On the Co-Design of AV-Enabled Mobility Systems

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The mobility ecosystem has dramatically changed over the years.
More modes, more actors, more interactions
You cannot assess the impact of MSs without a co-design framework

- +5.7 billion miles caused by app-based taxis, deadheading 30-60% of the time.
- Only 30% of e-scooters (ESs) rides substitute cars.
There are many questions to be answered

General questions:
- How should cities invest in the future of mobility?
- How should cities regulate the introduction of new mobility solutions?
- Will the outcome be socially, economically, and environmentally sustainable?

Particular questions:
- How performant should AVs be?
- What is the best fleet size?
- How will AVs affect public transportation systems?

To answer these questions, we need to co-design the whole system
You cannot decouple optimization problems of the single mobility solutions

State of the art fails to address coupled mobility design problems

Fleet sizing for flexible carsharing systems: Simulation-based approach [Barrios et al., 2014]

Towards a systematic approach to the design and evaluation of AMoD systems: a case study of Singapore [Spieser et al., 2014]

Autonomous Mobility-on-Demand systems for urban mobility [Pavone et al., 2014]

Dynamic ride-sharing and fleet sizing for a system of shared autonomous vehicles in Austin, Texas [Fagnant et al., 2018]

A review of urban transportation network design problems [Farahani et al., 2013]

Co-design of traffic network topology and control measures [Cong et al., 2015]

Estimating the potential for shared autonomous scooters [Kondor et al., 2019]
You cannot decouple optimization problems of the single mobility solutions

State of the art fails to address coupled mobility design problems

1) **No joint design of MSs and MSs-enabled mobility systems.**
2) **No compositional framework: Problem-specific, non-modular.**
3) **Not producing actionable information for stakeholders.**
4) **No long-term planning perspective.**
5) **Not considering interactions: No game-theoretical formulation.**

A review of urban transportation network design problems [Farahani et al., 2013]

Co-design of traffic network topology and control measures [Cong et al., 2015]

Estimating the potential for shared autonomous scooters [Kondor et al., 2019]
We want to co-design a full intermodal mobility system

The design of MSs and the one of the mobility system they enable are closely coupled

Scope

We develop a co-design framework to solve the problem of designing and deploying an intermodal mobility system from a central authority perspective by means of

- Fleet sizes,
- performance of the vehicles,
- public transit infrastructure,

optimizing for the system’s

- performance,
- costs, and
- environmental footprint.
Modeling – Network flow model for intermodal AMoD

- Mesoscopic analysis: Granularity level between microscopic and macroscopic.
- Network flow model: Trips are flows, not particles.
- Time-invariant model: We condense a time duration in one second.
Modeling – Network flow model for intermodal AMoD

Travel Requests

Travel requests are given by their origin, destination, and rate.

Constraints

Linear system constrained by

- Demand satisfaction.
- Flow conservation (including rebalancing policies).
- Road congestion.
- Flows are non-negative.
Modeling – Travel time and speed

### Road
- Each road arc has a speed limit.
- AVs safety protocols impose a maximum achievable speed.
- Too slow AVs are dangerous: we consider a minimum speed as well.

### Pedestrians
Constant walking speed on each walking arc.

### Public Transportation System
The public transit system operates at each node with a specific frequency.

### Intermodality
We model specific delays for specific mode switches.
Modeling – Energy consumptions and fleet size

Energy Consumption and Emissions

**AVs:**
- Urban driving cycle.
- Energy consumptions and emissions are proportional to the driven distance.

**Public Transportation:**
- We assume customers-independent operation.
- Constant energy consumption per unit time.

AVs Fleet Size
- We consider a variable AVs fleet size.
- We limit it to the number of vehicles available in the system.
We need a modular and compositional framework

We need a framework which allows to structure the mobility system design problem in a **modular** and **compositional** way.

### Mathematical theory of Co-Design

- A mathematical theory of Co-Design [Censi, 2015]
- A class of Co-Design problems with cyclic constraints and their solution [Censi, 2017]

**Offers a formalization of Co-Design problems**
- Provides modularity and compositionality
A design problem is a monotone relation between provided functionality and required resources.

\[
\langle F, \preceq_F \rangle \quad \text{design problem} \quad \langle R, \preceq_R \rangle
\]

- Any poset \( F \)
- Any poset \( R \)

**Examples:**
- **Functionality:**
  - Capacity [J]
  - Maximal current [A]

- **Resources:**
  - Mass [g]
  - Cost [USD]
Mathematical theory of Co-Design in few words

A design problem is a monotone relation between provided functionality and required resources.

functionality
\( \langle F, \leq_F \rangle \)

any poset

resources
\( \langle R, \leq_R \rangle \)

any poset

Monotonicity:
- If functionality \( f \) is feasible with resource \( r \), then any \( f' \leq_F f \) is feasible with \( r \).
- If functionality \( f \) is feasible with resource \( r \), then \( f \) is feasible with any resource \( r' \leq_R r \).

Typical queries:
- Given a certain functionality \( f \in F \), find the minimal resources \( r \in R \) that can realize it, or provide a proof that there are none.
- Given certain resources \( r \in R \), find the maximal functionality \( f \in F \) that can be realized, or provide a proof that there are none.
You can compose design problems in series, parallel and loop

Diagrammatic interconnection represents co-design constraints:

**Series**

**Parallel**

**Loop**

... and many more.
The AV design problem

We model vehicle autonomy as a monotone function of vehicle costs

Functionality:
- Maximal achievable speed.

Resources:
- Vehicle fixed costs.
- Vehicle operational costs.

Functionality to resources relation:
- Higher speed requires more advanced technology.
- Achievable speed as monotone function of costs.
The public transportation and I-AMoD design problems

acquired trains --- Subway
- fixed cost [USD]
- operational cost [USD]

total demand --- I-AMoD
- AV-driven distance [miles/s]
- acquired trains
- AV achievable speed [mph]
- AVs per fleet
- average travel time [s]
- AVs emissions [kg/s]
Putting things together: The monotone Co-Design problem

**Functionality:**
- Total demand.

**Resources:**
- Total system costs.
- Average travel time per trip.
- Total system emissions.
Co-Design user experience

The AV model in the Co-Design language:

catalogue {
    # Functionality
    provides velocity [miles/hour]
    # Resources
    requires fixed_cost [$]
    requires operational_cost [$/mile]

    model01 | 20 miles/hour | 29700 $ | 0.062 $/mile
    model02 | 25 miles/hour | 30400 $ | 0.062 $/mile
    model03 | 30 miles/hour | 32200 $ | 0.062 $/mile
    model04 | 35 miles/hour | 34700 $ | 0.062 $/mile
    model05 | 40 miles/hour | 35800 $ | 0.062 $/mile
    model06 | 45 miles/hour | 38000 $ | 0.062 $/mile
    model07 | 50 miles/hour | 39000 $ | 0.062 $/mile
}

velocity [mi/hr]

fixed_cost [USD]  operational_cost [USD/mi]
Case study – Washington D.C., USA

- Consider the D.C. intermodal network
  - Road and walking networks: OpenStreetMap
  - Public transit network: GTFS.

- Consider real demand: 15,872 travel requests.

- We want to find the optimal
  - Subway frequency in \{100\%, 133\%, 200\%\}.
  - AVs speed in \{20 \text{ mph}, 25 \text{ mph}, \ldots, 50 \text{ mph}\}.
  - AVs fleet size in \{0, 500, \ldots, 6000\}.

  to minimize
  - Travel time,
  - costs, and
  - emissions.
We perform an analysis of different AV’s automation costs

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Variable</th>
<th>Value</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Baseline road usage</strong></td>
<td>$u_{ij}$</td>
<td>93</td>
<td>%</td>
</tr>
<tr>
<td><strong>Vehicle operational cost</strong></td>
<td>$C_v$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>20 mph</td>
<td>$C_{v,0}$</td>
<td>0.084</td>
<td></td>
</tr>
<tr>
<td>25 mph</td>
<td>$C_{v,0}$</td>
<td>0.084</td>
<td></td>
</tr>
<tr>
<td>30 mph</td>
<td>$C_{v,0}$</td>
<td>0.062</td>
<td></td>
</tr>
<tr>
<td><strong>Vehicle cost</strong></td>
<td>$C_v$</td>
<td>0.084</td>
<td></td>
</tr>
<tr>
<td>20 mph</td>
<td>$C_{v,v}$</td>
<td>32.000</td>
<td>USD/mile</td>
</tr>
<tr>
<td>25 mph</td>
<td>$C_{v,v}$</td>
<td>32.000</td>
<td>USD/mile</td>
</tr>
<tr>
<td>30 mph</td>
<td>$C_{v,v}$</td>
<td>26.000</td>
<td>USD/mile</td>
</tr>
<tr>
<td><strong>Vehicle automation cost</strong></td>
<td>$C_{v,a}$</td>
<td></td>
<td></td>
</tr>
<tr>
<td>35 mph</td>
<td>$C_{v,a}$</td>
<td>0.084</td>
<td></td>
</tr>
<tr>
<td>40 mph</td>
<td>$C_{v,a}$</td>
<td>0.084</td>
<td></td>
</tr>
<tr>
<td>45 mph</td>
<td>$C_{v,a}$</td>
<td>0.084</td>
<td></td>
</tr>
<tr>
<td>50 mph</td>
<td>$C_{v,a}$</td>
<td>0.084</td>
<td></td>
</tr>
<tr>
<td><strong>Vehicle life</strong></td>
<td>$l_v$</td>
<td>5</td>
<td>years</td>
</tr>
<tr>
<td><strong>CO$_2$ per Joule</strong></td>
<td>$\gamma$</td>
<td>0.14</td>
<td>g/J</td>
</tr>
<tr>
<td><strong>Time from $t_R$ to $t_W$</strong></td>
<td>$t_{WR}$</td>
<td>300</td>
<td>s</td>
</tr>
<tr>
<td><strong>Time from $t_W$ to $t_R$</strong></td>
<td>$t_{RW}$</td>
<td>60</td>
<td>s</td>
</tr>
<tr>
<td><strong>Speed limit fraction</strong></td>
<td>$\beta$</td>
<td>1/3</td>
<td>-</td>
</tr>
<tr>
<td><strong>Subway operational cost</strong></td>
<td>$C_s$</td>
<td>148,000,000</td>
<td>USD/year</td>
</tr>
<tr>
<td>100 %</td>
<td>$C_{s,0}$</td>
<td>197,000,000</td>
<td>USD/year</td>
</tr>
<tr>
<td>133 %</td>
<td>$C_{s,0}$</td>
<td>295,000,000</td>
<td>USD/year</td>
</tr>
<tr>
<td>200 %</td>
<td>$C_{s,0}$</td>
<td>14,500,000</td>
<td>USD/year</td>
</tr>
<tr>
<td><strong>Subway fixed cost</strong></td>
<td>$C_s$</td>
<td>30</td>
<td>years</td>
</tr>
<tr>
<td><strong>Subway CO$_2$ emissions per train</strong></td>
<td>$m_{CO_2:s}$</td>
<td>140</td>
<td>ton/year</td>
</tr>
<tr>
<td><strong>Train fleet baseline</strong></td>
<td>$n_{b,base}$</td>
<td>112</td>
<td>trains</td>
</tr>
<tr>
<td><strong>Subway service frequency</strong></td>
<td>$\phi_{f,base}$</td>
<td>1/5</td>
<td>V/minutes</td>
</tr>
<tr>
<td><strong>Time from $t_R$ to $t_F$ and vice-versa</strong></td>
<td>$t_{WS}$</td>
<td>60</td>
<td>s</td>
</tr>
</tbody>
</table>
Results for constant automation costs

We can measure the tradeoffs between system’s performance, costs, and environmental impact:
We can always project multidimensional pareto fronts to lower dimensions

\[ \text{Emissions cost of } 40 \text{ USD/kg} \]
Results for constant automation costs

We can measure the tradeoffs between system’s performance and costs:

![Graph showing tradeoffs between system's performance and costs.](image-url)
The framework is modular: Try adding transportation modes

To consider micromobility, we add a layer:
The framework is modular: Try adding transportation modes

To consider micromobility, we interconnect another design problem:
The framework is compositional: Model refinement

We can explode the AV model into a more complex one:

[Work in progress]
Conclusions – Co-Design gives a broader perspective on systems’ design

1) No joint design of MSs and MSs-enabled mobility systems.
   - We provide a new perspective on the problem.
   - Pareto fronts of optimal solutions.

2) No compositional framework: Problem-specific, non-modular.
   - We can plug-in new modes of transportation.
   - We can refine model complexity.

3) Not producing actionable information for stakeholders.
   - We provide stakeholders with actionable information to reason about the problem.
   - Roundtable for discussions

4) No long-term planning perspective.

5) Not considering interactions: No game-theoretical formulation.

Papers and extended version of this talk at gioele.science/mobility