the performance of such AMoD systems.

• Validate these algorithms with case studies with real-world data.
In the literature

Control of AMoD systems

- **Queueing-theoretical models** [Zhang et al. 2014; Zhang et al. 2015; Calafiore et al. 2017]

- **Dynamic vehicle routing models** [Psaraftis ’88; Berbeglia, Cordeau, Laporte ’10; Pavone ’10; Pavone et al. 2011; Treleaven, Pavone, Frazzoli ’13; Spieser et al. ’14]

- **Fluidic models** [Pavone et al. 2012; Levin 2017]

No interaction with the built environment
In the literature

Traffic congestion

- Traffic modeling:
  - Static models [Wardrop 1952]
  - Simulation models [Treiber, Hennecke, Helbing, 2000; Maciejevski 2017; Fagnant et al. 2014, 2016]
  - Queueing models [Osorio, Bierlaire, 2009]

- Dynamic Traffic Assignment (DTA) and System-Optimal DTA [Janson 1991]

No optimization

No rebalancing
In the literature

EVs and the power network

- **Scheduling charging** [Rotering and Ilic 2011; Turitsyn et al. 2010; Tushar et al. 2012]
- **Location of charging stations** [Goeke and Schneider 2015; Pourazarm et al. 2016]
- **Macroeconomic effect of EVs** [Hadley and Tsvetkova 2009]
- **Game-theoretical models** [Sioshansi 2012; Wang et al. 2010]
- **Joint routing, charging, and economic dispatch** [Alizadeh et al. 2016; Khodayar et al. 2013]

No feedback

No spatial model

Private vehicles
Contribution

- Will AMoD systems increase urban congestion?


- Will fleets of electric vehicles help control the power network?

  Yes, if properly coordinated [Rossi et al., in preparation for RSS 2018]

Other contributions

- Randomised algorithms for efficient routing in AMoD systems

- Model-predictive control of AMoD fleets with charging constraints [Zhang, Rossi and Pavone 2016b, ICRA]


- Data-driven control of AMoD systems with LSTM estimation of customer demand [Iglesias et al. 2018, ICRA]
Network flow model

- Highly scalable (LP)
- Very expressive
- No stochasticity
- Continuum approximation

Expectation of a stochastic process
Flow decomposition and sampling

TODO: proper citations
PART I
AMoD SYSTEMS AND CONGESTION
Our approach: assumptions

Customer demand is time-invariant

The road network is node-symmetric

Congestion is a threshold phenomenon
Customers and roads

• Transportation requests: origin, destination, rate of demand (customers/minute)

• Trips:
  ‣ Customer trips service transportation requests
  ‣ Rebalancing trips realign vehicles with requests

• Road network model:
  ‣ Nodes: intersections
  ‣ Directed, capacitated edges: roads
Road network and flows

- Customer flows
- Rebalancing flows
- Graph cut \((S, \bar{S})\)
  - Edges separating \(S\) and \(\bar{S}\)
  - Cut capacity \(C_{\text{out}}, C_{\text{in}}\)
Road network and flows

• Customer flows

• Rebalancing flows

• Graph cut \((S, \bar{S})\)

  ‣ Edges separating \(S\) and \(\bar{S}\)

  ‣ Cut capacity \(C_{\text{out}}, C_{\text{in}}\)
Road network and flows

- Customer flows
- Rebalancing flows
- Graph cut $\{S, \bar{S}\}$
  - Edges separating $S$ and $\bar{S}$
  - Cut capacity $C_{out}, C_{in}$
**Linear model**

Write the mathematical formulation of the model:

\[
\begin{align*}
\text{minimize} & \quad \sum_{m \in \mathcal{M}} \sum_{(u,v) \in \mathcal{E}} t(u, v) f_m(u, v) + \rho \sum_{(u,v) \in \mathcal{E}} t(u, v) f_R(u, v) \\
\text{subject to} & \quad \sum_{\mathcal{V}} f_m(u, s_m) + \lambda_m = \sum_{\mathcal{V}} f_m(s_m, w) \quad \forall m \in \mathcal{M} \\
& \quad \sum_{\mathcal{V}} f_m(u, t_m) = \lambda_m + \sum_{\mathcal{V}} f_m(t_m, w) \quad \forall m \in \mathcal{M} \\
& \quad \sum_{\mathcal{V}} f_m(u, v) = \sum_{\mathcal{V}} f_m(v, w) \quad \forall m \in \mathcal{M}, v \in \mathcal{V}\setminus\{s_m, t_m\} \\
& \quad \sum_{\mathcal{V}} f_R(u, v) + \sum_{m \in \mathcal{M}} 1_{v=t_m} \lambda_m = \sum_{\mathcal{V}} f_R(v, w) + \sum_{m \in \mathcal{M}} 1_{v=s_m} \lambda_m \quad \forall v \in \mathcal{V} \\
& \quad f_R(u, v) + \sum_{m \in \mathcal{M}} f_m(u, v) \leq c(u, v) \quad \forall (u, v) \in \mathcal{E}
\end{align*}
\]
Theoretical results

**Sufficient condition** for feasibility of rebalancing

Node-symmetric road graph \(\xrightarrow{\text{Feasible}}\) Feasible rebalancing flows

1. In a node-symmetric road network, rebalancing does not increase congestion.

2. If goal is to maximize customer satisfaction, customer flows and rebalancing flows are decoupled and can be computed separately.
Are road networks symmetric?

<table>
<thead>
<tr>
<th>Urban center</th>
<th>Avg. frac. capacity disparity</th>
<th>Std. dev.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Chicago, IL</td>
<td>$1.2972 \cdot 10^{-4}$</td>
<td>$1.003 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>New York, NY</td>
<td>$1.6556 \cdot 10^{-4}$</td>
<td>$1.304 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>Colorado Springs, CO</td>
<td>$3.1772 \cdot 10^{-4}$</td>
<td>$2.308 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>Los Angeles, CA</td>
<td>$0.9233 \cdot 10^{-4}$</td>
<td>$0.676 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>Mobile, AL</td>
<td>$1.9368 \cdot 10^{-4}$</td>
<td>$1.452 \cdot 10^{-4}$</td>
</tr>
<tr>
<td>Portland, OR</td>
<td>$1.0769 \cdot 10^{-4}$</td>
<td>$0.778 \cdot 10^{-4}$</td>
</tr>
</tbody>
</table>

Very high degree of node-symmetry (even with many one-way streets)
A real-time congestion-aware rebalancing algorithm

- Customers are routed on **fastest route** as soon as a vehicle is available

- Empty vehicles are rebalanced by a **batch algorithm**
  - Tries to match a given vehicle distribution
  - Minimum-cost **congestion-free** rebalancing flows
  - Computationally efficient (**totally unimodular**)

\[
\begin{align*}
\text{minimize} & \quad \sum_{(u,v) \in \mathcal{E}} t(u,v) f_R(u,v) + \sum_{i \in \mathcal{S}_R} C_{ds_i} + \sum_{i \in \mathcal{T}_R} C_{dt_i} \\
\text{subject to} & \quad \sum_{u \in \mathcal{V}} f_R(u,v) + 1_{v \in \mathcal{S}_R}(v^e_u(t) - v^d_u(t) - ds_v) \\
& \quad = \sum_{w \in \mathcal{V}} f_R(v,w) + 1_{v \in \mathcal{T}_R}(v^d_u(t) - v^e_u(t) - dt_v), \quad \forall v \in \mathcal{V} \\
& \quad f_R(u,v) \leq c_R(u,v), \quad \forall (u,v) \in \mathcal{E}, \\
& \quad f_R(u,v) \geq 0, \quad \forall (u,v) \in \mathcal{E}, \\
& \quad ds_i, dt_j \geq 0, \quad \forall i \in \mathcal{S}_R, j \in \mathcal{T}_R.
\end{align*}
\]
Case study: NYC

- 24-hour simulation
- NYC taxi data: 480000 customers
- 8000 vehicles

Medium congestion: road capacity reduced by 75%

- Congestion-aware rebalancing
- Baseline rebalancing
- Nearest neighbors dispatch

Legend
- Manhattan road network
  - Motorway
  - Motorway link
  - Trunk road
  - Trunk road (link)
  - Primary road
  - Primary road (link)
  - Secondary road
  - Secondary road (link)
  - Tertiary road
  - Tertiary road (link)
Experimental results

Baseline

Congestion aware
A BCMP queuing network model for congested AMoD systems

Network flow model is equivalent to a queuing-theoretical model for systems with high availability

[Iglesias, Rossi, Zhang and Pavone, 2016, 2017]
PART II

AMoD SYSTEMS AND THE POWER NETWORK
The electric power network

- Well-regulated market run by Independent System Operator

- Economic dispatch:
  - Minimize cost of generation
  - Satisfy generation, transmission, and reliability constraints

- Locational Marginal Pricing

- Distribution network
AMoD and the power network

Goal: **socially optimal** control policy for the AMoD system and the power network
Assumptions

- **Cooperation** between the transportation system operator and the power network’s independent system operator

- Road network: *network flow* model

- Power transmission network: *DC* model

- Power distribution network: *thermal* constraints only

- Transportation system buys/sells electricity at *LMP* rate
Augmented AMoD network flow model
Linear model

\[
\begin{align*}
\text{minimize} & \quad V_T \left( \sum_{(v,w) \in \mathcal{E}} t_{v,w} \sum_{m=1}^{M} f_m(v,w) \right) + V_D \left( \sum_{(v,w) \in \mathcal{E}} d_{v,v_w} \sum_{m=0}^{M} f_m(v,w) \right) + \sum_{t=1}^{T} \sum_{g \in \mathcal{G}} o_g(t)p(g,t) \\
\text{subject to} & \quad \sum_{u:(u,v) \in \mathcal{E}} f_m(u,v) + 1_{v_v = v_m} 1_{v_e = t_m} \lambda_m^{c,\text{in}} = \sum_{w:(v,w) \in \mathcal{E}} f_m(v,w) + 1_{v_v = w_m} 1_{v_e = v_{t_m}} \lambda_m^{c,v_{t_m},\text{out}}, \\
& \quad \forall v \in \mathcal{V}, m \in \{1, \ldots, M\}, \\
& \quad \sum_{c=1}^{C} \lambda_m^{c,\text{in}} = \lambda_m, \\
& \quad \forall m \in \{1, \ldots, M\}, \\
& \quad \sum_{t=1}^{T} \sum_{c=1}^{C} \lambda_m^{c,\text{out}} = \lambda_m, \\
& \quad \forall m \in \{1, \ldots, M\}, \\
& \quad \sum_{u:(u,v) \in \mathcal{E}} f_0(u,v) + \sum_{m=1}^{M} 1_{v_v = v_m} 1_{v_e = t_m} \lambda_m^{c,v_{t_m},\text{out}} + N_f(v) = \sum_{w:(v,w) \in \mathcal{E}} f_0(v,w) + \sum_{m=1}^{M} 1_{v_v = w_m} 1_{v_e = v_{t_m}} \lambda_m^{c,v_{t_m},\text{in}} + N_F(v), \\
& \quad \forall v \in \mathcal{V}, \\
& \quad \sum_{m=0}^{M} \left( \sum_{m=0}^{M} f_m(v,w) \right) \leq J_{(v,v_w)}(v,w), \\
& \quad \forall (v,v,w) \in \mathcal{E}_R, \forall t_v \in \{1, \ldots, T\}, \\
& \quad \sum_{(v,w) \in \mathcal{E}_G} \left( \sum_{m=0}^{M} f_m(v,w) \right) \leq \overline{J}_s, \\
& \quad \forall s \in \mathcal{S}, t \in \{1, \ldots, T\}, \\
& \quad \sum_{g \in \mathcal{G}} \left( \sum_{m=0}^{M} f_m(v,w) \right) \leq \overline{J}_g(v,w), \\
& \quad \forall g \in \mathcal{G}, v \in \mathcal{V}, t \in \{1, \ldots, T\}, \\
& \quad \sum_{(v,w) \in \mathcal{E}} \left( \sum_{m=0}^{M} f_m(v,w) \right) \leq \overline{J}_e(v,w), \\
& \quad \forall s \in \mathcal{S}, t \in \{1, \ldots, T\}.
\end{align*}
\]
Flow bundling

Bundle flows with same destination

Flow decomposition algorithm

Theorem: flow bundling is lossless

$O((|\mathcal{V}_R|^2T)(|\mathcal{E}_R| + |S|)CT)$

$O(|\mathcal{V}_R|(|\mathcal{E}_R| + |S|)CT)$
Case study: Dallas-Fort Worth

Road network
- 25 nodes
- 173 road links
- 30 charge levels

Trips
- 10 hours
- 6250 O-D-T pairs
- 400,000 customers

EV fleet
- 150,000 EVs

Power network
- 282 generators
- 2007 buses
- 2481 transmission lines
## Experimental results

<table>
<thead>
<tr>
<th></th>
<th>No cars</th>
<th>P-AMoD</th>
<th>Uncoordinated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Avg. passenger travel time</td>
<td>-</td>
<td>1h15m11s</td>
<td>1h15m11s</td>
</tr>
<tr>
<td>Tot. energy demand [GWh]</td>
<td>517.498</td>
<td>520.541</td>
<td>520.979</td>
</tr>
<tr>
<td>Tot. electricity expenditure [k$]</td>
<td>39,604.71</td>
<td>39,264.84</td>
<td>39,629.50</td>
</tr>
<tr>
<td>w.r.t. no cars [k$]</td>
<td>-</td>
<td>-339.87</td>
<td>+24.79</td>
</tr>
<tr>
<td>Avg. power price in DFW [$/MWh]</td>
<td>78.68</td>
<td>75.79</td>
<td>77.47</td>
</tr>
<tr>
<td>TSO tot. elec. expenditure [k$]</td>
<td>-</td>
<td>227.98</td>
<td>296.82</td>
</tr>
</tbody>
</table>

*TSO*: Transmission System Operator
Coordination **does not affect** passenger travel times
Coordination **reduces** the total price of electricity w.r.t. baseline, despite extra demand!

**TSO:** **23.5% lower** electricity bill (**$35M/year**)  
Local power network customers: **2.2% lower** electricity bill (**$122M/year**)
Self-interested actors

Why would a self-interested transportation system operator (TSO) optimize for social welfare?

**Theorem: the social optimum is a Nash equilibrium**

For TSO, optimal charging schedule is the best response to given electricity prices (and vice versa).

**Theorem: the equilibrium can be computed without sharing private information**

TSO and ISO can compute the optimum with a dual decomposition algorithm. Only public information (price of electricity and charging schedule) is shared.
A real-time P-AMoD algorithm

- **Assumption**: customer-carrying vehicles always follow **shortest route**; no charging when customers on board

- **Suboptimal**, but **fast** (1h→1m)

- **Receding-horizon** implementation

- Fractional output is **sampled**
Experimental results

10:50 a.m.

TSO: 13.9% lower electricity bill ($16M/year)
Total electricity expenditure reduced by 75M/year w.r.t. greedy
Local power network customers: 0.88% lower electricity bill
Conclusions

**AMoD systems do not increase congestion if properly routed**

- Capacitated network flow model with theoretical guarantees
- Model-predictive control algorithm
- 22% reduction in customer wait times compared to baseline algorithm (NYC)

**AMoD systems can act as mobile storage units in the power network**

- Joint model for AMoD systems and power network
- Control algorithm: efficient *socially optimal* solution with bundling
- Socially optimal solution is a Nash equilibrium, can be computed with no private information
- Cooperation reduces in 23% lower electricity price for TSO, $120M in savings for power network customers (DFW)
Future research directions

- Customer demand **prediction**
- **Stochastic control** of AMoD systems
- How should AMoD systems interact with **public transportation**?
- Will AMoD systems foster adoption of **renewable** energy sources?
- What will the effect of AMoD systems on **pollution** be?
Acknowledgements

This research was supported by the National Science Foundation under CAREER Award CMMI-1454737, by the Toyota Research Institute (TRI), and by the Office of Naval Research (ONR).
This research was supported by the National Science Foundation under CAREER Award CMMI-1454737, by the Toyota Research Institute (TRI), and by the Office of Naval Research (ONR).
Thanks!

Contact: hello@federico.io
Thanks!

Contact: hello@federico.io
Thanks!

Contact: hello@federico.io
References


References


References


Would you guess this weighs as much as a small adult? What? Uh, probably.

Great!

*THUMP*
*CLICK*

Please fasten your seat belt. Take me to Anchorage, Alaska. Navigating. *SLAM*

I love self-driving cars. ...Whose car was that? Dunno, but they shouldn't have left it running.
UPCOMING AND RECENTLY-ACHIEVED
SELF-DRIVING CAR MILESTONES

• AUTOMATIC EMERGENCY BRAKING
• HIGHWAY LANE-KEEPING
• SELF-PARKING
• FULL HIGHWAY AUTONOMY
• FIRST SEX IN A SELF-DRIVING CAR
• FULL TRIPS WITH NO INPUT FROM DRIVER
• FULL TRIPS BY EMPTY CARS
• SELF-REFUELING OF EMPTY CARS
• AN EMPTY CAR WANDERING THE HIGHWAYS FOR MONTHS OR YEARS UNTIL SOMEONE NOTICES THE CREDIT CARD FUEL CHARGES
• CARS THAT READ OTHER CARS’ BUMPER STICKERS BEFORE DECIDING WHETHER TO CUT THEM OFF
• AUTONOMOUS ENGINE REVVING AT RED LIGHTS
• SELF-LOATHING CARS
• AUTONOMOUS CANYON JUMPING
• CARS CAPABLE OF ARGUING ABOUT THE TROLLEY PROBLEM ON FACEBOOK

xkcd.com/1925
More results on congestion

Customer wait and service time

- Low congestion: road capacity reduced by 70%
- Medium congestion: road capacity reduced by 75%
- High congestion: road capacity reduced by 80%
P-AMoD: full results

Price paid by the TSO
- coordinated: 227977.072133
- uncoordinated: 296817.428591

Unit price paid by the TSO
- coordinated: 7491.27746558
- uncoordinated: 8526.40186212

Price paid by all
- ISO only: 39604707.8459
- coordinated: 39264836.8294
- uncoordinated: 39629497.7003

Price paid by all per 100 KW
- ISO only: 7653.1096073
- coordinated: 7543.07587502
- uncoordinated: 7606.73059846

Price paid by everyone else
- ISO only: 39604707.8459
- coordinated: 39036859.7572
- uncoordinated: 39332680.2717

Price per hundred KW paid by everyone else
- ISO only: 7653.1096073
- coordinated: 7543.3804841
- uncoordinated: 7600.54406513

Cost of generation
- ISO only: 40529884.5782
- coordinated: 40756002.7821
- uncoordinated: 40917155.1849

Cost of generation per hundred KW
- ISO only: 7831.88868807
- coordinated: 7829.54027502
- uncoordinated: 7853.89153051

Price paid by all in Dallas
- ISO only: 12832491.2268
- coordinated: 12591742.8793

Price per hundred KW paid by all in Dallas
- ISO only: 7868.57561461
- coordinated: 7579.51783894
- uncoordinated: 7747.77901222

Price paid by everyone else in Dallas
- ISO only: 12832491.2268
- coordinated: 12363765.8072
- uncoordinated: 12608384.6256

Price per hundred KW paid by everyone else in Dallas
- ISO only: 7868.57561461
- coordinated: 7581.16443766
- uncoordinated: 7731.15882576

Price paid by everyone else NOT in Dallas
- ISO only: 26772216.6191
- coordinated: 26673093.95
- uncoordinated: 26724295.6461

Price per hundred KW paid by everyone else NOT in Dallas
- ISO only: 7553.96209363
- coordinated: 7525.99396176
- uncoordinated: 7540.44086681

Price paid by all at charging nodes
- ISO only: 2243271.04358
- coordinated: 2390693.73131
- uncoordinated: 2501941.65175

Price per hundred KW paid by all at charging nodes
- ISO only: 7862.43259969
- coordinated: 7571.53715428
- uncoordinated: 7815.47304232

Price paid by everyone else at charging nodes
- ISO only: 2243271.04358
- coordinated: 2162716.65918
- uncoordinated: 2205124.22316

Price per 100 KW paid by everyone else at charging nodes
- ISO only: 7862.43259969
- coordinated: 7580.09782801
- uncoordinated: 7728.73194622

https://phobos.stanford.edu:8899/notebooks/AMoD-power/atx/DFW_scenario_prep_Federico.ipynb
Suboptimal Linear model

\[
\begin{align*}
\text{minimize} & \quad f_m, \lambda_{m}^{c,\text{in}}, \lambda_{m}^{c,\text{t,out}}, N_F, \theta, p \\
\text{subject to} & \quad \sum_{t=1}^{T} \sum_{s=1}^{C} \lambda_{m}^{c,\text{t,out}} = \lambda_{m}, \\
& \quad \forall m \in \{1, \ldots, M\}, \\
& \quad \sum_{c=1}^{C} \lambda_{m}^{c,\text{in}} = \lambda_{m}, \\
& \quad \forall m \in \{1, \ldots, M\}, \\
& \quad \sum_{u: (u,v) \in \mathcal{E}} f_0(u,v) + \sum_{m=1}^{M} 1_{v = v_m} \lambda_{m}^{c,v,\text{t,out}} + N_F(v) \\
& \quad = \sum_{w: (v,w) \in \mathcal{E}} f_0(v,w) + \sum_{m=1}^{M} 1_{v = v_m} 1_{t_v = t_m} \lambda_{m}^{c,v,\text{in}} + N_F(v), \\
& \quad \forall v \in \mathcal{V}, \\
& \quad \sum_{(v,w) \in \mathcal{E}_R} f_m(v,w) \leq T_{(v,w) \in \mathcal{E}_R}, \\
& \quad \forall (v,w) \in \mathcal{E}_R, \forall t \in \{1, \ldots, T\}, \\
& \quad \sum_{s \in \mathcal{S}, t \in \{1, \ldots, T\}} \left( \sum_{m=0}^{M} f_m(v,w) \right) \leq 3_s, \\
& \quad \forall s \in \mathcal{S}, t \in \{1, \ldots, T\}, \\
& \quad \sum_{t=1}^{T} \sum_{g \in \mathcal{G}} o_g(t)p(g,t) \\
& \quad = V_D \left( \sum_{(v,w) \in \mathcal{E}} d_{v,v,w} \sum_{m=0}^{M} f_m(v,w) \right) + \sum_{t=1}^{T} \sum_{g \in \mathcal{G}} o_g(t)p(g,t) \\
& \quad \sum_{(u,v) \in \mathcal{E}_P} \frac{\theta(u,t) - \theta(v,t)}{x_{u,v}} + 1_{v \in \mathcal{P}} p(v,t) = 1_{v \in \mathcal{E}} \frac{\theta(v,t) - \theta(w,t)}{x_{v,w}}, \\
& \quad \forall v \in \mathcal{B}, t \in \{1, \ldots, T\}, \\
& \quad -p_{b_1,b_2} = \frac{\theta(b_1,t) - \theta(b_2,t)}{x_{b_1,b_2}} \leq p_{b_1,b_2}, \\
& \quad \forall (b_1, b_2) \in \mathcal{E}_P, t \in \{1, \ldots, T\}, \\
& \quad p_g(t) \leq p(g,t) \leq \overline{p}_g(t), \\
& \quad \forall g \in \mathcal{G}, t \in \{1, \ldots, T\}, \\
& \quad -p_g^-(t) \leq p(g,t+1) - p(g,t) \leq p_g^+(t), \\
& \quad \forall g \in \mathcal{G}, t \in \{1, \ldots, T-1\}, \\
& \quad d_l(t) \leq d_l(t), \\
& \quad \forall l \in \mathcal{L}, t \in \{1, \ldots, T\}, \\
& \quad d_t(t) = d_{t,e}(t) + J_C \delta c_{\mathcal{M}_R}(l) \sum_{(v,w) \in \mathcal{E}_P} \sum_{m=0}^{M} f_m(v,w) \\
& \quad + J_C \delta c_{\mathcal{M}_R}(l) \sum_{(v,w) \in \mathcal{E}_P} \sum_{m=1}^{M} f_m(v,w), \\
& \quad \forall l \in \mathcal{L}, t \in \{1, \ldots, T\}. 
\end{align*}
\]
Algorithm 1 Dual decomposition distributed algorithm for the P-AMoD problem

$k \leftarrow 1$
ISO sets $\lambda_{\text{ISO}}^{\text{eq},k} \leftarrow$ dual solution to Economic Dispatch problem with $\{d_i\} = \{d_{i,e}\}$.

repeat
  ISO informs TSO of $\lambda_{\text{ISO}}^{\text{eq},k}$
  TSO sets $\{f_m^k, \lambda_m^{\text{in},k}, \lambda_m^{\text{out},k}, N_F^k\} \leftarrow$ solution to VRCP Problem with $p(v,w) = \lambda_{\text{ISO}}^{\text{eq},k}$
  ISO sets $\{\theta^k, p^k\} \leftarrow$ solution to Lagrangian relaxation of Economic Dispatch Problem
  TSO informs ISO of proposed charging schedule $f_m^k$.
  ISO updates $\lambda_{\text{ISO}}^{\text{eq},k+1} \leftarrow \lambda_{\text{ISO}}^{\text{eq},k} + \alpha k f_{\text{ISO}}^{\text{eq}}(f_m^k, \theta^k, p^k)$
  $k \leftarrow k + 1$
until $\|\lambda_{\text{ISO}}^{\text{eq},k+1} - \lambda_{\text{ISO}}^{\text{eq},k}\| \leq \varepsilon$
Fleet activity: P-AMoD vs uncoordinated
Table 1: Customer travel times with and without rebalancing for different levels of network asymmetry.

<table>
<thead>
<tr>
<th>Cap. reduction</th>
<th>Average travel time [s]</th>
<th>Travel time increase</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Without reb.</td>
<td>With reb.</td>
</tr>
<tr>
<td>0%</td>
<td>58.00</td>
<td>58.67</td>
</tr>
<tr>
<td>10%</td>
<td>58.12</td>
<td>59.15</td>
</tr>
<tr>
<td>20%</td>
<td>58.49</td>
<td>59.67</td>
</tr>
<tr>
<td>30%</td>
<td>59.26</td>
<td>60.56</td>
</tr>
<tr>
<td>40%</td>
<td>60.65</td>
<td>61.78</td>
</tr>
<tr>
<td>50%</td>
<td>63.66</td>
<td>64.55</td>
</tr>
<tr>
<td>60%</td>
<td>72.04</td>
<td>72.13</td>
</tr>
</tbody>
</table>
A map of New York
Full P-AMoD results
Receding-horizon P-AMoD
Receding-horizon P-AMoD

TSO expense