Co-Design to Enable User-Friendly Tools to Assess the Impact of Future Mobility Solutions

G. Zardini\textsuperscript{1,3}, N. Lanzetti\textsuperscript{2,3}, A. Censi\textsuperscript{1}, E. Frazzoli\textsuperscript{1}, and M. Pavone\textsuperscript{3}

\textsuperscript{1}Institute for Dynamic Systems and Control (IDSC), ETH Zürich
\textsuperscript{2}Automatic Control Lab, ETH Zürich
\textsuperscript{3}Autonomous Systems Lab, Stanford University
The mobility ecosystem has dramatically changed over the years

Zurich 1800

Zurich 1900

Zurich now

The future?
More modes, more actors, more interactions

AVs
Taxis
Trains
Bikes
E-scooters
Companies
Governments
Politicians
Citizens
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.
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

<table>
<thead>
<tr>
<th>Road</th>
</tr>
</thead>
<tbody>
<tr>
<td>• Each road arc has a speed limit.</td>
</tr>
<tr>
<td>• AVs safety protocols impose a maximum achievable speed.</td>
</tr>
<tr>
<td>• Too slow AVs are dangerous: We consider a minimum speed as well.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Pedestrians</th>
</tr>
</thead>
<tbody>
<tr>
<td>Constant walking speed on each walking arc.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Public Transportation System</th>
</tr>
</thead>
<tbody>
<tr>
<td>The public transit system operates at each node with a specific frequency.</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intermodality</th>
</tr>
</thead>
<tbody>
<tr>
<td>We model specific delays for specific mode switches.</td>
</tr>
</tbody>
</table>
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**.
Mathematical theory of Co-Design in few words

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

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

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 mobility co-design problem
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 design problem

Functionality:
• Acquired trains.

Resources:
• Train fleet fixed costs.
• Train fleet operational costs.

We design the service frequency assuming

\[
\frac{\text{frequency of the line}}{\text{baseline frequency of the line}} = \frac{\text{number of trains}}{\text{baseline number of trains}}.
\]

Functionality to resources relation:
• More trains, higher fixed costs.
• More trains require more operators: higher operational costs.
The I-AMoD design problem

**Functionality:**
- Total satisfied demand.

**Resources:**
- Achievable speed.
- Available AVs per fleet.
- Acquired trains.
- Average trip travel time.
- AVs-driven distance.
- AVs emissions.
The I-AMoD design problem

- - - - AV-driven distance \([\text{miles/s}]\)
- - - - acquired trains
- - - - AV achievable speed \([\text{mph}]\)
- - - - AVs per fleet
- - - - average travel time \([\text{s}]\)
- - - - AVs emissions \([\text{kg/s}]\)

Functionality to resources relation: Linear program, \textit{minimize average travel time}, subject to
- Conservation of flows and non-negativity.
- Road congestion.
- Fleet limitations.
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:

```sql
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
}
```
Co-Design user experience

Automatically generated interconnection:

```plaintext
mcp

vehicle_model = instance` vehicle
subway_model = instance` subway
amod_model = instance` amod_time

provides total_requests using amod_model

requires cost_operation [$/hour]
requires CO2_total [kg/s]
requires cost_time [$$]

# Operational costs
operational_cost_veh = operational_cost_veh required by vehicle_model \cdot d_road required by amod_model
operational_cost_sub = operational_cost_sub required by subway_model
operational_cost_hour = operational_cost_veh + operational_cost_sub

# Fixed costs
fixed_cost_veh = fixed_cost required by vehicle_model \cdot number_veh_available required by amod_model
fixed_cost_sub = fixed_cost required by subway_model \cdot number_subway required by amod_model
```

![Diagram of interconnection](image-url)
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\ mph, 25\ mph, \ldots, 50\ 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>
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<tbody>
<tr>
<td>Baseline road usage</td>
<td>$u_{ij}$</td>
<td>93</td>
<td>%</td>
</tr>
<tr>
<td>Vehicle operational cost</td>
<td>$C_{v,o}$</td>
<td>0.084</td>
<td>USD/mile</td>
</tr>
<tr>
<td>Vehicle cost</td>
<td>$C_{v,v}$</td>
<td>32,000</td>
<td>USD/car</td>
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<td>20 mph</td>
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<td>8,700</td>
<td>0</td>
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</tr>
<tr>
<td>40 mph</td>
<td>11,100</td>
<td>0</td>
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</tr>
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<td>13,000</td>
<td>0</td>
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<td>0</td>
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</tr>
<tr>
<td>Vehicle life</td>
<td>$i_v$</td>
<td>5</td>
<td>years</td>
</tr>
<tr>
<td>CO2 per Joule</td>
<td>$\gamma$</td>
<td>0.14</td>
<td>g/kJ</td>
</tr>
<tr>
<td>Time from $\gamma$ to $\gamma_R$</td>
<td>$\tau_{WR}$</td>
<td>300</td>
<td>s</td>
</tr>
<tr>
<td>Time from $\gamma_R$ to $\gamma_W$</td>
<td>$\tau_{RW}$</td>
<td>60</td>
<td>s</td>
</tr>
<tr>
<td>Speed limit fraction</td>
<td>$\beta$</td>
<td>$\frac{1}{3}$</td>
<td>-</td>
</tr>
<tr>
<td>Subway operational cost</td>
<td>$C_{s,o}$</td>
<td>148,000,000</td>
<td>USD/year</td>
</tr>
<tr>
<td>133 %</td>
<td>197,000,000</td>
<td>USD/year</td>
<td></td>
</tr>
<tr>
<td>200 %</td>
<td>295,000,000</td>
<td>USD/year</td>
<td></td>
</tr>
<tr>
<td>Subway fixed cost</td>
<td>$C_{s,f}$</td>
<td>14,500,000</td>
<td>USD/train</td>
</tr>
<tr>
<td>Train life</td>
<td>$t_s$</td>
<td>30</td>
<td>years</td>
</tr>
<tr>
<td>Subway CO2 emissions per train</td>
<td>$m_{CO2,s}$</td>
<td>140</td>
<td>ton/year</td>
</tr>
<tr>
<td>Train fleet baseline</td>
<td>$n_{s,baseline}$</td>
<td>112</td>
<td>trains</td>
</tr>
<tr>
<td>Subway service frequency</td>
<td>$\phi_{f,baseline}$</td>
<td>$\frac{1}{5}$</td>
<td>minutes</td>
</tr>
<tr>
<td>Time from $\gamma$ to $\gamma_F$ and vice-versa</td>
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</table>

Overall, the demand dataset includes 15,872 travel requests, corresponding to a demand rate of 24.22 per Joule. To account for the large presence of ride-hailing companies, we scale the taxi demand rate by a factor of 5. To account for congestion effects, we compute the nominal road capacity as in Zardini, Lanzetti, Salazar, Censi, Frazzoli, and Pavone (2018), and investigate the influence of different AV’s costs on the design objectives and operational costs.
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
Results for constant automation costs

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

\[ C_{\text{tot}} \] [Mil USD/month]

\[ t_{\text{avg}} \] [min]

9% 53%

(13,24.4) (15,21.4) (23,18.6) (28,17.8) (43,17.1)
We perform an analysis of different AV’s automation costs

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<td>CO$_2$ per Joule</td>
<td>$\gamma$</td>
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<td>g/kJ</td>
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<td>Time from $R_W$ to $R_R$</td>
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<td>60</td>
<td>s</td>
</tr>
</tbody>
</table>

Note: The table summarizes the main parameters together with their bibliographic sources in Table 1.
Results for speed-dependent automation costs

We can compare tradeoffs between performance and costs for different simulation parameters:

- +5% AVs fleet size
- −9% AVs speed
- +7% train fleet

The graph shows the relationship between the total cost ($C_{tot}$) and the average travel time ($t_{avg}$) for different simulation parameters. The tradeoffs are visualized with colored bars indicating the costs and times for various scenarios.
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:
Case study revisited – Washington D.C., USA

• Consider the D.C. intermodal network
  – Road, micromobility, and walking networks: OpenStreetMap
  – Public transit network: GTFS.

• Consider real demand: 16,430 travel requests.

• We want to find the optimal
  – Subway frequency in \{100\%, 133\%, 200\\%\}.
  – AVs speed in \{20\ mph, 25\ mph, \ldots, 50\ mph\}.
  – AVs fleet size in \{0, 500, \ldots, 6000\}.
  – Micromobility solution in \{ES, SB, M, FCM\}.
  – Micromobility fleet size in \{0, 500, \ldots, 4000\}.

  to minimize
  – Travel time,
  – costs, and
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<td>%</td>
</tr>
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<td>AVs operational cost</td>
<td>$C_{V_{AV}}$</td>
<td>0.084</td>
<td>USD/mile</td>
</tr>
<tr>
<td>Vehicle cost</td>
<td>$C_V$</td>
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<td>USD/car</td>
</tr>
<tr>
<td>20 mph</td>
<td></td>
<td>32,000</td>
<td>32,000</td>
</tr>
<tr>
<td>25 mph</td>
<td></td>
<td>20,000</td>
<td>3,700</td>
</tr>
<tr>
<td>30 mph</td>
<td></td>
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<td>4,400</td>
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<td>AV automation cost</td>
<td>$C_{VA}$</td>
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<td>6,200</td>
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<td>15,000</td>
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<td>12,000</td>
</tr>
<tr>
<td>50 mph</td>
<td></td>
<td>15,000</td>
<td>13,000</td>
</tr>
<tr>
<td>AV life</td>
<td>$l_V$</td>
<td>5</td>
<td>5</td>
</tr>
<tr>
<td>CO₂ per Joule</td>
<td>$\gamma$</td>
<td>0.14</td>
<td>0.14</td>
</tr>
<tr>
<td>Time from $%_V$ to $%_W$</td>
<td>$t_{NW}$</td>
<td>300</td>
<td>300</td>
</tr>
<tr>
<td>Time from $%_W$ to $\gamma_W$</td>
<td>$t_{NW}$</td>
<td>60</td>
<td>60</td>
</tr>
<tr>
<td>Speed limit fraction</td>
<td>$\beta$</td>
<td>1/1.3</td>
<td>1/1.3</td>
</tr>
<tr>
<td>µMV operational cost</td>
<td>$C_{M,I}$</td>
<td>0.79</td>
<td>1.58</td>
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<td>µMV cost</td>
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<td>550</td>
<td>8,860</td>
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<td>µMV achievable speed</td>
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<td>10</td>
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<td>µMV life</td>
<td>$l_M$</td>
<td>0.085</td>
<td>0.033</td>
</tr>
<tr>
<td>µMV emissions</td>
<td>$m_{CO2_{M,net}}$</td>
<td>0.101</td>
<td>0.101</td>
</tr>
<tr>
<td>Time from $%_W$ to $%_M$</td>
<td>$t_{WM}$</td>
<td>60</td>
<td>60</td>
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<tr>
<td>Time from $%_M$ to $%_W$</td>
<td>$t_{MW}$</td>
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<td>$C_{S,O}$</td>
<td>100%</td>
<td>148,000,000</td>
</tr>
<tr>
<td>Subway fixed cost</td>
<td>$C_{S,F}$</td>
<td>150%</td>
<td>222,000,000</td>
</tr>
<tr>
<td>Subway CO₂ emissions per train</td>
<td>$m_{CO2_S}$</td>
<td>200%</td>
<td>295,000,000</td>
</tr>
<tr>
<td>Train life</td>
<td>$l_S$</td>
<td>14,500,000</td>
<td>USD/train</td>
</tr>
<tr>
<td>Train year</td>
<td>30</td>
<td>USD/year</td>
<td></td>
</tr>
<tr>
<td>Subway CO₂ emissions per train</td>
<td>$m_{CO2_S}$</td>
<td>112</td>
<td>140,000</td>
</tr>
<tr>
<td>Train fleet baseline</td>
<td>$n_{base}$</td>
<td>1/6</td>
<td>1/6</td>
</tr>
<tr>
<td>Subway service frequency</td>
<td>$n_{WS}$</td>
<td>60</td>
<td>60</td>
</tr>
</tbody>
</table>
Results with speed-dependent automation cost and micromobility

We can compute the same tradeoffs as before, with more modes of transportation:
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 additional materials at gioele.science/mobility