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

G. Zardini[1,3], N. Lanzetti[2,3], A. Censi[1], E. Frazzoli[1], and M. Pavone[3]

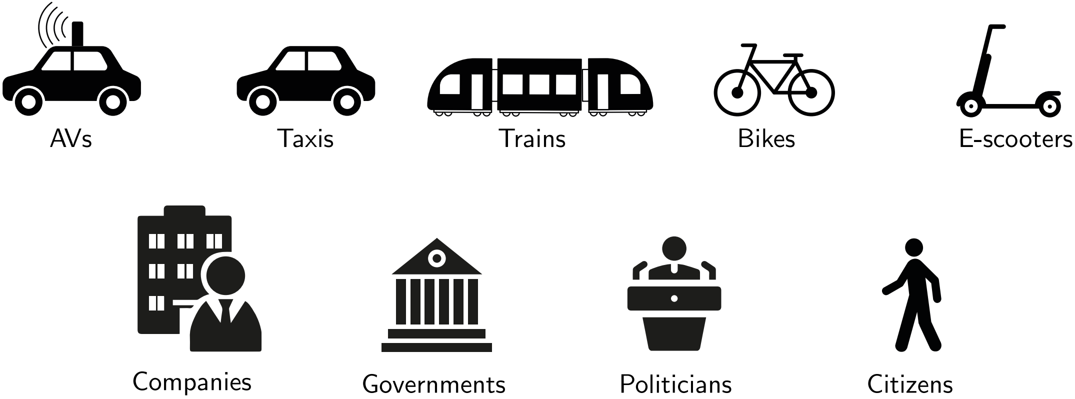
[1]Institute for Dynamic Systems and Control (IDSC), ETH Zürich

[2]Automatic Control Lab, ETH Zürich

[3]Autonomous Systems Lab, Stanford University

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

WSJ

MTA Blames Uber for Decline in New York City Subway, Bus Ridership

Usage dips for mass transit coincided with taxi and ride-hailing trips, data shows

July 20, 2018

Pave Over the Subway? Cities Face Tough Bets on Driverless Cars

- +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 systen 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

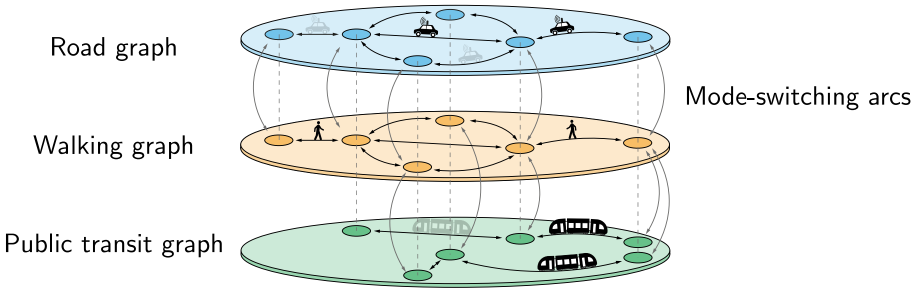
We develop a **co-design** framework to solve the problem of *designing* and *deploying* an intermodal mobility system from a **central authority perspective** by means of

- 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 numer 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]

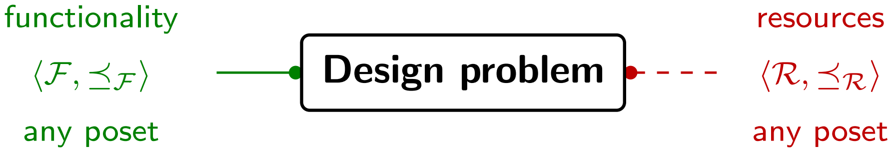
A class of Co-Design problems with cyclic constraints and their solution [Censi, 2017]

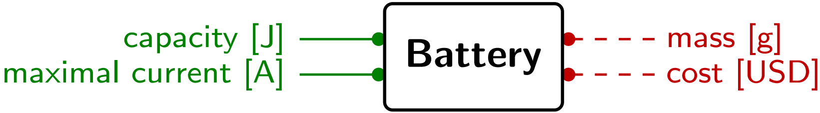
Offers a formalization of Co-Design problems

Provides modularity and compositionality

Mathematical theory of Co-Design in few words

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





Mathematical theory of Co-Design in few words

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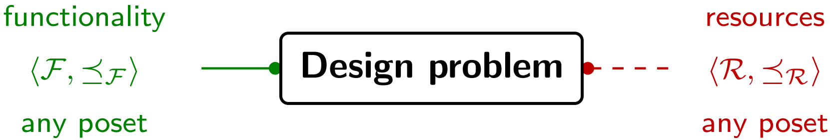


Monotonicity:

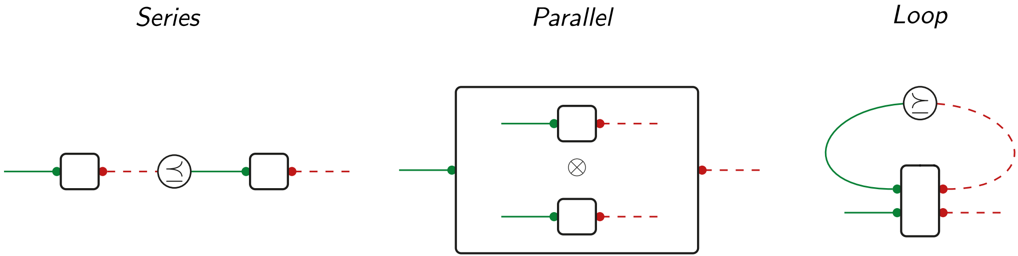
- If functionality f is feasible with resource r, then any $f' \preceq_{\mathcal{F}} f$ is feasible with r.
- If functionality f is feasible with resource r, then f is feasible with any resource $r' \succeq_{\mathcal{R}} r$.

Typical queries:

- Given a certain **functionality** $f \in \mathcal{F}$, find the *minimal* **resources** $r \in \mathcal{R}$ that can realize it, or provide a proof that there are *none*.
- Given certain **resources** $r \in \mathcal{R}$, find the *maximal* **functionality** $f \in \mathcal{F}$ that can be realized, or provide a proof that there are *none*.

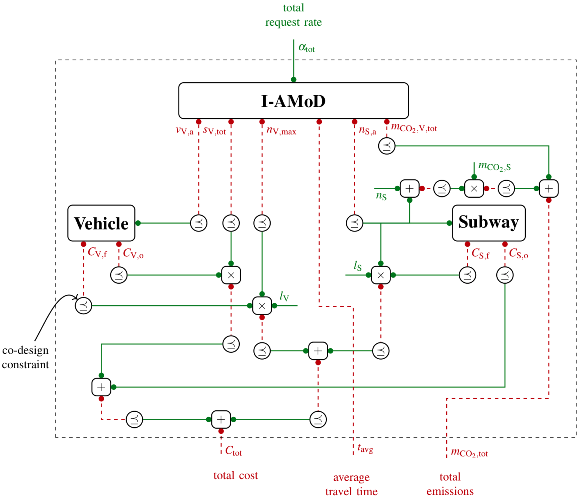
You can compose design problems in series, parallel and loop

Diagrammatic interconnection represents co-design constraints:



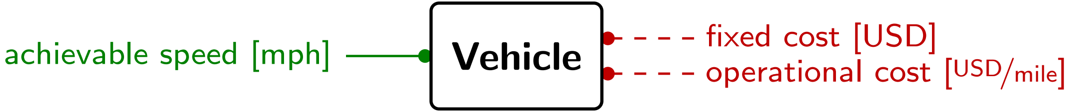
... and many more.

The mobility co-design problem



The AV design problem

We model vehicle autonomy as a monotone function of vehicle costs



Functionality:

- Maximal achievable speed.

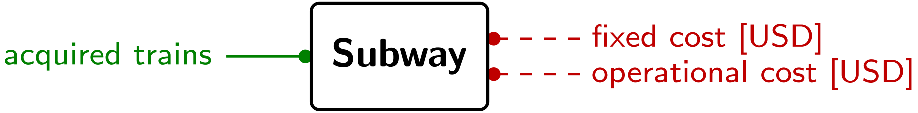
Resources:

- 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



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:

- Acquired trains.

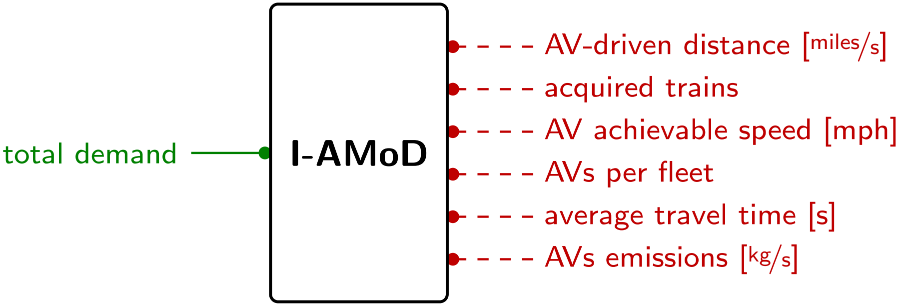
Resources:

- Train fleet fixed costs.
- Train fleet operational costs.

Functionality to **resources** relation:

- More trains, higher fixed costs.
- More trains require more operators: higher operational costs.

The I-AMoD design problem



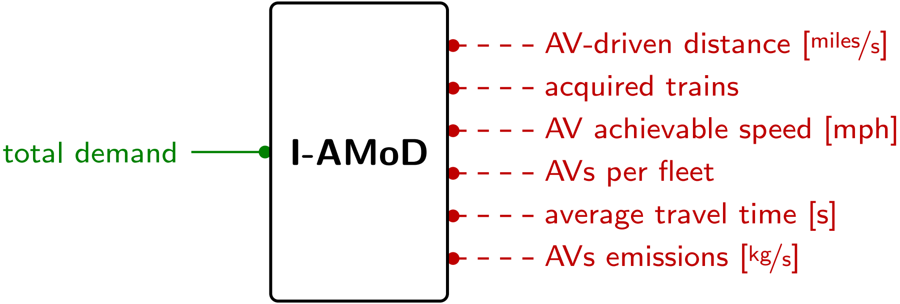
Functionality:

- 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



Functionality to **resources** relation: Linear program, *minimize average travel time*, subject to

- Conservation of flows and non-negativity.
- Road congestion.
- Fleet limitations.

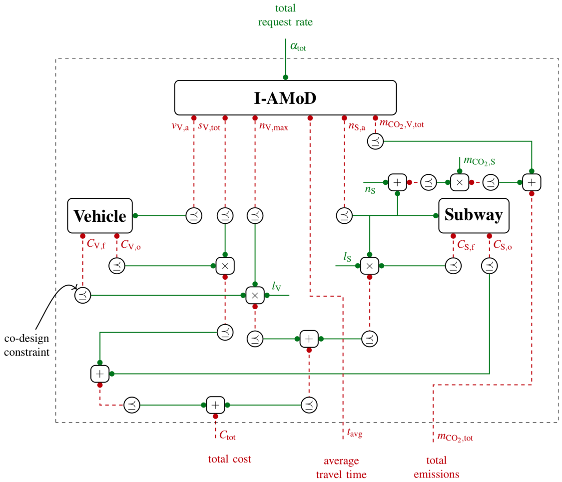
Putting things together: The monotone Co-Design problem

Functionality:

- Total demand.

Resources:

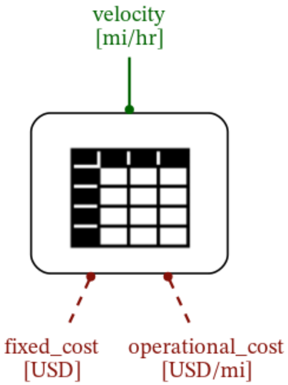
- Total system costs.
- Average travel time per trip.
- Total system emissions.



Co-Design user experience

The AV model in the Co-Design language:

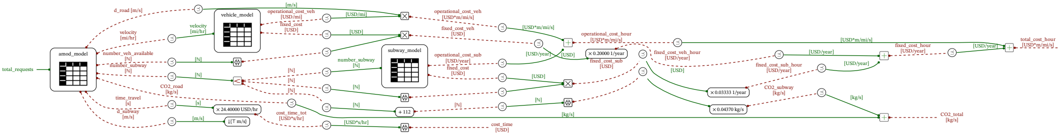
```
catalogue {
    # Functionality
    provides velocity [miles/hour]
    # Resources
    requires fixed_cost [$]
    requires operational_cost [$/mile]

    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:

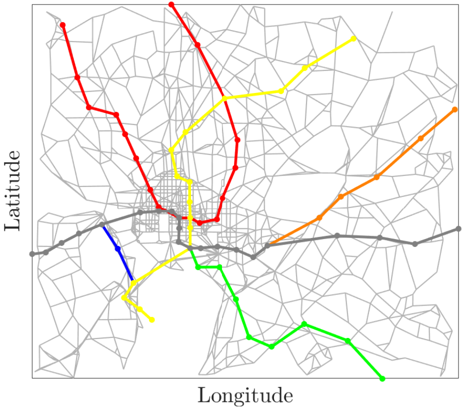
```
mcdp {
    vehicle_model = instance` vehicle
    subway_model  = instance` subway
    amod_model    = instance` amod_time

    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 · 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 * number_veh_available required by amod_model
    fixed_cost_sub       = fixed_cost required by subway_model * number_subway required by amod_model
```



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**.

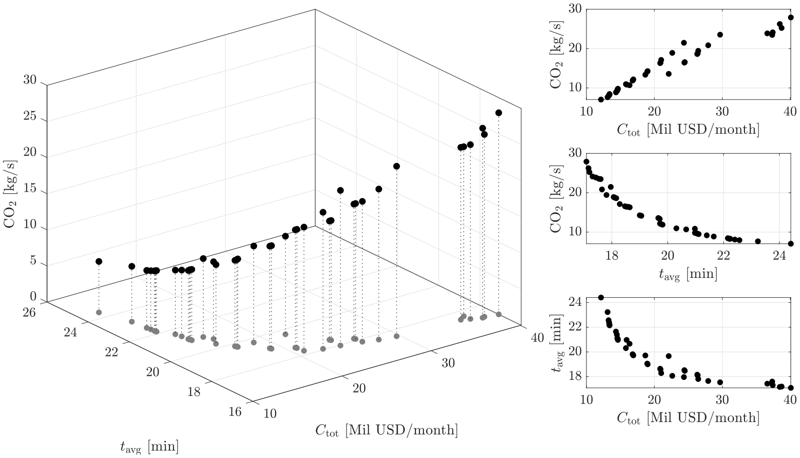


We perform an analysis of different AV's automation costs

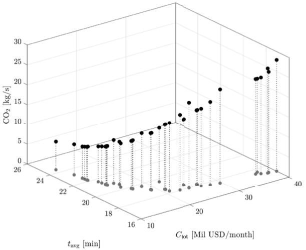
Parameter		**Variable**	**Value**					**Units**
Baseline road usage		u_{ij}	93					%
			Case 1	**Case 2.1**	**Case 2.2**	**Case 3.1**	**Case 3.2**	
Vehicle operational cost		$C_{v,o}$	0.084	0.084	0.062	0.084	0.084	USD/mile
Vehicle cost		$C_{v,v}$	32,000	32,000	26,000	32,000	32,000	USD/car
Vehicle automation cost	20 mph	$C_{v,a}$	15,000	20,000	3,700	0	500,000	USD/car
	25 mph		15,000	30,000	4,400	0	500,000	USD/car
	30 mph		15,000	55,000	6,200	0	500,000	USD/car
	35 mph		15,000	90,000	8,700	0	500,000	USD/car
	40 mph		15,000	115,000	9,800	0	500,000	USD/car
	45 mph		15,000	130,000	12,000	0	500,000	USD/car
	50 mph		15,000	150,000	13,000	0	500,000	USD/car
Vehicle life		l_v	5	5	5	5	5	years
CO_2 per Joule		γ	0.14	0.14	0.14	0.14	0.14	g/kJ
Time from $\mathcal{G}_W$ to $\mathcal{G}_R$		t_{WR}	300	300	300	300	300	s
Time from $\mathcal{G}_R$ to $\mathcal{G}_W$		t_{RW}	60	60	60	60	60	s
Speed limit fraction		β	$\frac{1}{1.3}$	$\frac{1}{1.3}$	$\frac{1}{1.3}$	$\frac{1}{1.3}$	$\frac{1}{1.3}$	-
Subway operational cost	100 %	$C_{s,o}$	148,000,000					USD/year
	133 %		197,000,000					USD/year
	200 %		295,000,000					USD/year
Subway fixed cost		$C_{s,f}$	14,500,000					USD/train
Train life		l_s	30					years
Subway CO_2 emissions per train		$m_{CO_2,s}$	140					ton/year
Train fleet baseline		$n_{s,\text{baseline}}$	112					trains
Subway service frequency		$\varphi_{j,\text{baseline}}$	$\frac{1}{6}$					1/minutes
Time from $\mathcal{G}_W$ to $\mathcal{G}_P$ and vice-versa		t_{WS}	60					s

Results for constant automation costs

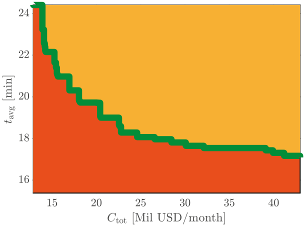
We can measure the tradeoffs between system's performance, costs, and environmental impact:



We can always project multidimensional pareto fronts to lower dimensions

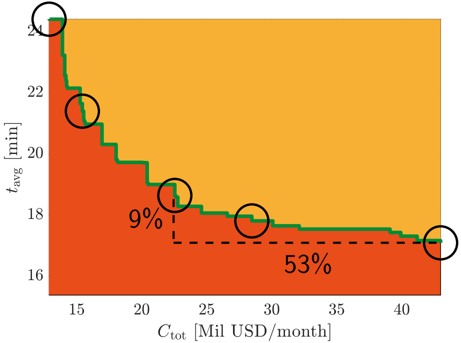


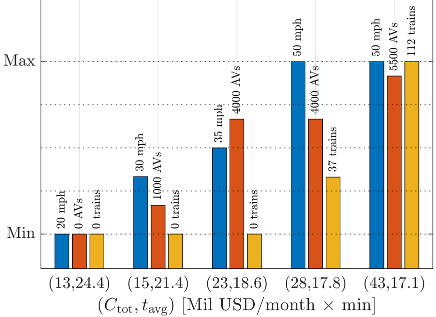
+ **Emissions cost of 40 USD/kg**



Results for constant automation costs

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





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Vehicle automation cost	20 mph	$C_{v,a}$	15,000	20,000	3,700	0	500,000	USD/car
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	30 mph		15,000	55,000	6,200	0	500,000	USD/car
	35 mph		15,000	90,000	8,700	0	500,000	USD/car
	40 mph		15,000	115,000	9,800	0	500,000	USD/car
	45 mph		15,000	130,000	12,000	0	500,000	USD/car
	50 mph		15,000	150,000	13,000	0	500,000	USD/car
Vehicle life		l_v	5	5	5	5	5	years
CO_2 per Joule		γ	0.14	0.14	0.14	0.14	0.14	g/kJ
Time from $\mathcal{G}_W$ to $\mathcal{G}_R$		t_{WR}	300	300	300	300	300	s
Time from $\mathcal{G}_R$ to $\mathcal{G}_W$		t_{RW}	60	60	60	60	60	s
Speed limit fraction		β	$\frac{1}{1.3}$	$\frac{1}{1.3}$	$\frac{1}{1.3}$	$\frac{1}{1.3}$	$\frac{1}{1.3}$	-
Subway operational cost	100 %	$C_{s,o}$	148,000,000					USD/year
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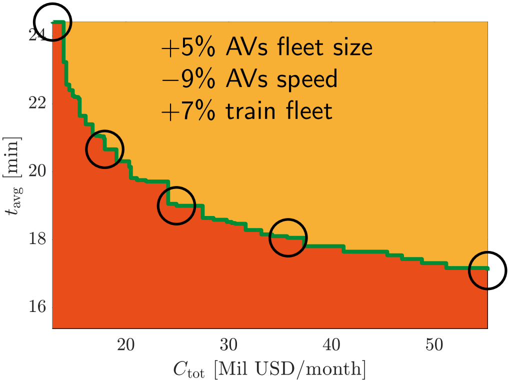
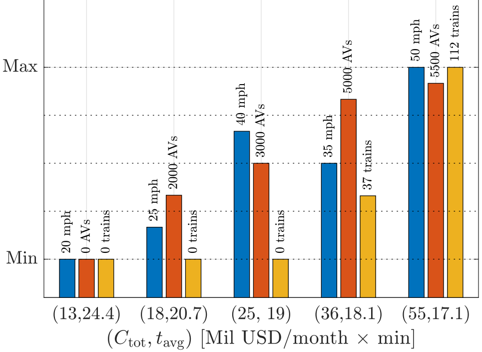
Train fleet baseline		$n_{s,\text{baseline}}$	112					trains
Subway service frequency		$\varphi_{j,\text{baseline}}$	$\frac{1}{6}$					1/minutes
Time from $\mathcal{G}_W$ to $\mathcal{G}_P$ and vice-versa		t_{WS}	60					s

Results for speed-depedent automation costs

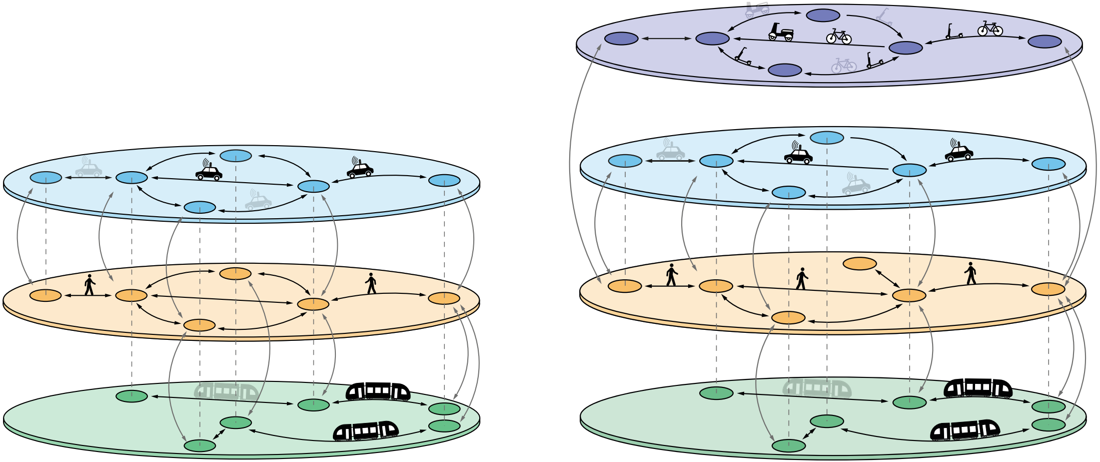
We can compare tradeoffs between performance and costs for different simulation parameters:





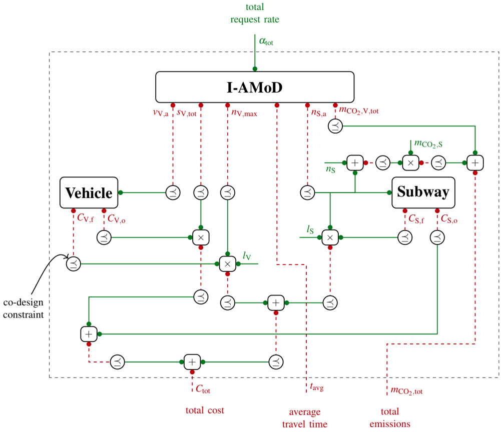
The framework is modular: Try adding transportation modes

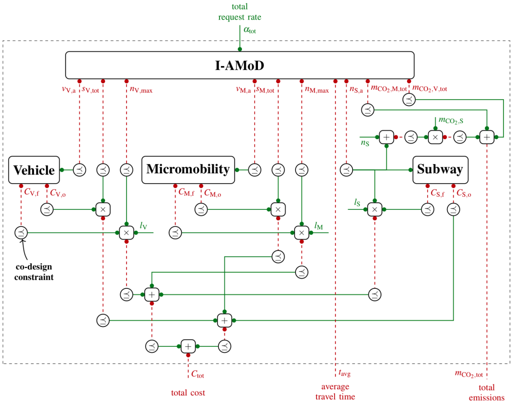
To consider micromobility, we add a layer:



The framework is modular: Try adding transportation modes

To consider micromobility, we interconnect another design problem:



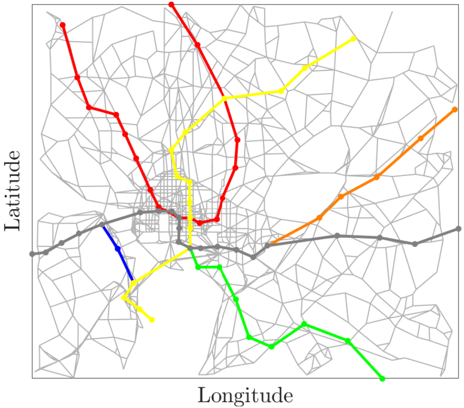


Case study revisited – Washington D.C., USA

- 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 $\{20\,\text{mph}, 25\,\text{mph}, \ldots, 50\,\text{mph}\}$.
  - **AVs fleet size** in $\{0, 500, \ldots, 6000\}$.
  - **Micromobility solution** in $\{\text{ES}, \text{SB}, \text{M}, \text{FCM}\}$.
  - **Micromobility fleet size** in $\{0, 500, \ldots, 4000\}$.

to **minimize**

- **Travel time**,
- **costs**, and
- **emissions**.



We perform an analysis of different AV's automation costs

Parameter		Variable			Value					Units
Road usage		u_{ij}				93				%
			S1	**S2 (2020)**	**S2 (2025)**	**S3**	**S4**	**S5 (2020)**	**S5 (2025)**	
AVs operational cost		$C_{\mathrm{V,o}}$	0.084	0.084	0.062	0.084	0.50	0.084	0.062	USD/mile
Vehicle cost		C_{V}	32,000	32,000	26,000	32,000	32,000	32,000	26,000	USD/car
	20 mph		15,000	20,000	3,700	500,000	0	20,000	3,700	USD/car
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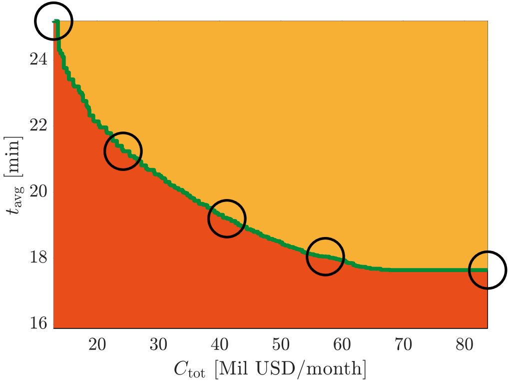
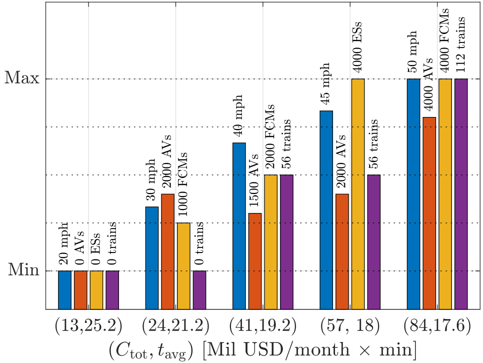
	50 mph		15,000	150,000	13,000	500,000	0	150,000	13,000	USD/car
AV life		l_{V}	5	5	5	5	5	5	5	year
CO_2 per Joule		γ	0.14	0.14	0.14	0.14	0.14	0.14	0.14	g/kJ
Time from $\mathcal{G}_{\mathrm{W}}$ to $\mathcal{G}_{\mathrm{R,V}}$		t_{WV}	300	300	300	300	300	300	300	s
Time from $\mathcal{G}_{\mathrm{R,V}}$ to $\mathcal{G}_{\mathrm{W}}$		t_{VW}	60	60	60	60	60	60	60	s
Speed limit fraction		β	1/1.3	1/1.3	1/1.3	1/1.3	1/1.3	1/1.3	1/1.3	–
			ES		**SB**		**M**		**FCM**	
μMV operational cost		$C_{\mathrm{M,o}}$	0.79		1.58		2.05		1.20	USD/mile
μMV cost		$C_{\mathrm{M,f}}$	550		8,860		1,000		3,000	USD/μMV
μMV achievable speed		$v_{\mathrm{M},ij}$	15		10		15		15	mph
μMV life		l_{M}	0.085		7.0		10.0		10.0	year
μMV emissions		$m_{\mathrm{CO_2,M,tot}}$	0.101		0.033		0.158		0.033	kg/mile
Time from $\mathcal{G}_{\mathrm{W}}$ to $\mathcal{G}_{\mathrm{R,M}}$		t_{WM}	60		60		60		60	s
Time from $\mathcal{G}_{\mathrm{R,M}}$ to $\mathcal{G}_{\mathrm{W}}$		t_{MW}	60		60		60		60	s
	100 %					148,000,000				USD/year
Subway operational cost	150 %	$C_{\mathrm{S,o}}$				222,000,000				USD/year
	200 %					295,000,000				USD/year
Subway fixed cost		$C_{\mathrm{S,f}}$				14,500,000				USD/train
Train life		l_{S}				30				year
Subway CO_2 emissions per train		$m_{\mathrm{CO_2,S}}$				140,000				kg/year
Train fleet baseline		$n_{\mathrm{S,base}}$				112				train
Subway service frequency		$\varphi_{j,\mathrm{baseline}}$				1/6				1/min
Time from $\mathcal{G}_{\mathrm{W}}$ to $\mathcal{G}_{\mathrm{P}}$ and vice-versa		t_{WS}				60				s

Results with speed-dependent automation cost and micromobility

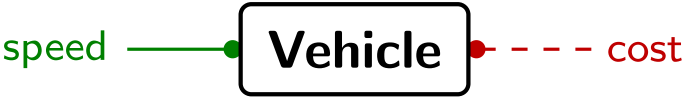
We can compute the same tradeoffs as before, with more modes of transportation:

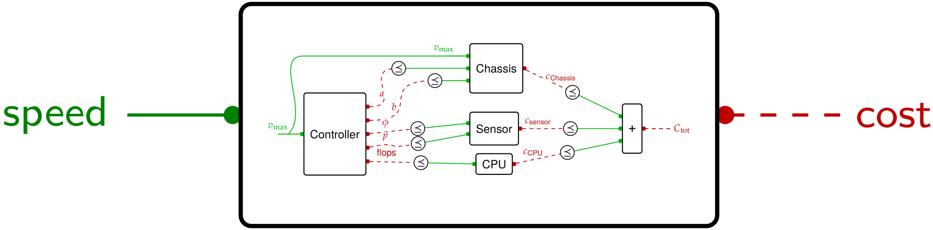




The framework is compositional: Model refinement

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`