Disruptive Technologies or Disrupting the Narratives? Transdisciplinary Challenges and Opportunites from ACE+ Technologies in Mobility

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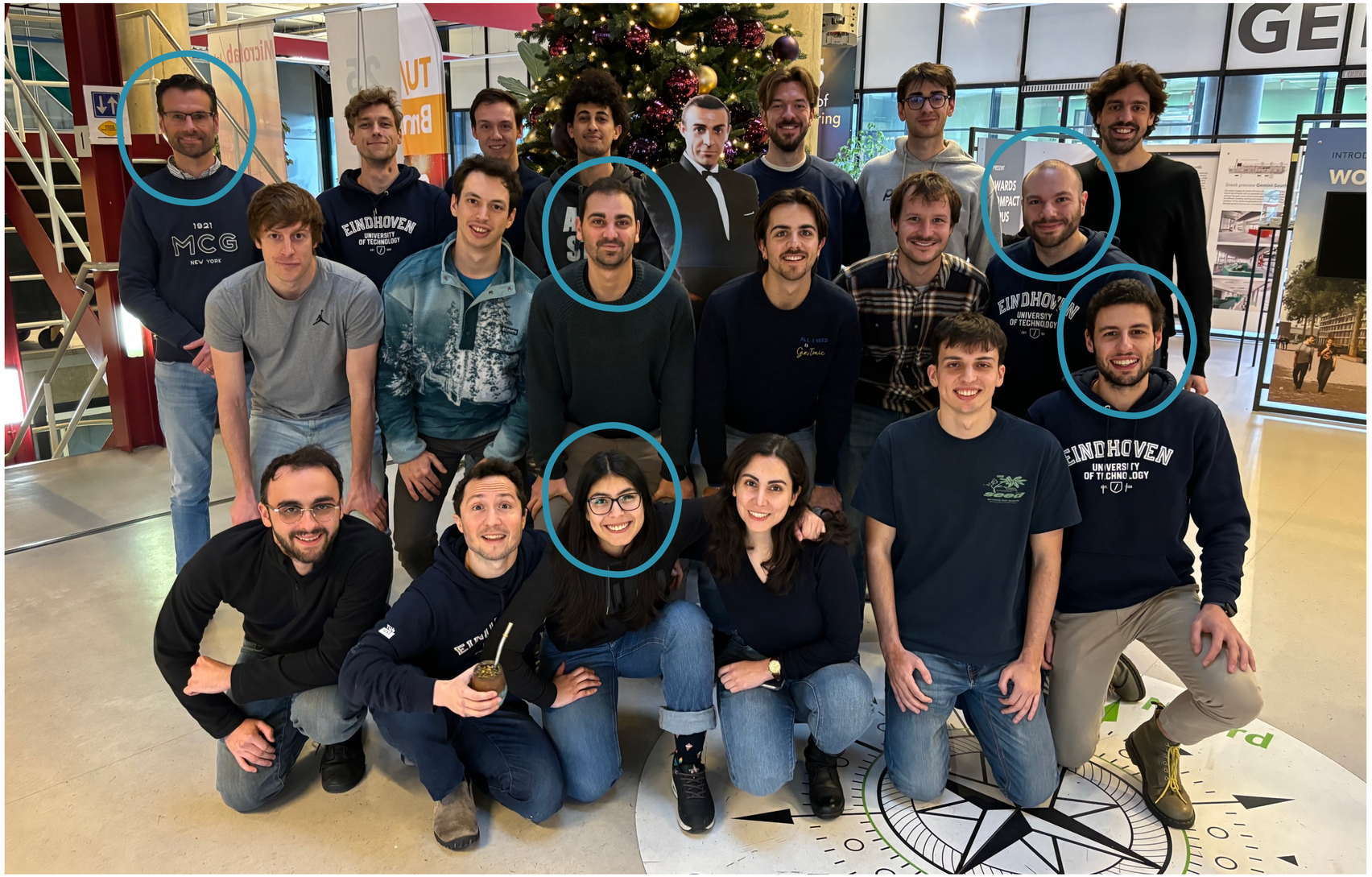
Porto, 3.4.2025

Modeling and Optimization for Vehicle Electrification, Mobility, Energy and Novel Topics (MOVEMENT) Research Group



Christmas 2024 with my colleague Prof. T. Hofman (left)

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Sara Betancur Giraldo
Leonardo Pedroso
Maurizio Clemente
Prof. Theo Hofman
Prof. Maurice Heemels
Prof. Karel Martens

MOVEMENT
RESEARCH GROUP

Facts about Mobility

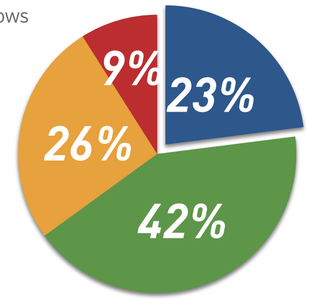
Challenges

WSJ

TRANSIT

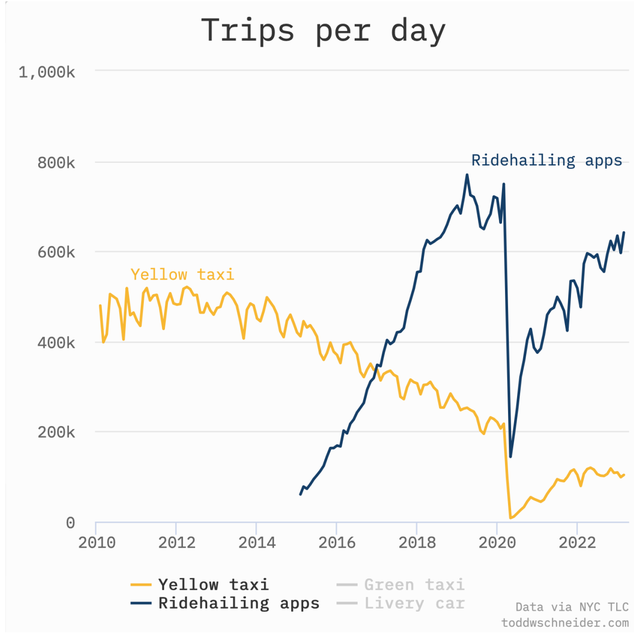
MTA Blames Uber for Decline in New York City Subway, Bus Ridership

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



Transport *Electricity and Heat*
Industry *Buildings*

GHG Emissions in the World 2022
IEA via The World Bank



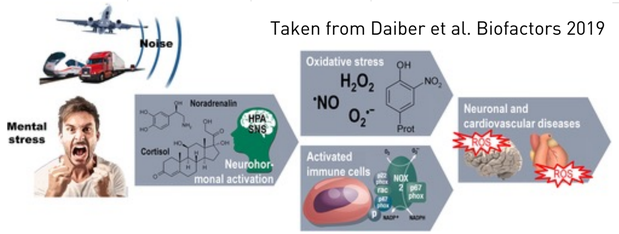
Traffic jams cost Dutch industry €1.4bn last year, says transport lobby group

Business November 19, 2019

Noise Pollution Isn't Just Annoying — It's Bad for Your Health

Published 27 Jun 2018 | Reviewed 27 Jun 2018 | Author Knvul Sheikh | Source BrainFacts/SfN

Taken from Daiber et al. Biofactors 2019



Contents lists available at ScienceDirect

Journal of Transport Geography

journal homepage: www.elsevier.com/locate/jtrangeo

Transport and mobility justice: Evolving discussions

Ersilia Verlinghieri*, Tim Schwanen

Transport Studies Unit, School of Geography and the Environment University of Oxford, UK

Facts about Mobility

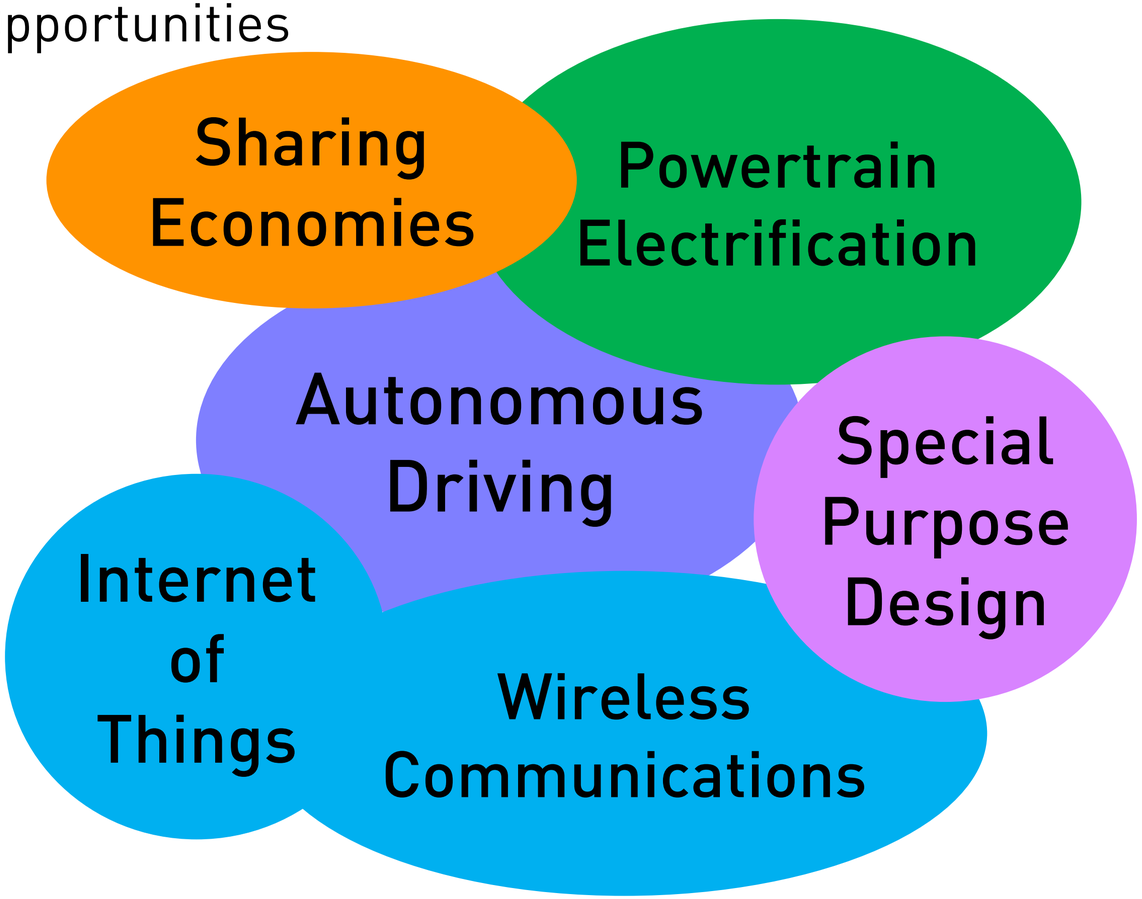
Challenges

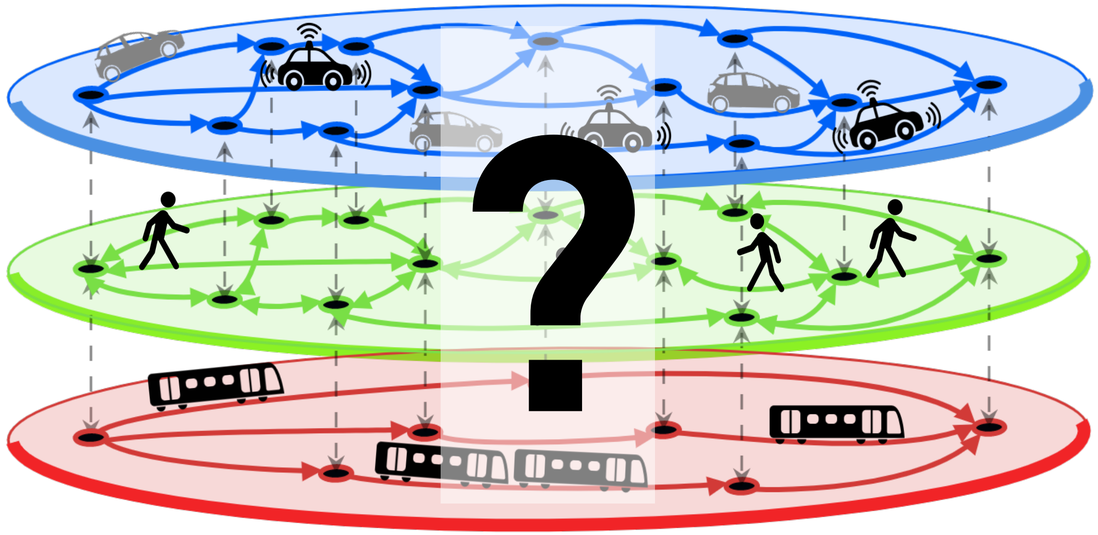
Opportunities

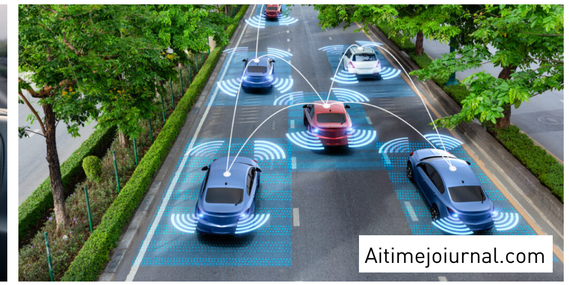
- Sharing Economies
- Powertrain Electrification
- Autonomous Driving
- Special Purpose Design
- Internet of Things
- Wireless Communications

Facts about Mobility

Opportunities



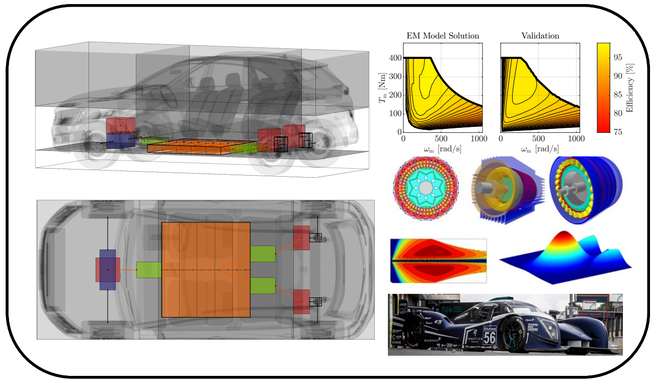




How can we combine all these opportunities to design and operate mobility eco-systems?

Optimization Models to Design and Operate Mobility Systems

Single Vehicle Optimization

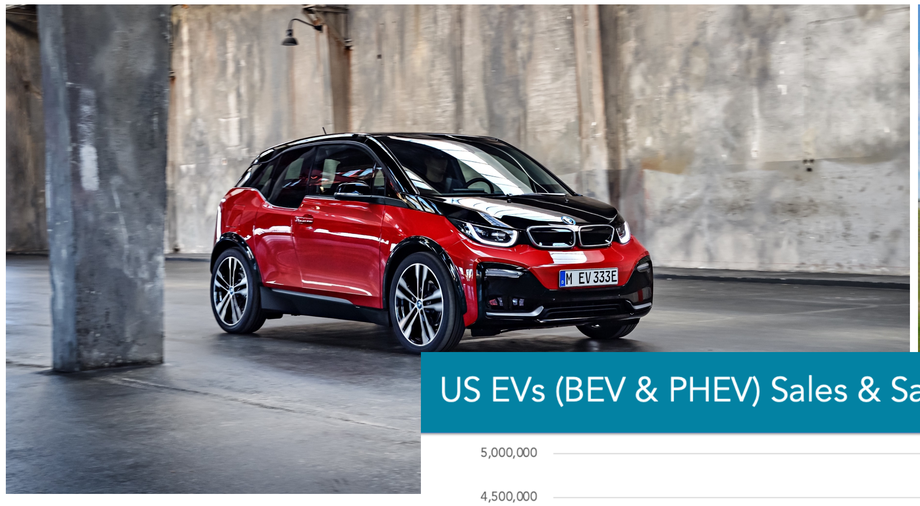


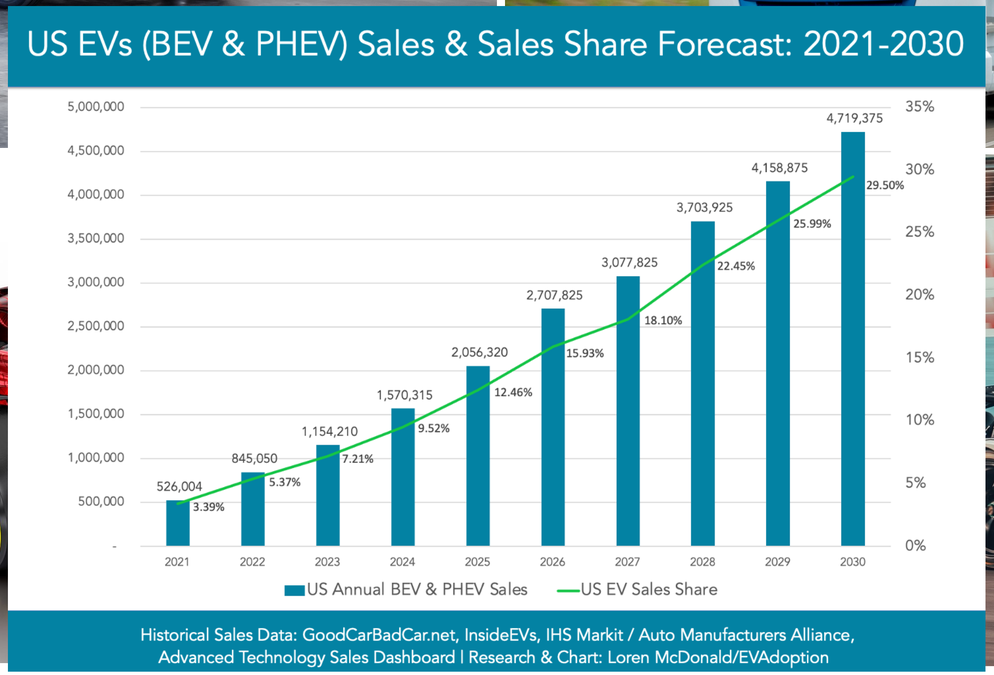
Mobility System Optimization

Multi-level Design of Mobility Systems

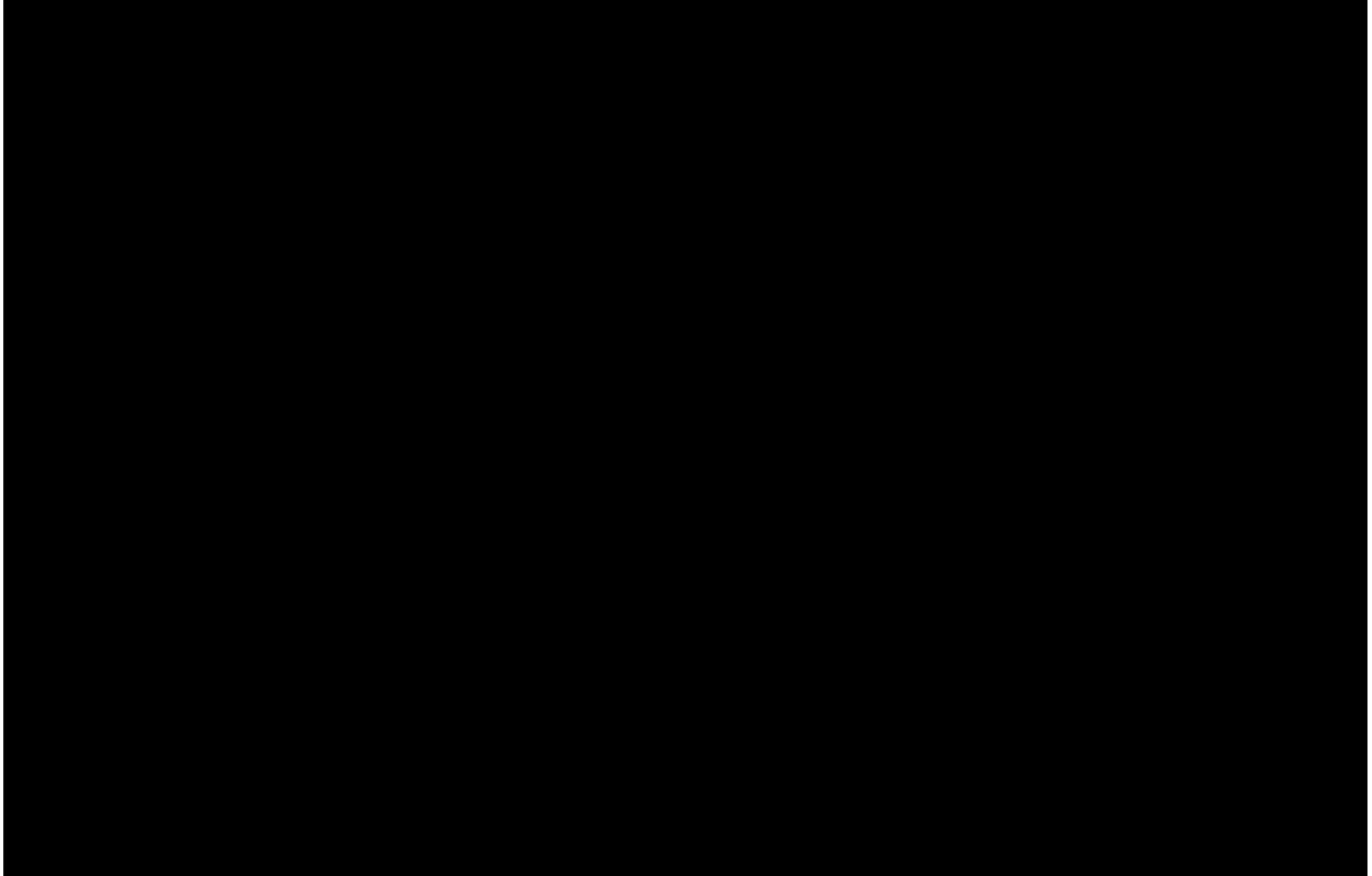
Humans in the Loop

Electrification of Vehicle Propulsion Systems





BMW Group PressClub, available online at https://www.press.bmwgroup.com/global/photo; DAF Image Library, available online at https://www.daf.com/nl-nl/nieuws-en-media/daf-image-library
Formula 1 Image Gallery, available online at https://www.formula1.com/en/latest; Porsche AG Press Database, available online at https://press.porsche.com/



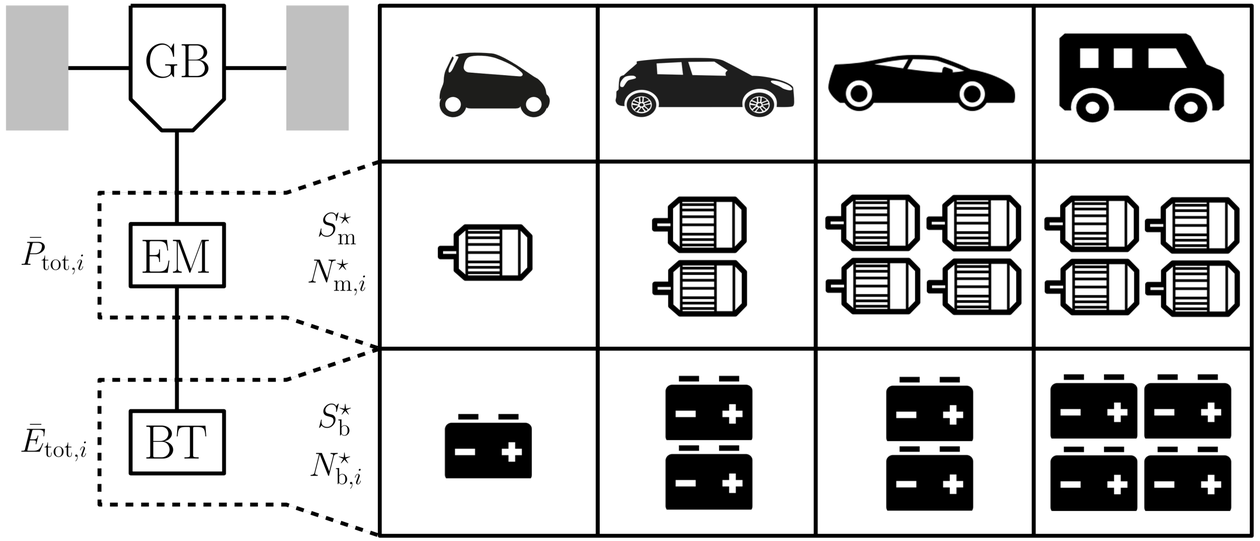
INMOTION
CHARGING AHEAD

10%-80% SOC Charging

Yet EVs (also non-racing) are still quite expensive...

Leveraging Product Family Design Optimization

- Exploiting **product family design** strategies to **reduce production cost.** [3,4,5]
- Trading **powertrain efficiency** for **modularity** and **standardization**: Different vehicle products are equipped with the **same components**
- **Joint optimization** of **EM** and **Battery** modules **size and multiplicity** for a family of Electric Vehicles.



[3] J. Jiao, T. W. Simpson, and Z. Siddique, "Product family design and platform-based product development: a state-of-the-art review," Journal of Intelligent Manufacturing, vol. 18, no. 1, pp. 5–29, 2007.

[4] K. Otto, K. Holtta-Otto, T. W. Simpson, D. Krause, S. Ripperda, and S. K. Moon, "Global views on modular design research: Linking alternative methods to support modular product family structure design," ASME Journal of Mechanical Design, vol. 138, no. 7, p. 071101, 2016.

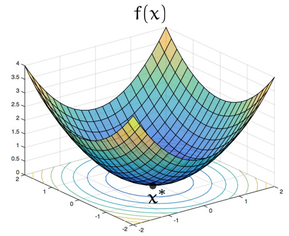
[5] T. W. Simpson, Z. Siddique, and J. Jiao, Product Platform and Product Family Design Methods and Applications, 1st ed. Springer US, 2006.

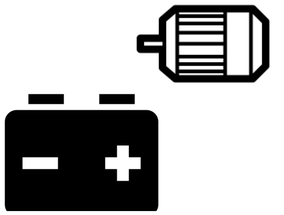
Trade-off efficiency (individually designed) VS production cost ("one size fits all")

How can we **optimize** the **components** for the **family** in a **concurrent** fashion?

Clemente, **Salazar**, Hofman, "Concurrent Powertrain Design for a Family of Electric Vehicles", IFAC AAC, 2022
Clemente, **Salazar**, Hofman "Concurrent Design Optimization of Shared Powertrain Modules in a Family of Electric Vehicles", Applied Energy, 2024

Convex Optimization





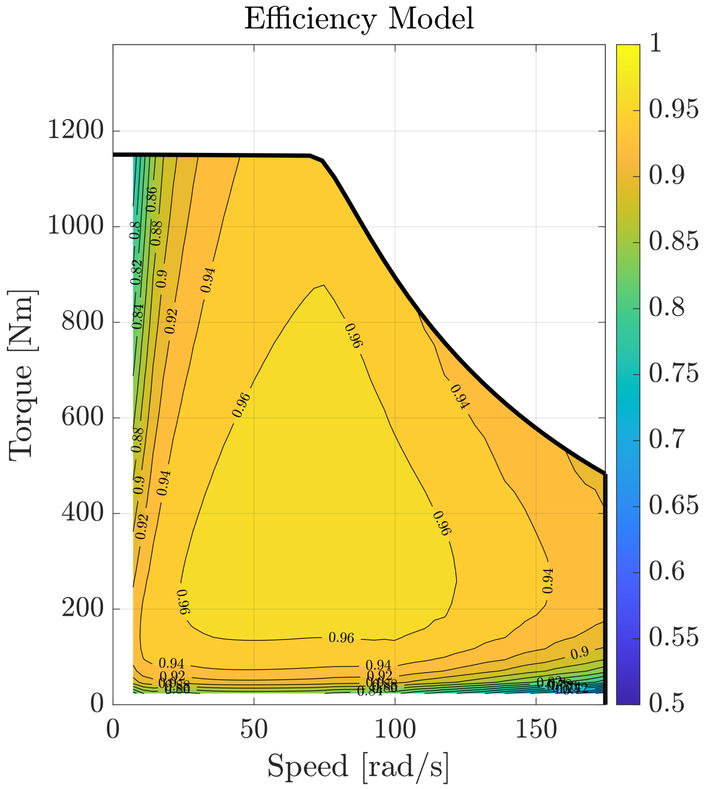
Pros

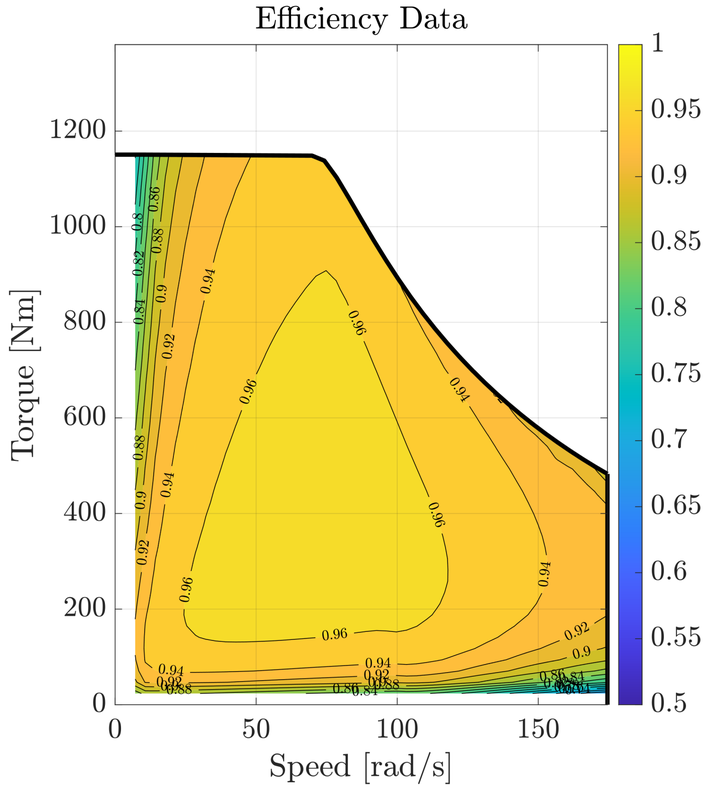
- Global Optimal Solutions
- Solved in Polynomial Time (Fast)

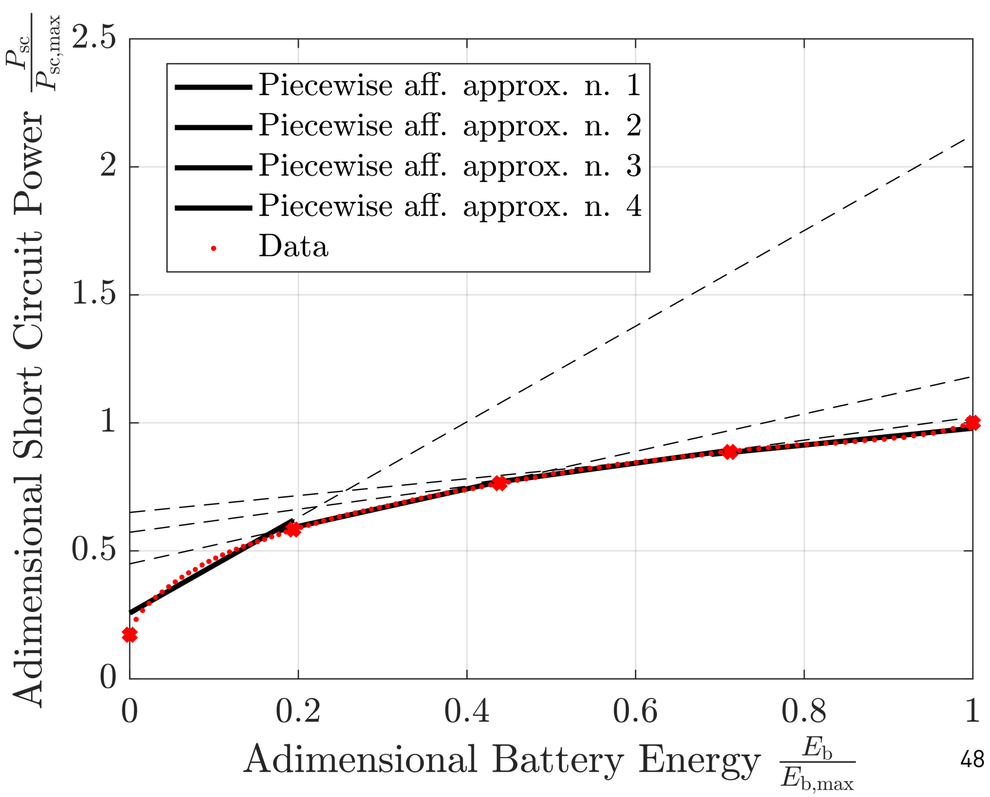
Cons

- Approximated Models
- Needs tractable formulation

Second-Order Conic Programming (SOCP)







Total Cost of Ownership Model

Operation cost

$$J_{\mathrm{TCO}} = C_{\mathrm{a}} + C_{\mathrm{op}} = C_{\mathrm{p}} + C_{\mathrm{op}} = C_{\mathrm{g}} + c_{\mathrm{b}} E_{\mathrm{c}} + c_{\mathrm{m}} P_{\mathrm{m}} + c_{\mathrm{e}} F_{\mathrm{v}} d_{\mathrm{life}}$$

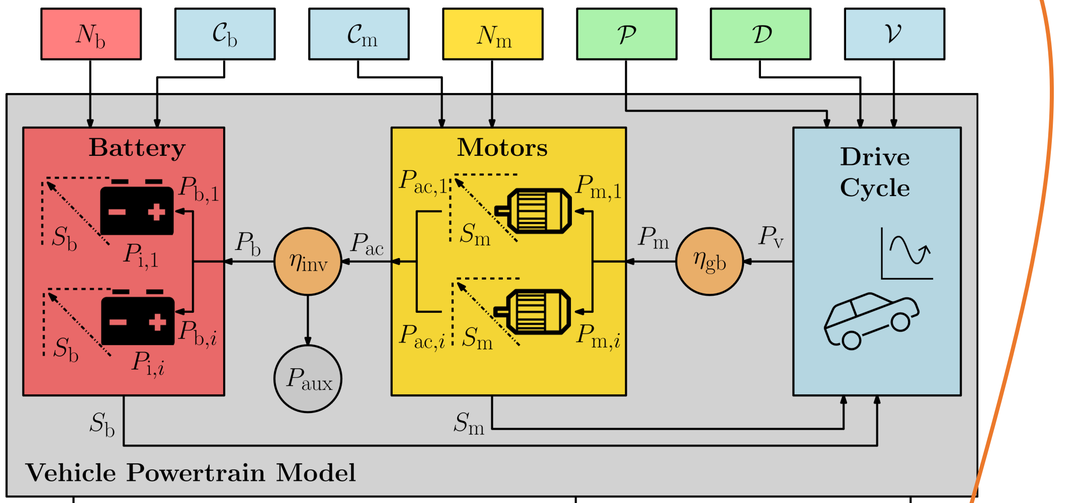
Acquisition price

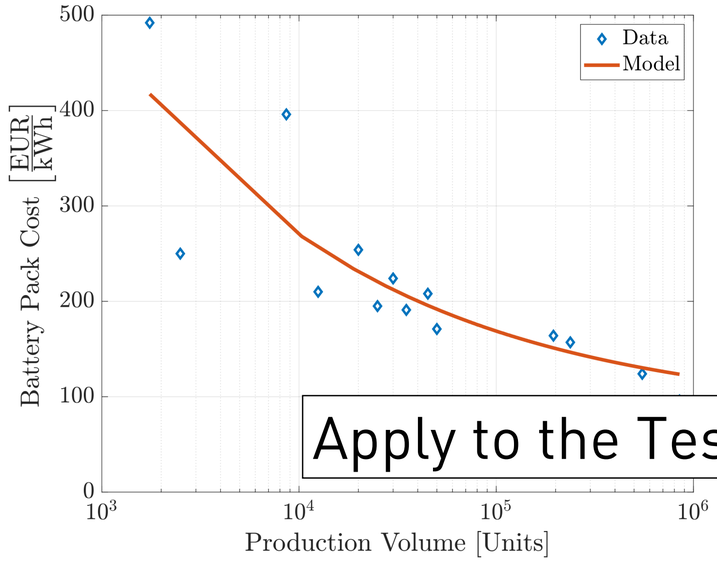
Glider cost

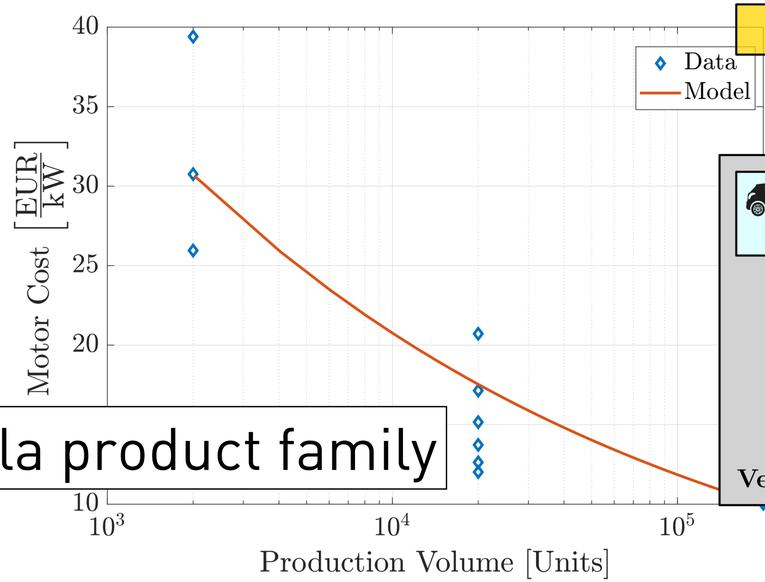
Energy per distance

$$c_{\mathrm{b}} = c_{\mathrm{b},0} + \frac{\lambda_{1,b}}{(n-1)^{\lambda_{2,\mathrm{b}}}}$$

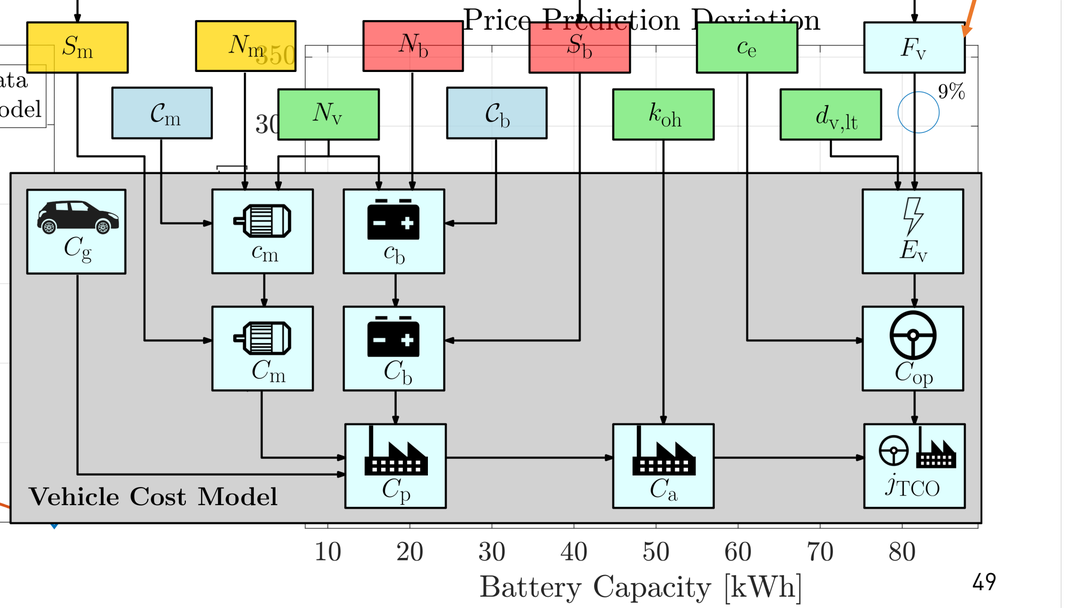
$$c_{\mathrm{m}} = c_{\mathrm{m},0} + \frac{\lambda_{1,m}}{(n-1)^{\lambda_{2,m}}}$$



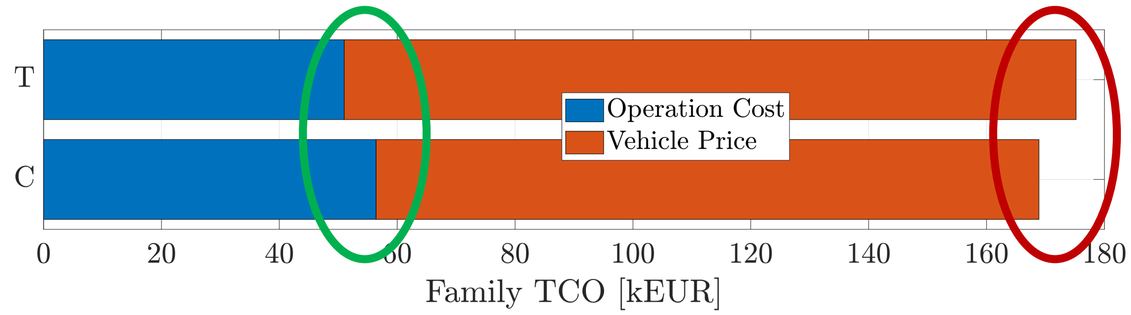


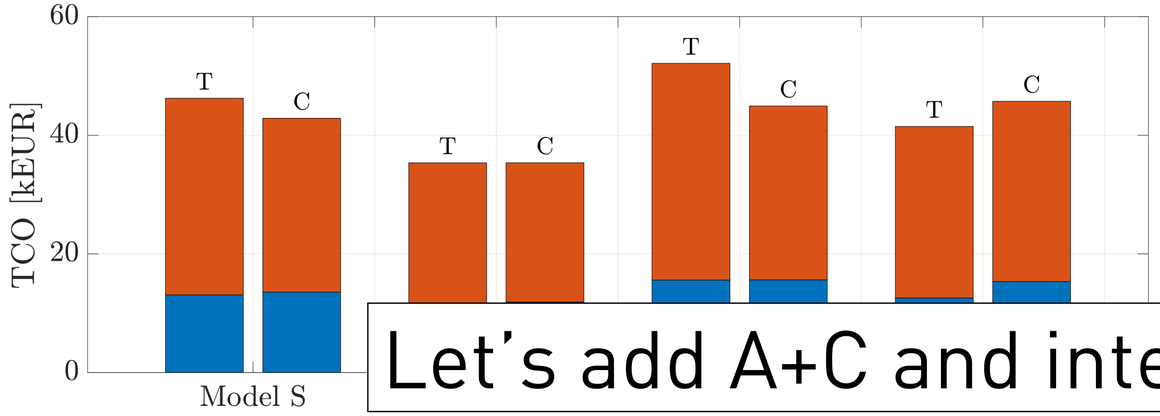


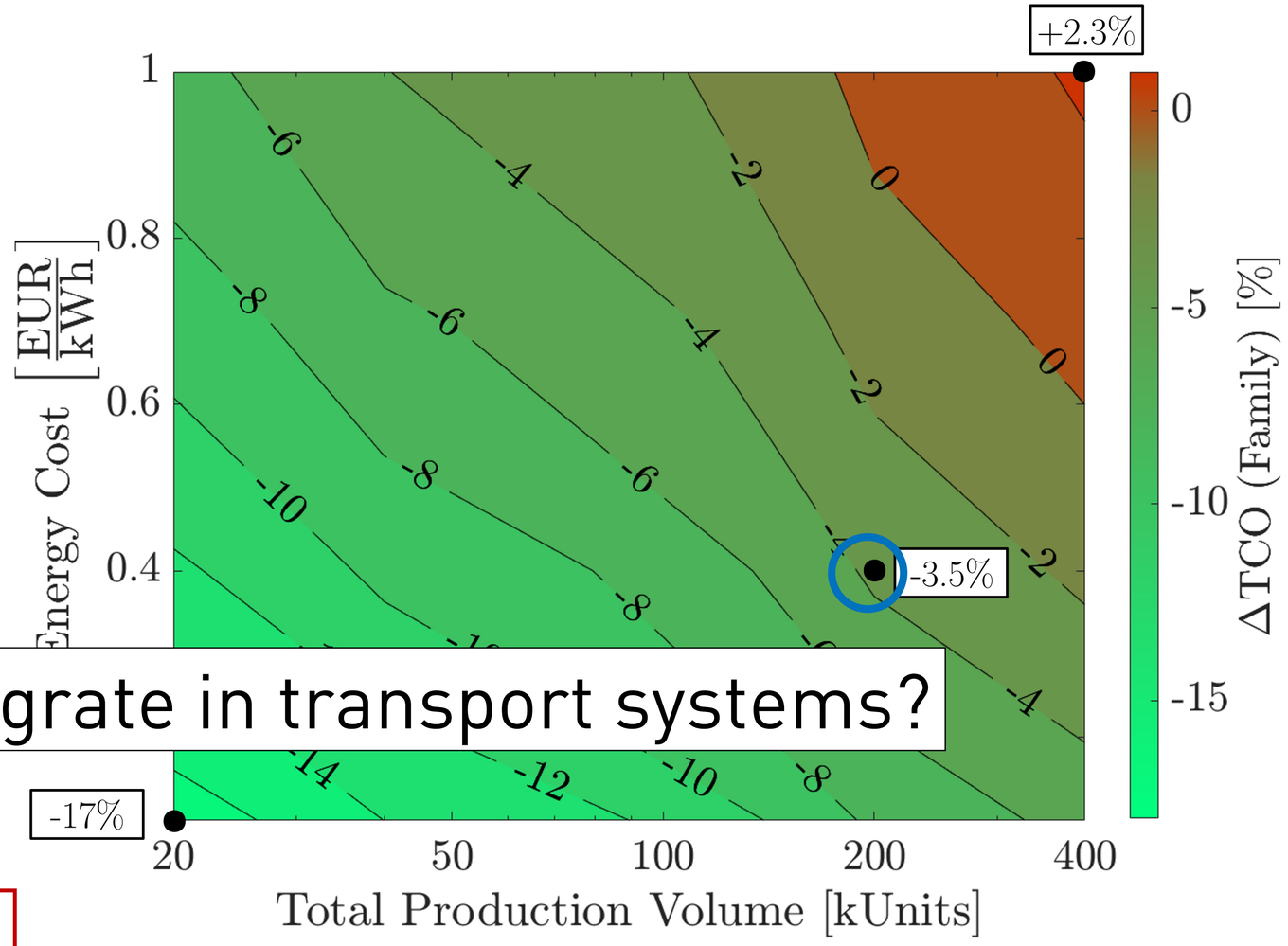
Apply to the Tesla product family



Concurrent Design Optimization Can Significantly Reduce TCO







Let's add A+C and integrate in transport systems?

Tailored design more efficient

Concurrent family design overall cheaper!

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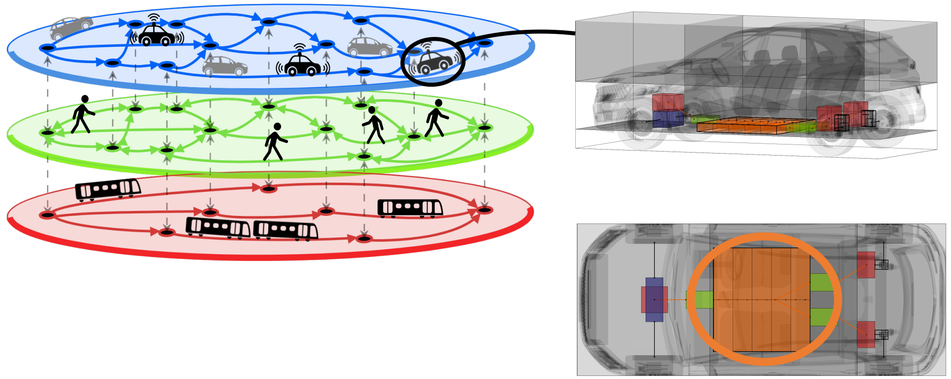
Opportunities from Autonomous Mobility-on-Demand (AMoD)

Vehicle Autonomy

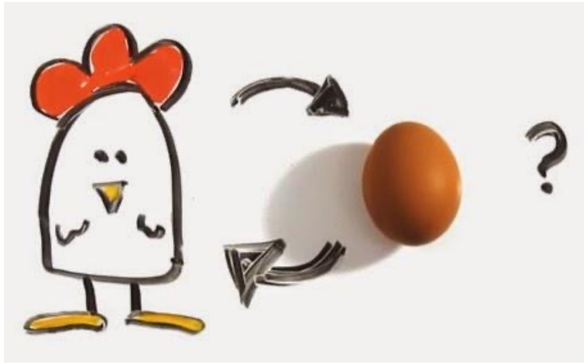
Car Sharing



Combine **autonomy**, **connectivity** and **electrification:**
Fleets of **electric robotaxis** providing mobility.

Challenge:

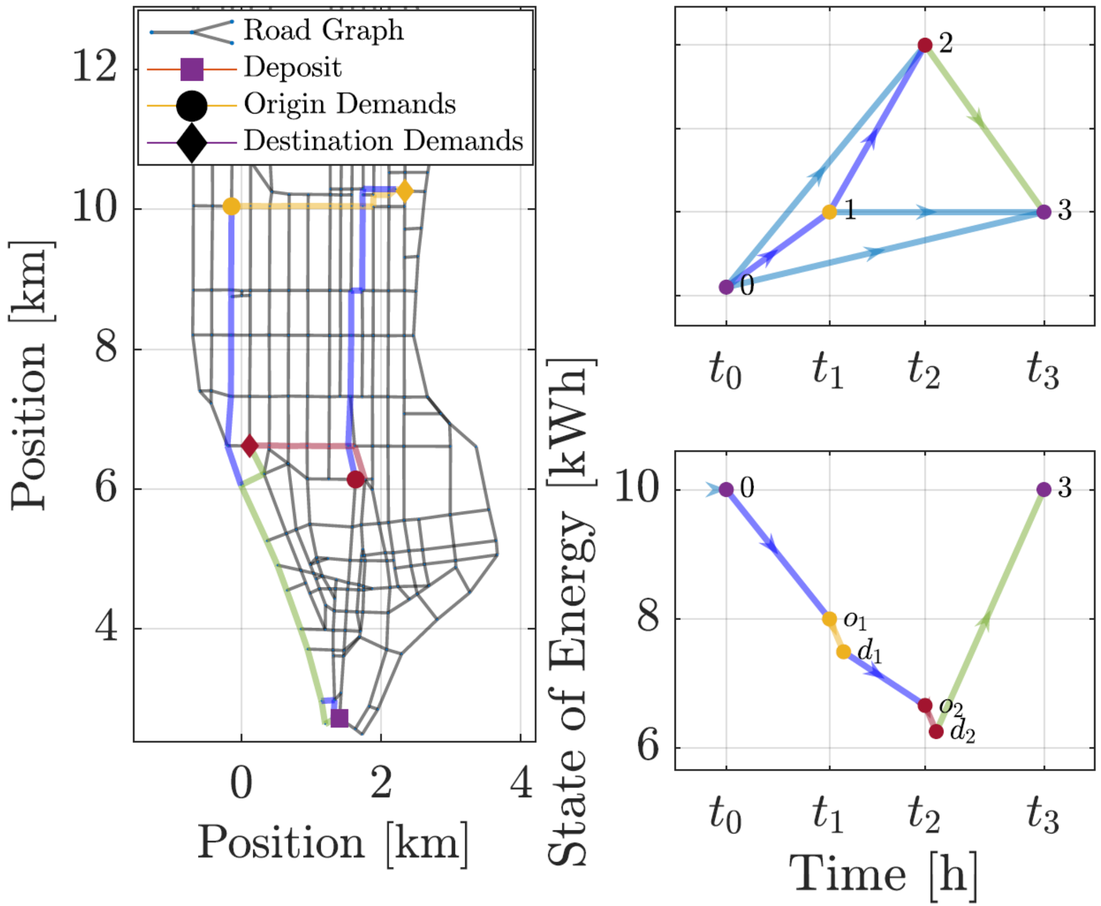
1. **Design** the **individual vehicles** for the intended fleet **operations**
2. **Operate** the fleet accounting for the individual vehicles' **design**



knowband.com

How to **jointly optimize fleet and battery sizing**, and **fleet operations**?
Multi-scale problem!

Represent Trips on an Electric Directed Acyclic Graph (DAG)



- Pre-compute the fastest paths
- Pre-compute **all the possible transitions** between travel requests to create a DAG
- **Include detours** to a charging station to charge the vehicle
- Jointly optimize **number of vehicles**, their **individual battery size** and the **operation of the fleet**

Paparella, Hofman, **Salazar**, *"Joint Optimization of Number of Vehicles, Battery Capacity and Operations of an Electric Autonomous Mobility-on-Demand Fleet"*, CDC, 2022
Paparella, Hofman, **Salazar**, *"Electric Autonomous Mobility-on-Demand: Jointly Optimal Vehicle Design and Fleet Operation"*, IEEE T-ITS, 2024

Objective Function: Total Cost of Ownership

$$J = \left(\sum_k p_0^k + p_{\text{el}} \sum_k \sum_{i,j,c} C_{ijc}^k \right) - \sum_i p_i b_{\text{r}}^i$$

Electricity price

Energy charged

Revenue generated by serving requests

Vehicle initial cost (amortized) $$p_0^k = \frac{\left(p_{\text{v}} b_{\text{v}}^k + p_{\text{b}} E_{\text{b}}^k \right)}{\tau_{\text{v}}}$$ [€/day]

Vehicle's consumption $$\Delta e^k = \Delta e_0 + \Delta e_{\text{b}} E_{\text{b}}^k$$ [kWh/km]

Mixed-integer Linear Program: Can solve it with global optimality guarantees…

Paparella, Hofman, **Salazar**, *"Joint Optimization of Number of Vehicles, Battery Capacity and Operations of an Electric Autonomous Mobility-on-Demand Fleet"*, CDC, 2022
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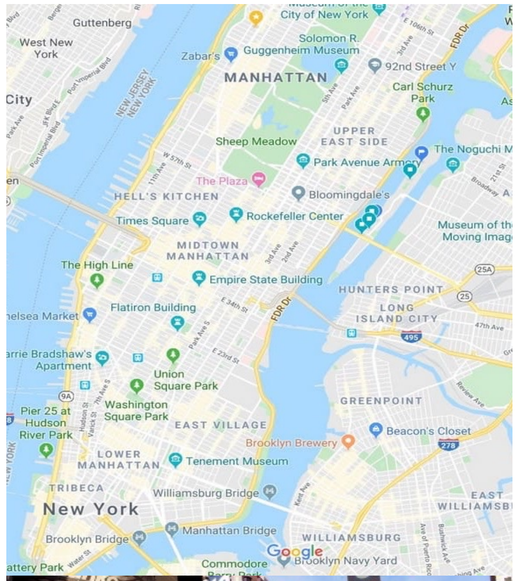
Case-study for Manhattan



- Yellow Taxi Cab Data
- Simulation over 7 days in March 2018
- 2400 requests per day
- Private chargers spread in the area

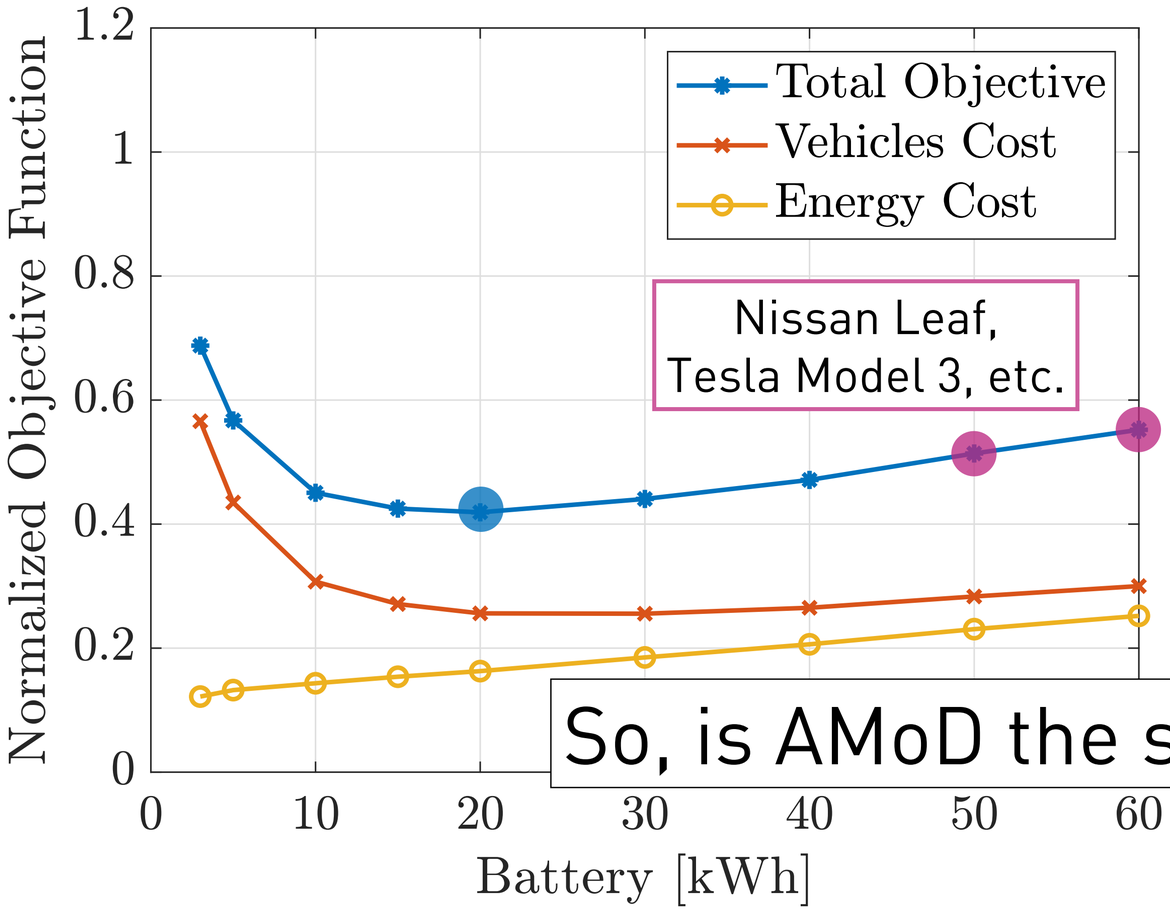
Solve **multiple smaller scenarios** and use the solutions to approximate a **distribution** of the solution for the whole problem

What if we use the same battery size for each vehicle?

Paparella, Hofman, **Salazar**, *"Joint Optimization of Number of Vehicles, Battery Capacity and Operations of an Electric Autonomous Mobility-on-Demand Fleet"*, CDC, 2022

Paparella, Hofman, **Salazar**, *"Electric Autonomous Mobility-on-Demand: Jointly Optimal Vehicle Design and Fleet Operation"*, IEEE T-ITS, 2024

Results for a Unique Battery Size



Jointly optimizing fleet design and operations:
-60% battery size, and hence lower vehicle costs
-20% energy consumption due to lower weight

So, is AMoD the solution to mobility?

Paparella, Hofman, **Salazar**, *"Joint Optimization of Number of Vehicles, Battery Capacity and Operations of an Electric Autonomous Mobility-on-Demand Fleet"*, CDC, 2022
Paparella, Hofman, **Salazar**, *"Electric Autonomous Mobility-on-Demand: Jointly Optimal Vehicle Design and Fleet Operation"*, IEEE T-ITS, 2024

The Engineer Trap

Autonomy

Connectivity

Electrification

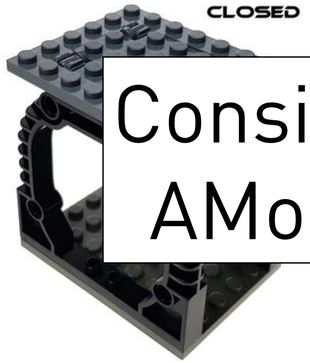
?

Disruptive technologies = societal solutions?

E.g., a decade ago, TNCs (E.g., Uber and Lyft) promised to address congestion, emissions and justice issues.

Instead, they ended up making the situation worse…
Erhardt et al. Science Advances 2019
Diao et al. Nature Sustainability 2021
Turón Entrepreneurship and Sustainability Issues 2021

Now, we are risking to fall into another **engineer trap**, engineering **disruptive answers** to the **wrong question**…



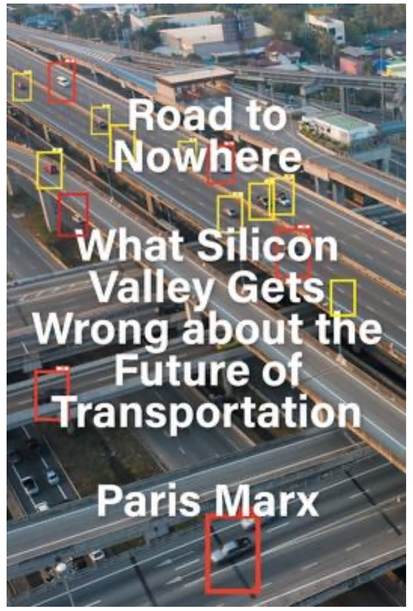
Consider the smartest AMoD system ever…

WSJ

TRANSIT

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



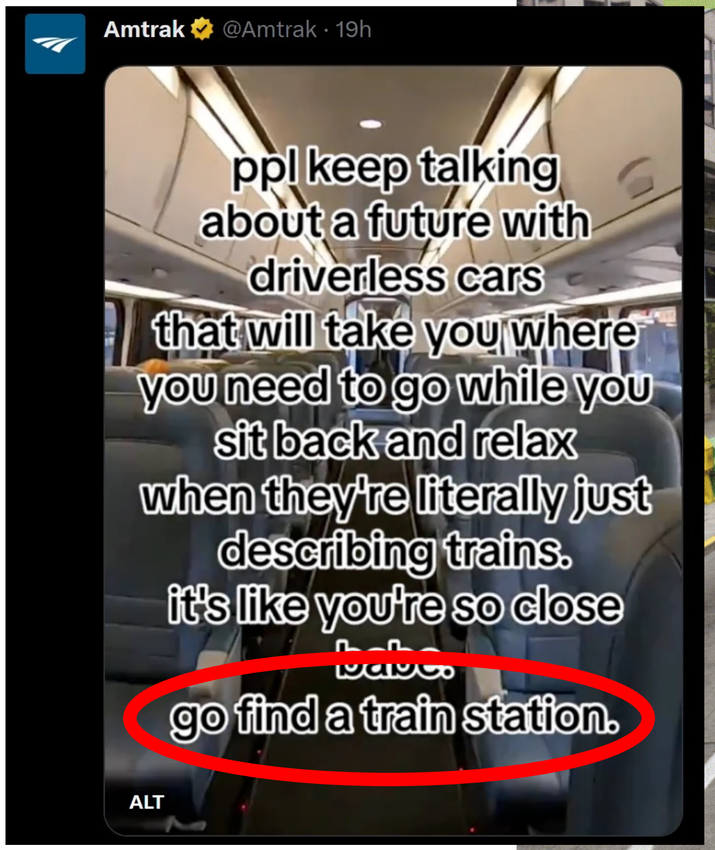
Road Traffic Efficiency

Road Traffic Efficiency

Why Public Transit?

Why Public Transit?

Why Public Transit?



The Magic of the Bicycle

Energy efficiency in transport

"In case of doubt, use the bike…"?

Cycling LCA
96kgCO2 to produce bike with 20000km life-time

21 gCO2/km = **26 gCO2/km**

Walking LCA
8kgCO2 to produce sneakers for 800km life-time

35 gCO2/km = **45 gCO2/km**

w.l.o.g., Combine the **best of all worlds** in an **intermodal** manner?

What is the question?

Figure 1. **Mechanism of increased catchment areas**

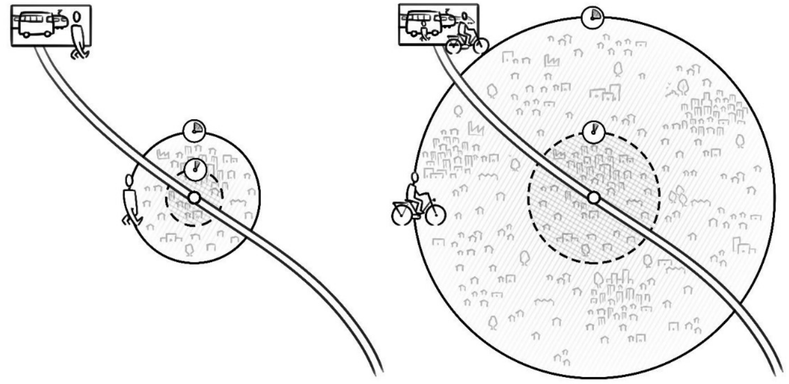
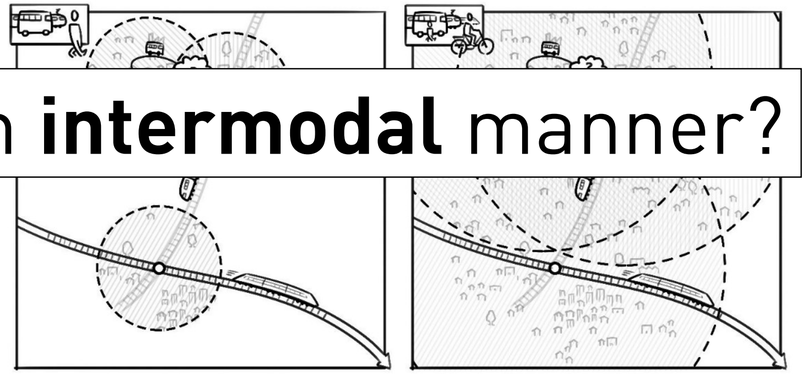
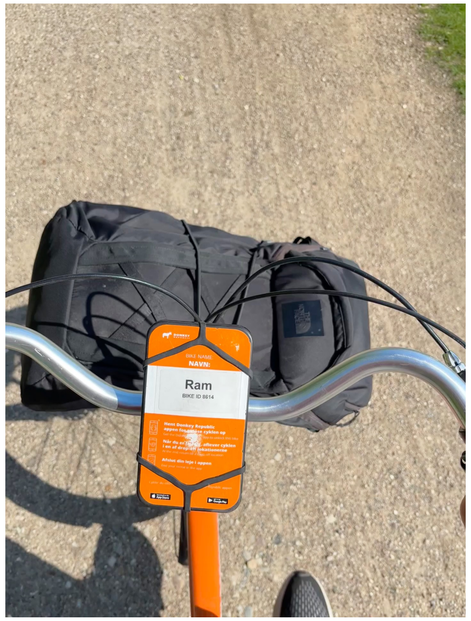


Figure 2. **Mechanism of increased choice**



How can we combine all these opportunities to design and operate mobility eco-systems?

Cycling



Vehicle Autonomy

+

Car Sharing

Public Transit

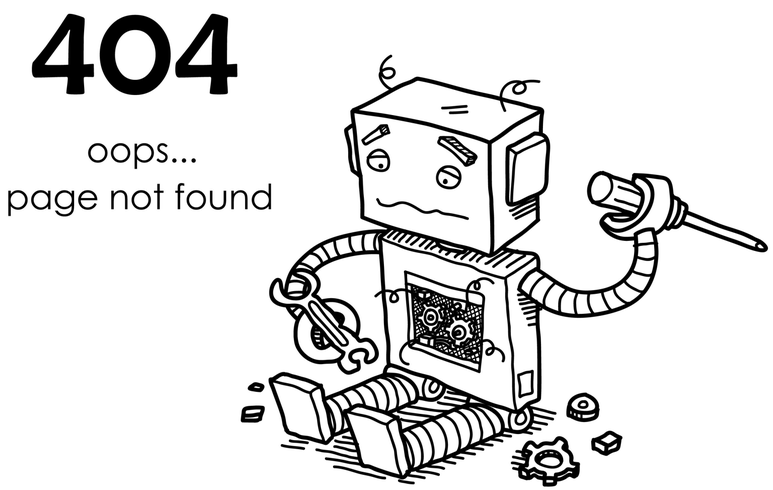
+

?

A Double **How**

How can we combine all these opportunities to design and operate mobility eco-systems?

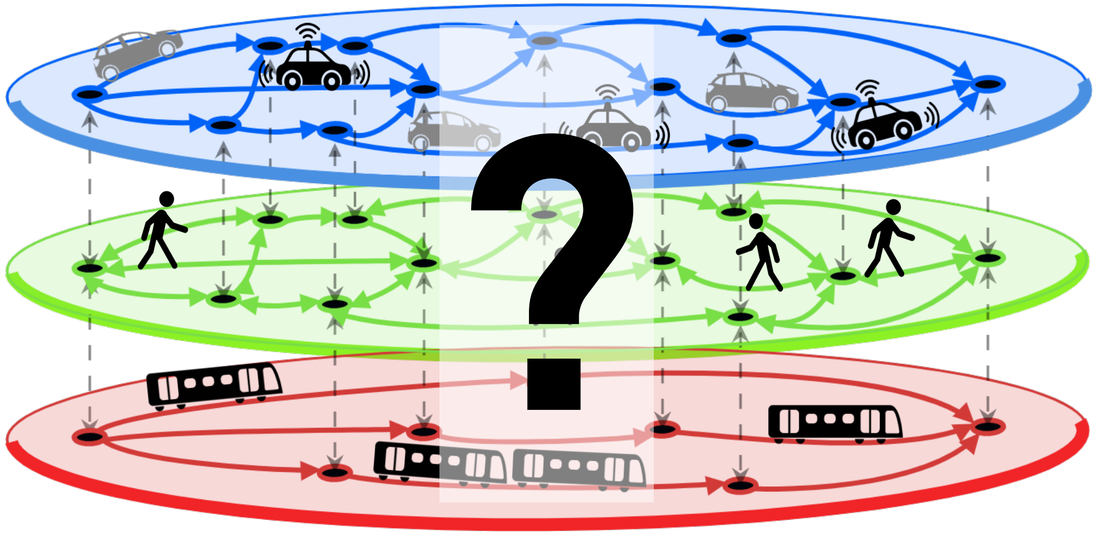
1. In line with which principles?



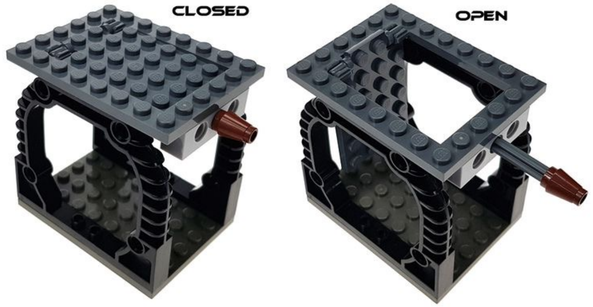
Justice?

Wellbeing?

2. What are potential implementable solutions?

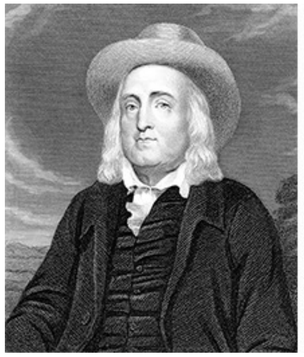


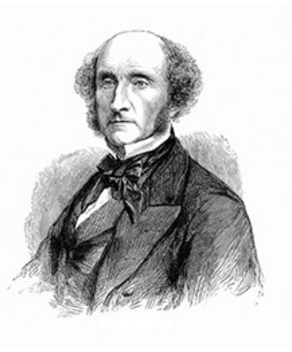
State of the art?



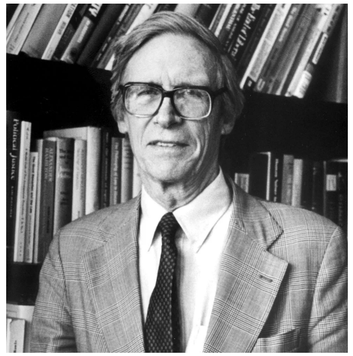
Conceptual Principles

Theories of Justice (incomplete)

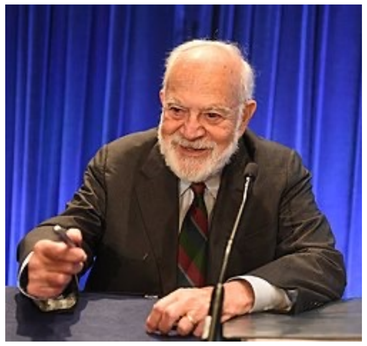




Utilitarianism
J. Bentham (1748-1832) and
J. Stuart Mill (1806-1873)



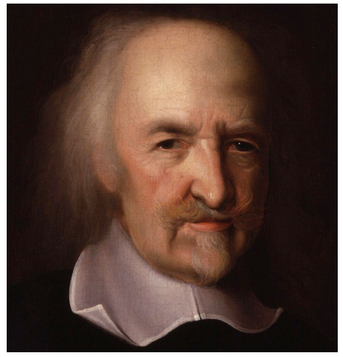
(Luck) Egalitarianism
J. Rawls (1921-2002) and
R. Dworkin (1931-2013)



Sufficientarianism
H. Frankfurt (1921-2002)

Limitarianism
I. Robeyns (1972-)

Theories of Wellbeing (incomplete)



Hedonism
T. Hobbes (1588-1679)

Eudaimonia
Aristotle (384-322 BC)

Capabilities Approach
A. Sen (1933-) and M. Nussbaum (1947-)

State of the Art and Contribution

How can we combine all these opportunities to design and operate mobility eco-systems?

1. In line with which conceptual principles?

Theories of Justice:
Utilitarianism (Bentham and Stuart Mill, 1800s)
Egalitarianism (Rawls 1971, Dworkin 2002)
Sufficientarianism (Crisp 2003, Frankfurt 2018)
…
Theories of Wellbeing:
Hedonism (Mill 1963, Griffin 1986)
Capabilitie
…
Applicatio
Transport
Vecchio ar
Mobiliy Ju
Mobility Experience (Ingvardson et al. 2020, te Brömmelstroet et al. 2021, Łukavska et al. 2023,…)

For evaluation: Cannot systematically provide implementable solutions

2. What are potential implementable solutions?

Network Design Problems (design):
(Bi-level) design problems ({R} Farahani et al. 2013, Jiang et al. 2023, Cianfanelli et al. 2023, …)

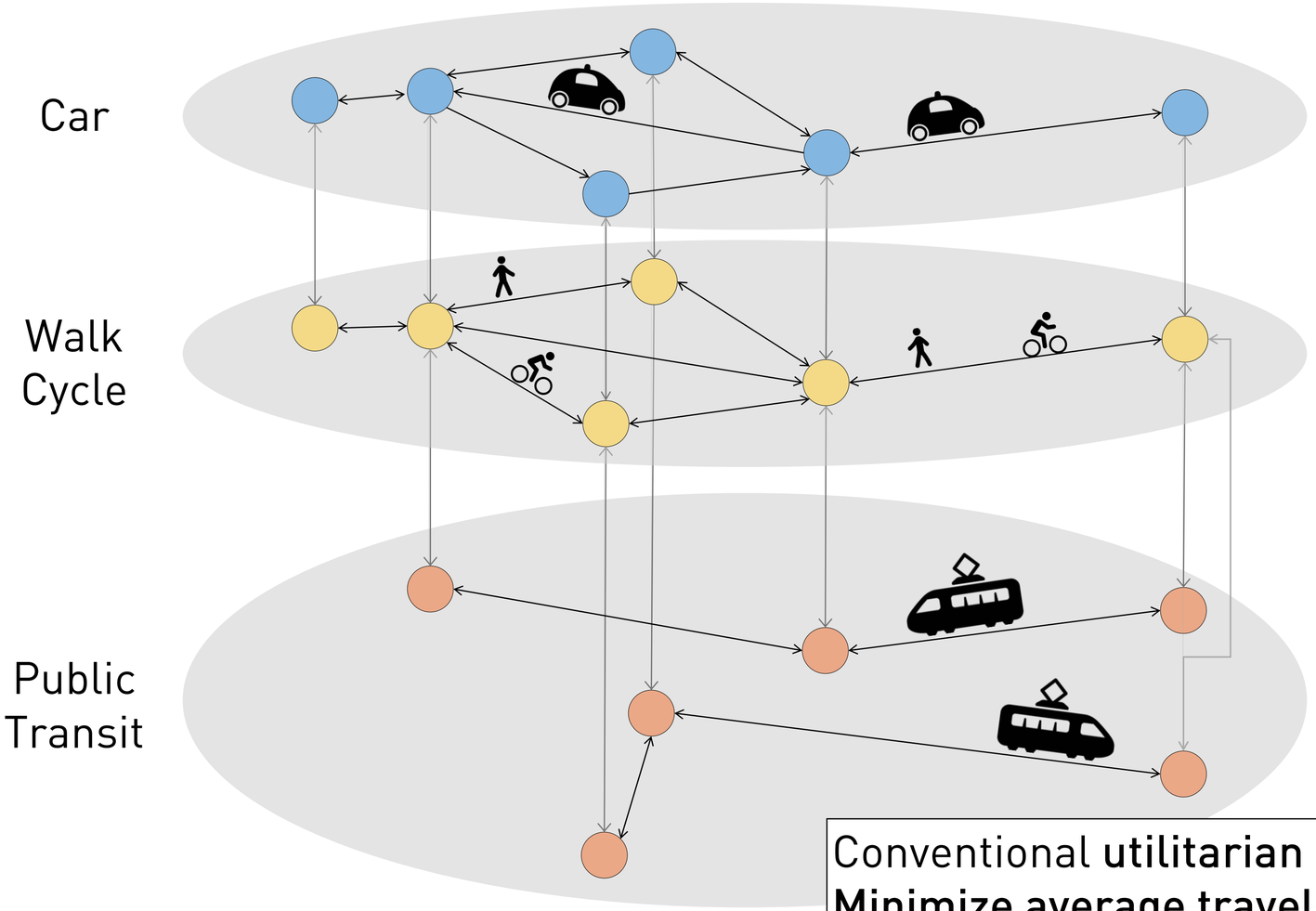
Autonomous Mobility-on-Demand (planning):
Queueing models (Zhang et al. 2014, Iglesias et al. 2017, …)
Agent-based models (Fagnant et al. 2014, Adnan et al. 2016,
t al. 2017,
in-Betech
al. 2024,…)
with EV charging (Luke et al. 2021, Paparella et al. 2024,…)
Mobility Equity Metrics (Bang et al. 2024, Bang et al 2024b)

Not considering principles of justice, if not utilitarianism or pure economics metrics

Today's contribution: a Conceptual, Modeling and Optimization Framework for (Design and) Planning of **Transport** Systems in line with Principles of **Justice**

Application to **Intermodal AMoD** System with **Network Flow Models**

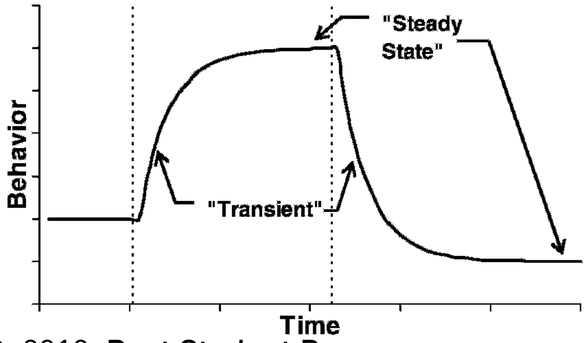
Intermodal Autonomous Mobility-on-Demand



Network Flow Model for Mesoscopic Analysis and Optimization

Represent customers and vehicles as **flows** and use **time-invariant** demand

Transient vs. Equilibrium

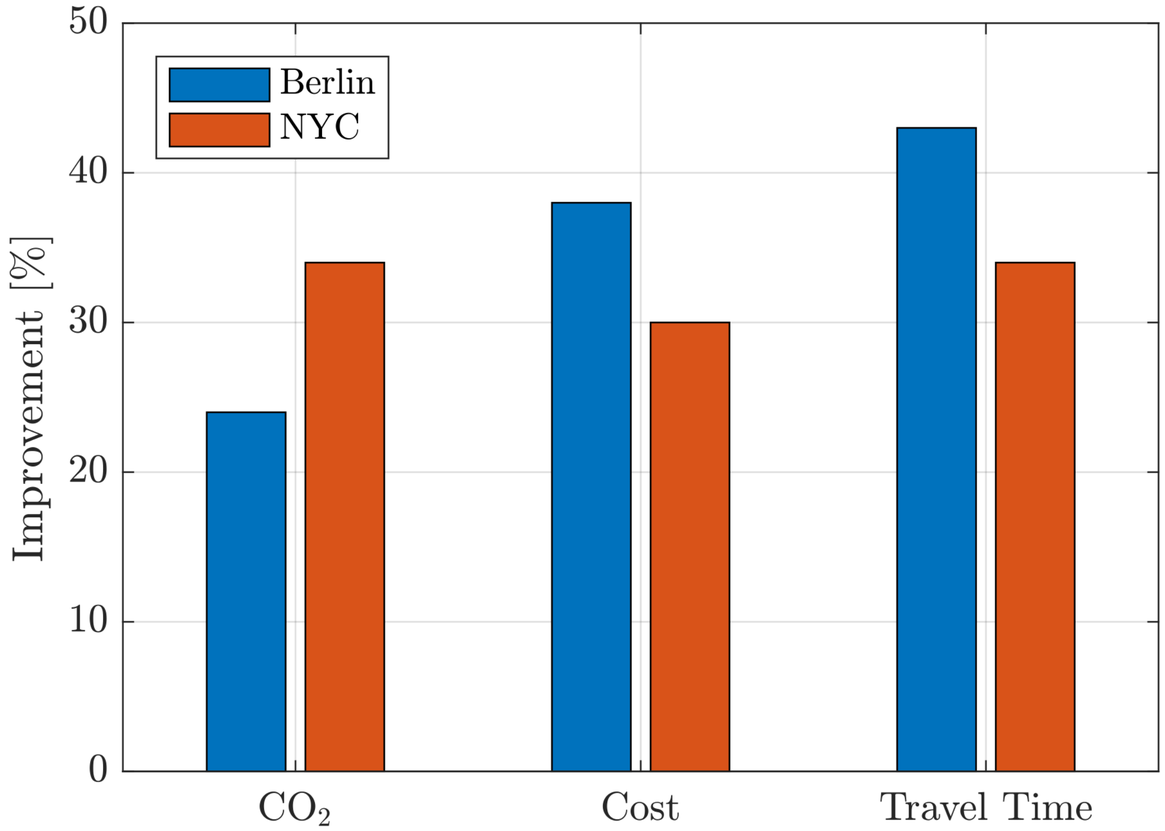


Conventional **utilitarian** approach:
Minimize average travel time

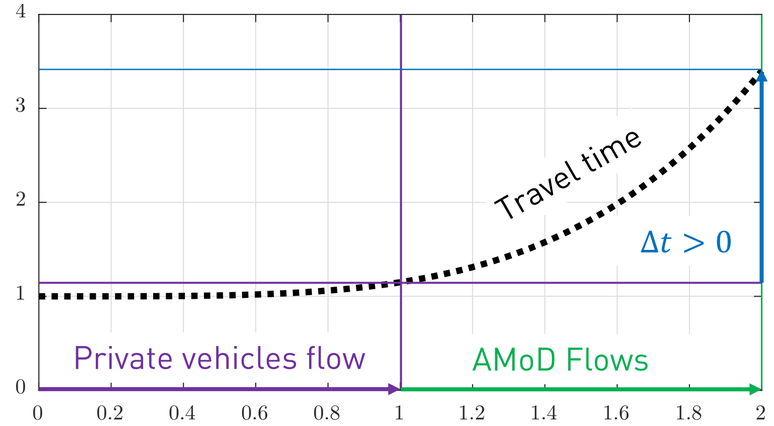
Salazar, Rossi, Schiffer, Onder, Pavone, "On the Interaction between AMoD and Public Transportation Systems", ITSC, 2018, **Best Student Paper**

Salazar, Lanzetti, Rossi, Schiffer, Pavone, "Intermodal AMoD", *IEEE Transactions on Intelligent Transportation Systems*, 2019

Pure AMoD VS Intermodal AMoD: Achievable Benefits



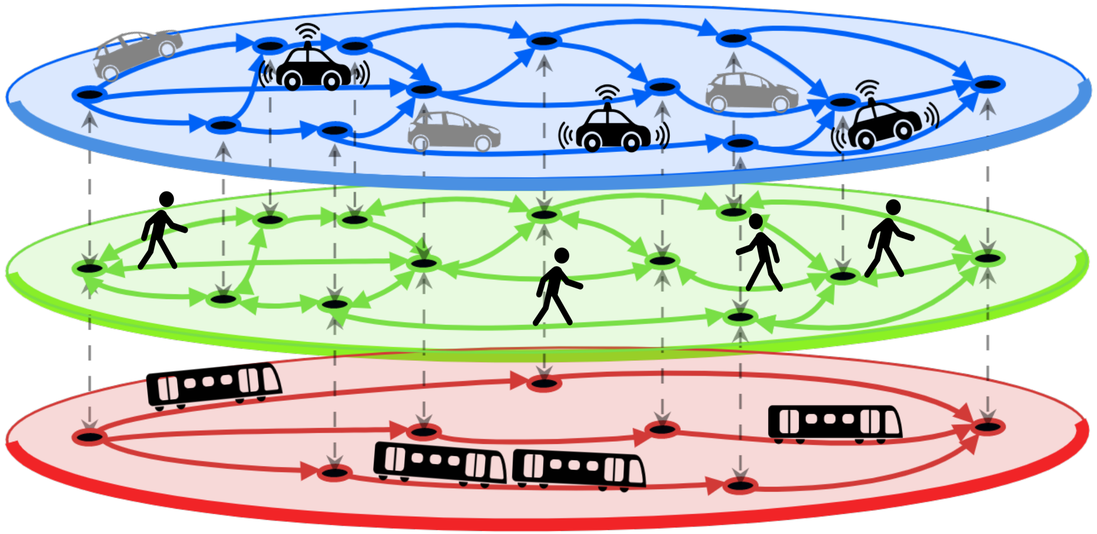
Intermodality significantly reduces **travel times**, **number of vehicles**, **emissions** and **cost**!



What if we have a **mix** between **private** and **intermodal shared** mobility?

Salazar, Rossi, Schiffer, Onder, Pavone, "On the Interaction between AMoD and Public Transportation Systems", ITSC, 2018, **Best Student Paper**
Salazar, Lanzetti, Rossi, Schiffer, Pavone, "Intermodal AMoD", *IEEE Transactions on Intelligent Transportation Systems*, 2019

Routing and Rebalancing I-AMoD Systems in **Mixed Traffic**



I-AMoD + Private Vehicles Problem

$$\min_{x^u, x^r, x^p} J(x)$$

s.t. ...

$$x^p \in \mathrm{TAP}(x^u, x^r)$$

x^p: Private vehicles

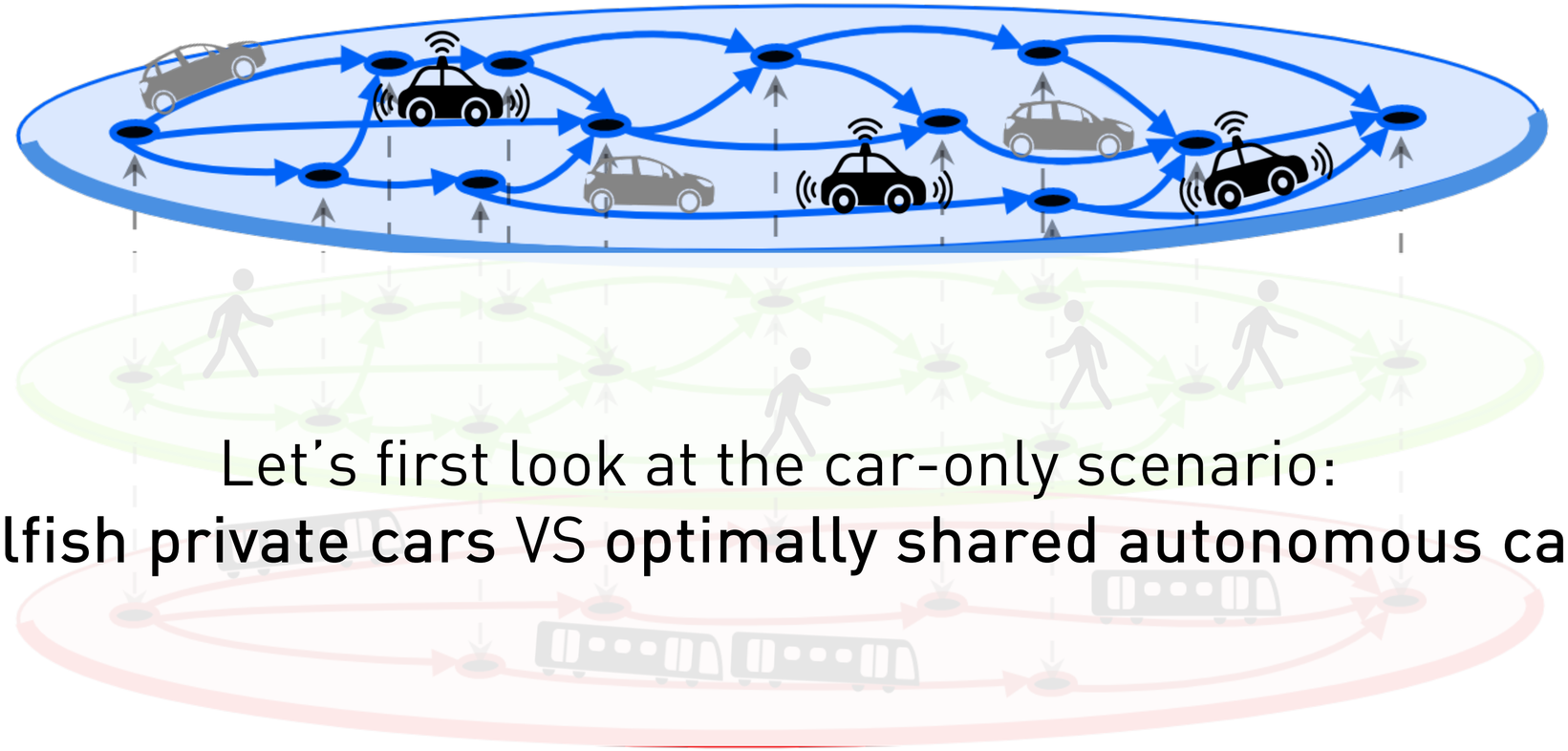
x^u: Users' intermodal flows

x^r: Rebalancing empty vehicles

Equilibrium Problem:
Solve iteratively for different I-AMoD penetration levels

Wollenstein-Betech, **Salazar**, Houshmand, Pavone, Paschalidis, Cassandras, «Routing and Rebalancing I-AMoD Systems in Mixed Traffic», IEEE T-ITS, 2021, Societal Impact Dissertation Award

Routing and Rebalancing I-AMoD Systems in **Mixed Traffic**



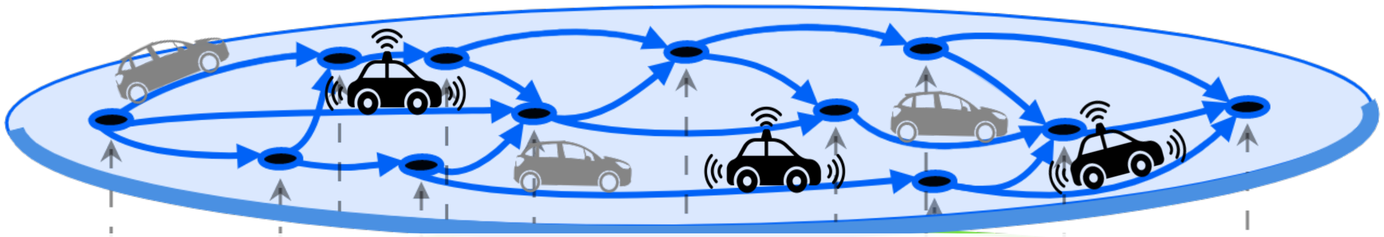
Let's first look at the car-only scenario:
Selfish private cars VS **optimally shared autonomous cars**

Optimize travel time for **intermodal system (black)** routes knowing
that **private vehicles (grey)** are selfishly optimizing their travel time

What is the impact of the fraction of shared and private users?

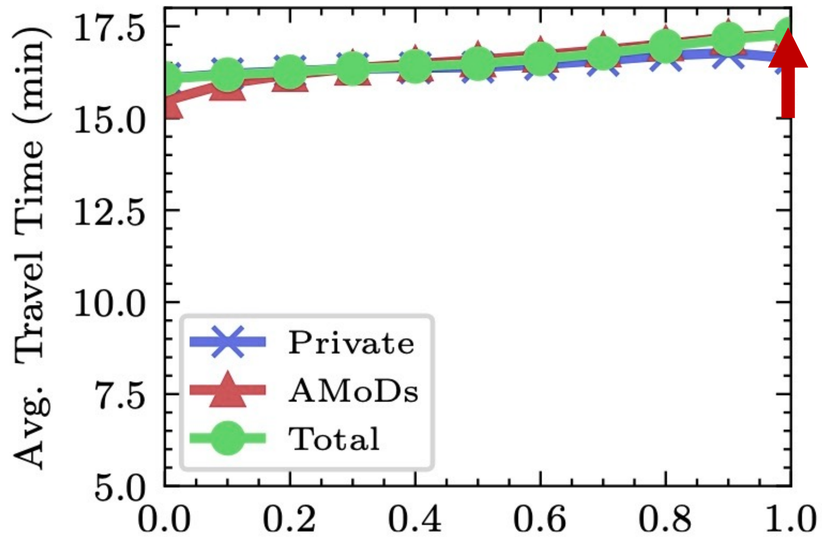
Wollenstein-Betech, **Salazar**, Houshmand, Pavone, Paschalidis, Cassandras, «Routing and Rebalancing I-AMoD Systems in Mixed Traffic», IEEE T-ITS, 2021, Societal Impact Dissertation Award

Routing and Rebalancing Pure AMoD Systems in **Mixed Traffic**



What is the impact of **intermodality**?

0 = all private cars, 1 = all shared mobility



Even if **optimally** routed, autonomous vehicles cause **more traffic** because of **empty miles**!

Wollenstein-Betech, **Salazar**, Houshmand, Pavone, Paschalidis, Cassandras, «Routing and Rebalancing I-AMoD Systems in Mixed Traffic», IEEE T-ITS, 2021, Societal Impact Dissertation Award

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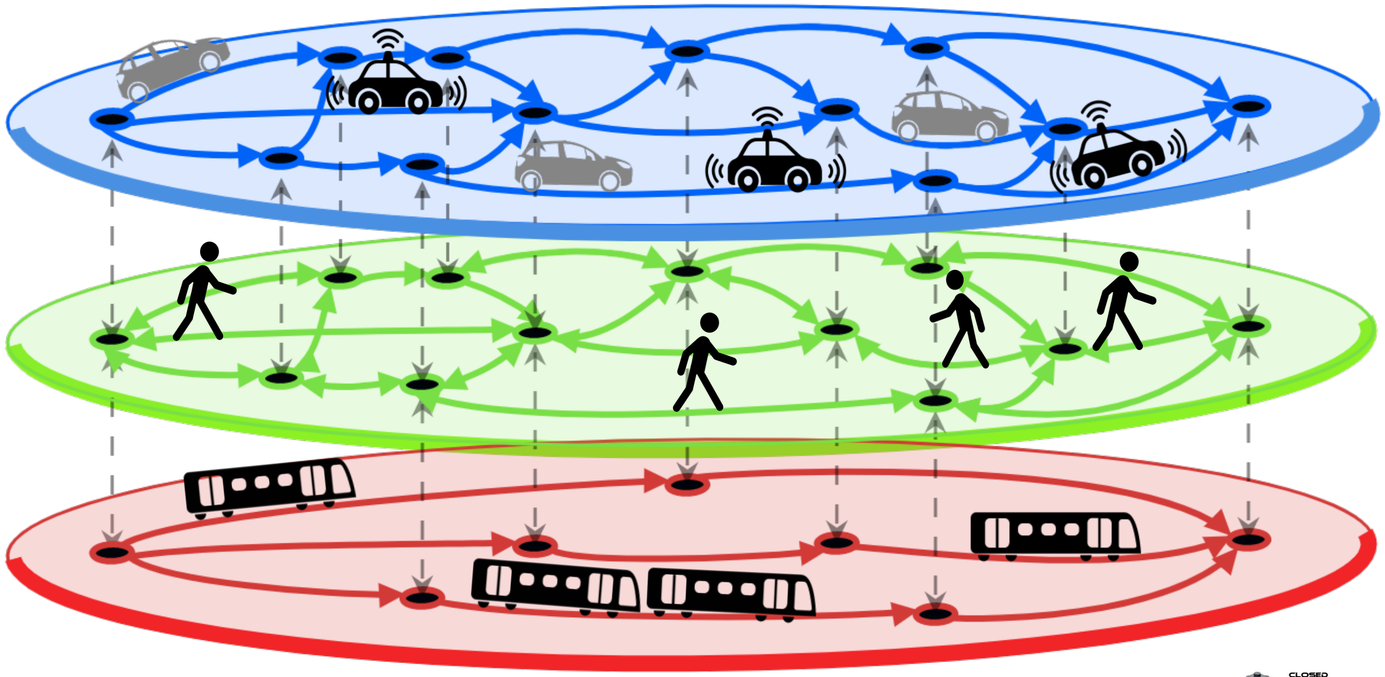
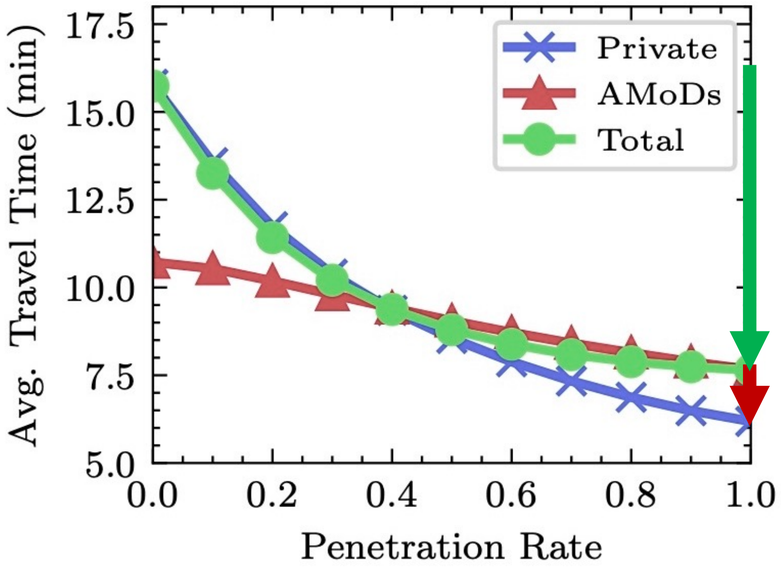
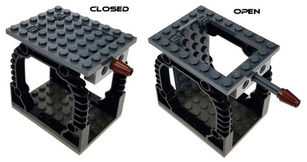


System-optimal I-AMoD improves the performance w.r.t. to selfish vehicles!





0 = all private cars, 1 = all shared mobility

Dilemma: it is better to be
e not!

But wait, are we optimizing for the right **objective**?

Wollenstein-Betech, **Salazar**, Houshmand, Pavone, Paschalidis, Cassandras, «Routing and Rebalancing I-AMoD Systems in Mixed Traffic», IEEE T-ITS, 2021, Societal Impact Dissertation Award

What is the main purpose of transportation?

Is minimizing average travel time the right way?

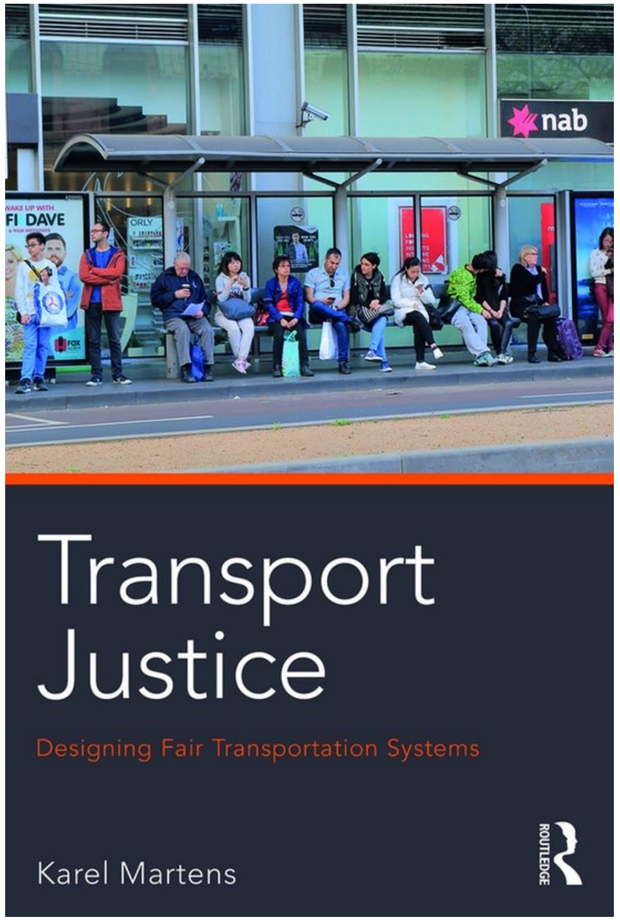
The purpose of transportation is to provide **accessibility**

What is **accessibility**? Measure of **freedom** to get to places

For instance, destinations reachable within a **reasonable** time (e.g., 20min)…

How should we distribute it?

We need a **distributive principle of justice!**



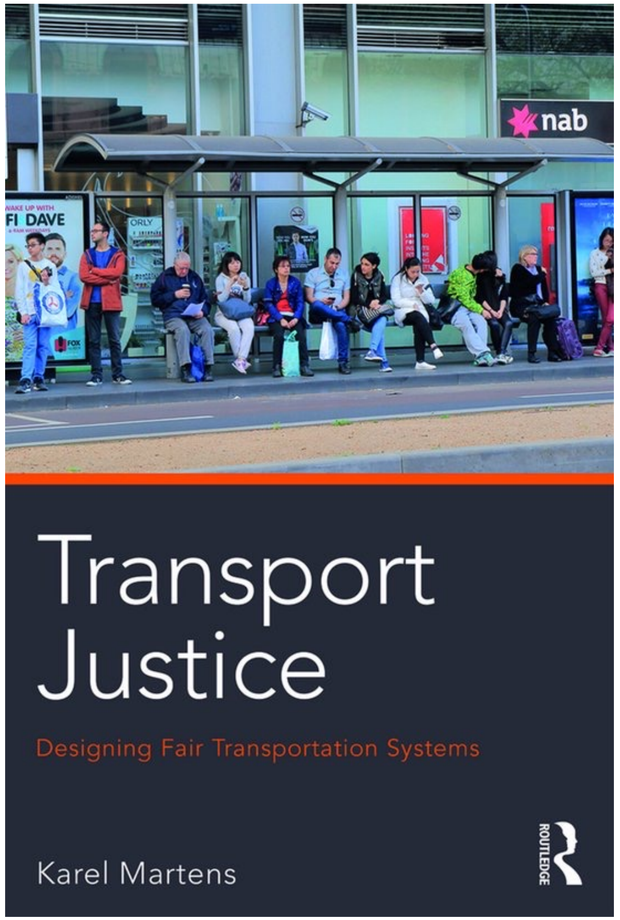
Martens, Transport Justice - Designing Fair Transportation Systems, Taylor Francis - Routledge, 2017
Ryan, Martens, "Defining and Implementing a Sufficient Level of Accessibility: What's Stopping Us?", TRPA, 2023

Which principle of justice?

Utilitarianism: *"greatest good for the greatest number"*, Bentham and Stuart Mill 1800s:
Maximize good / Minimize bad ***on average***

But what about the **worse off**?

Sufficientarianism: *"make sure everyone has enough"*, Walzer 1971, Crisp 2003 and Martens 2017:
Minimize ***deficit*** *to a* ***sufficiency*** *threshold*



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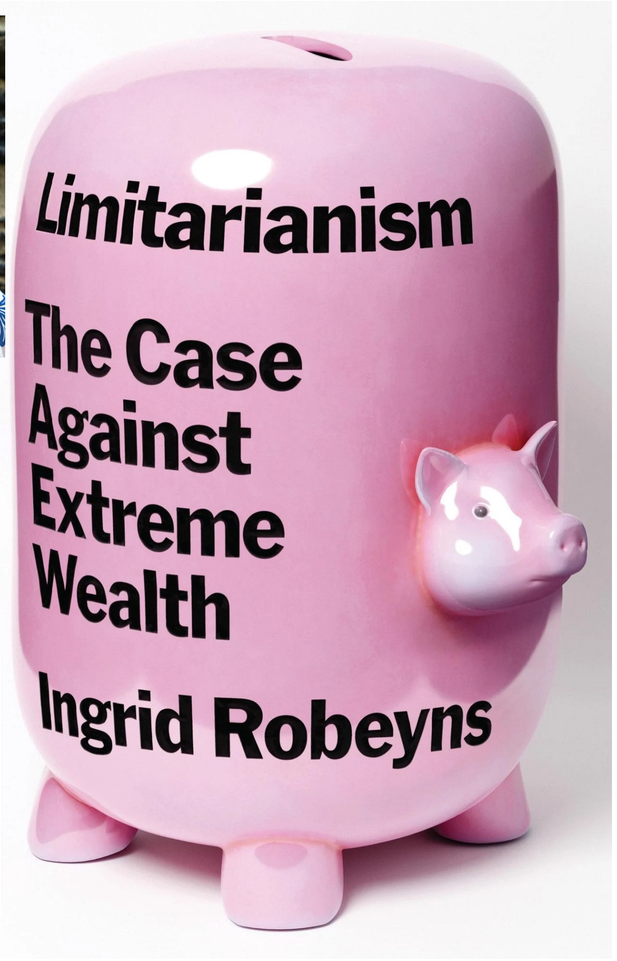
Limitarianism: *"It is* ***morally impermissible*** *for people to have* ***excessive wealth*** *as long as there are people with their basic needs unmet and as long as political systems are not impermeable to money"*, Robeyns 2024



L. Winner 1980: "Artifacts have Politics": can be mechanism for setting the affairs of a community!

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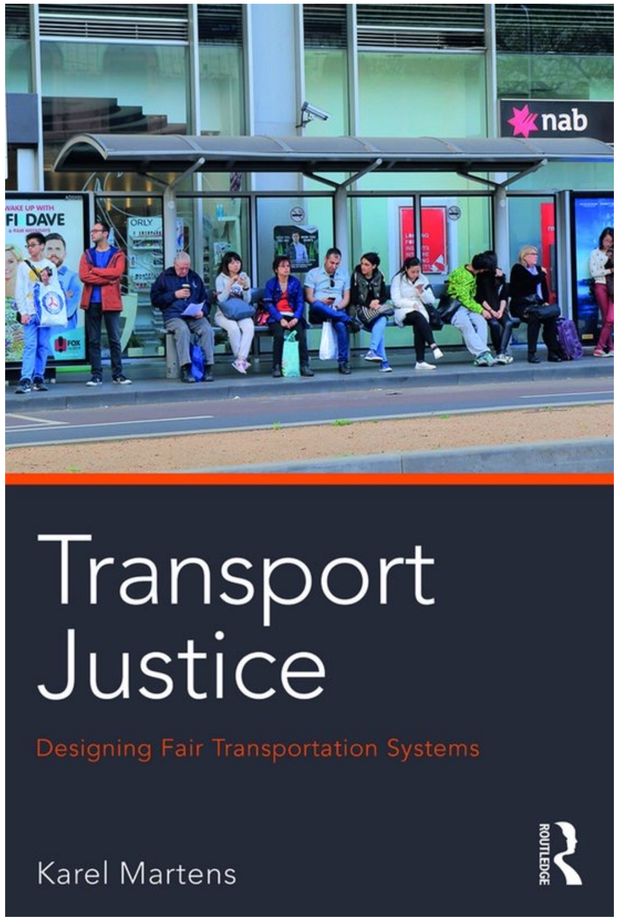
Beyond **utilitarian efficiency**: **sufficientarian** perspective on travel time, minimizing **unreachability** of given destinations

Min **commute insufficiency** = **extra travel time above 20min**



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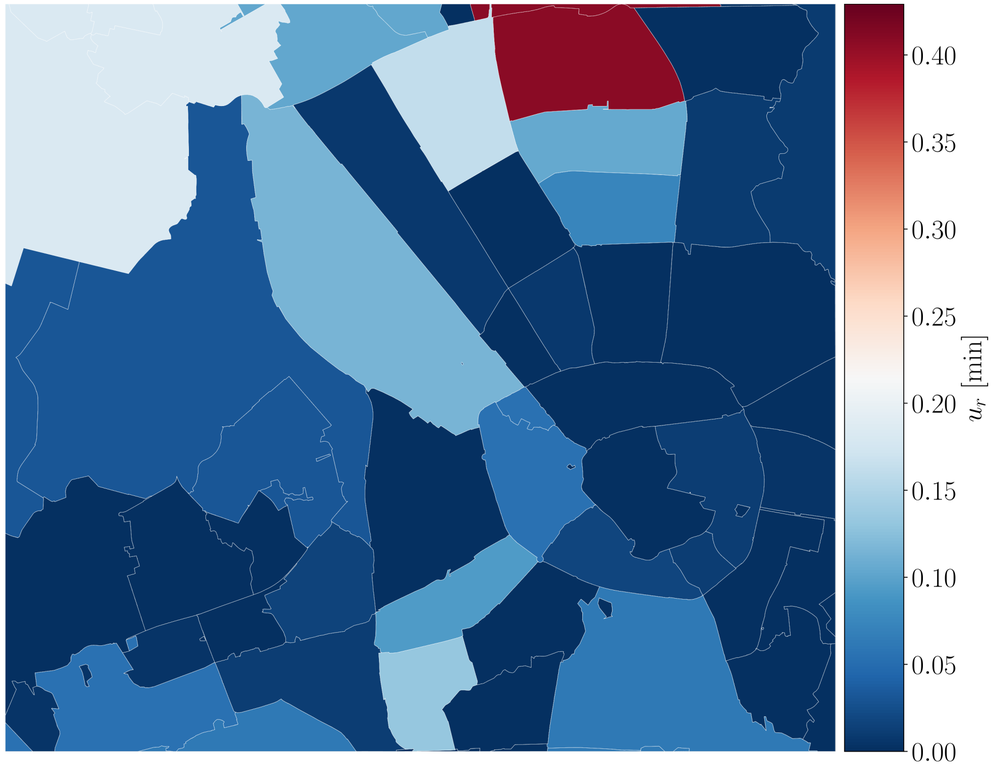
Ryan, Martens, "Defining and Implementing a Sufficient Level of Accessibility: What's Stopping Us?", TRPA, 2023

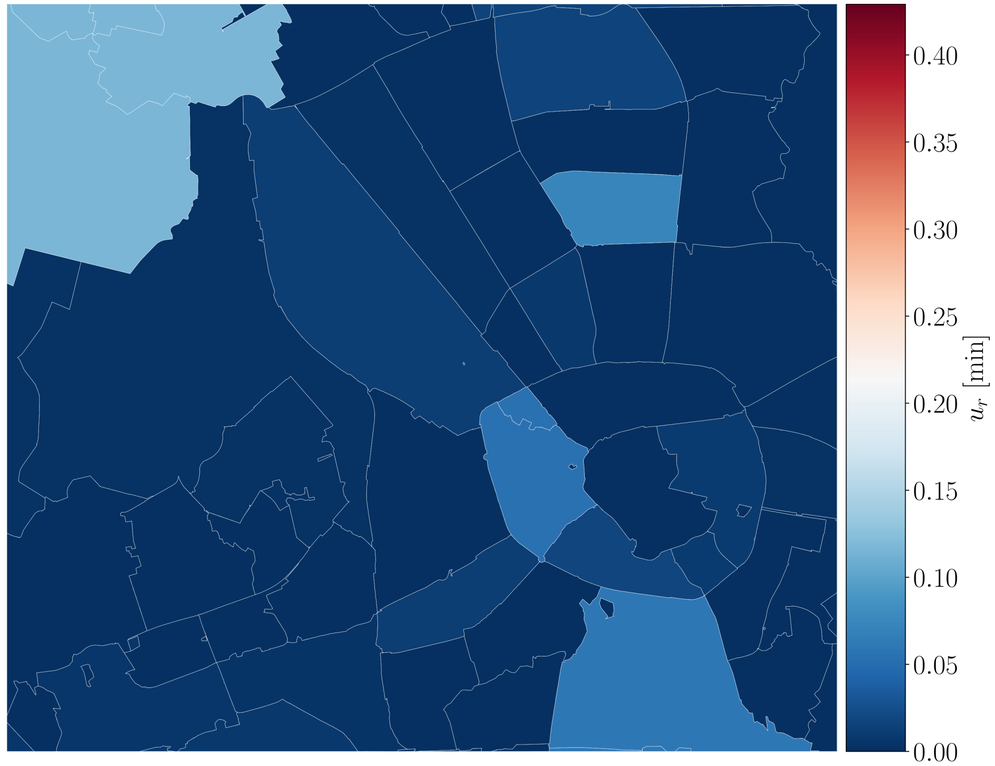
Case Study: Eindhoven – Commute Sufficiency

Utilitarian Efficiency vs. Commute Sufficiency

Utilitarian Efficiency: Minimum Travel Time



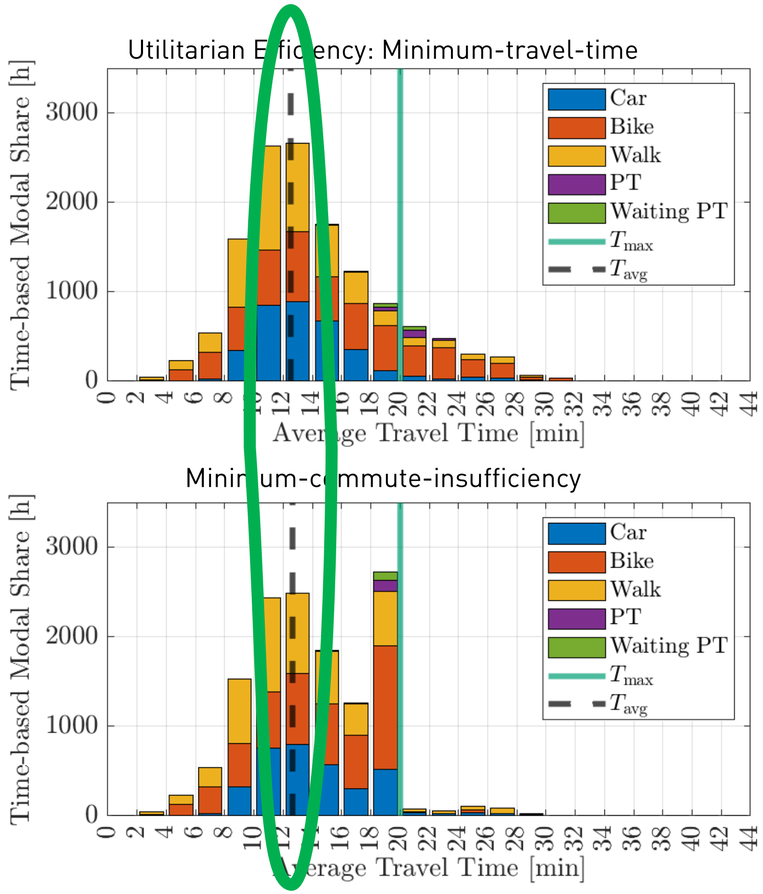
Commute Sufficiency



Salazar, Betancur Giraldo, Paparella, Pedroso, "On Accessibility Fairness in Intermodal AMoD Systems", IFAC CTS, 2024
[1] Arentze, Timmermans, "A Learning-based Transportation Oriented Simulation System", TRPB, 2004
[2] Rasouli, Kim, Yang, "Albatross IV: from Single Day to Multi Time Horizon Travel Demand Forecast", TRB, 2018

Case Study: Eindhoven – Commute Sufficiency

Utilitarian Efficiency vs. Commute Sufficiency



We can achieve almost **no commute insufficiency** with the **same average travel time**!

We can be **FAIR** without sacrificing **PERFORMANCE**

Salazar, Betancur Giraldo, Paparella, Pedroso, "On Accessibility Fairness in Intermodal AMoD Systems", IFAC CTS, 2024
[1] Arentze, Timmermans, "A Learning-based Transportation Oriented Simulation System", TRPB, 2004
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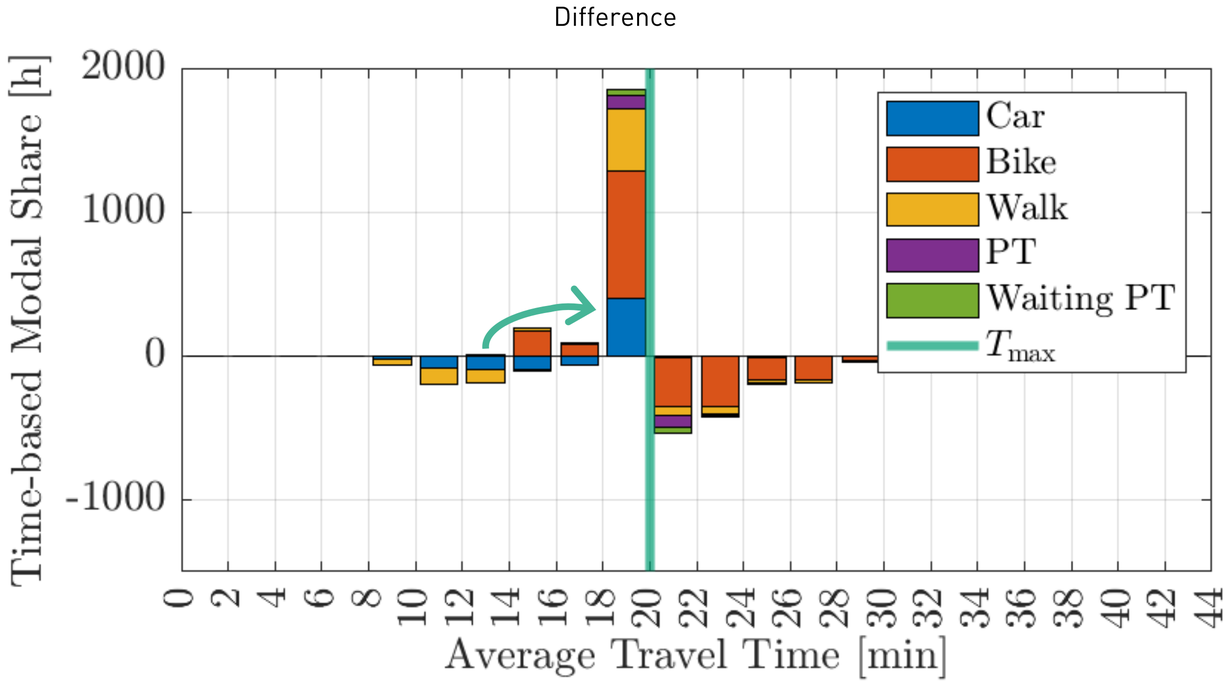
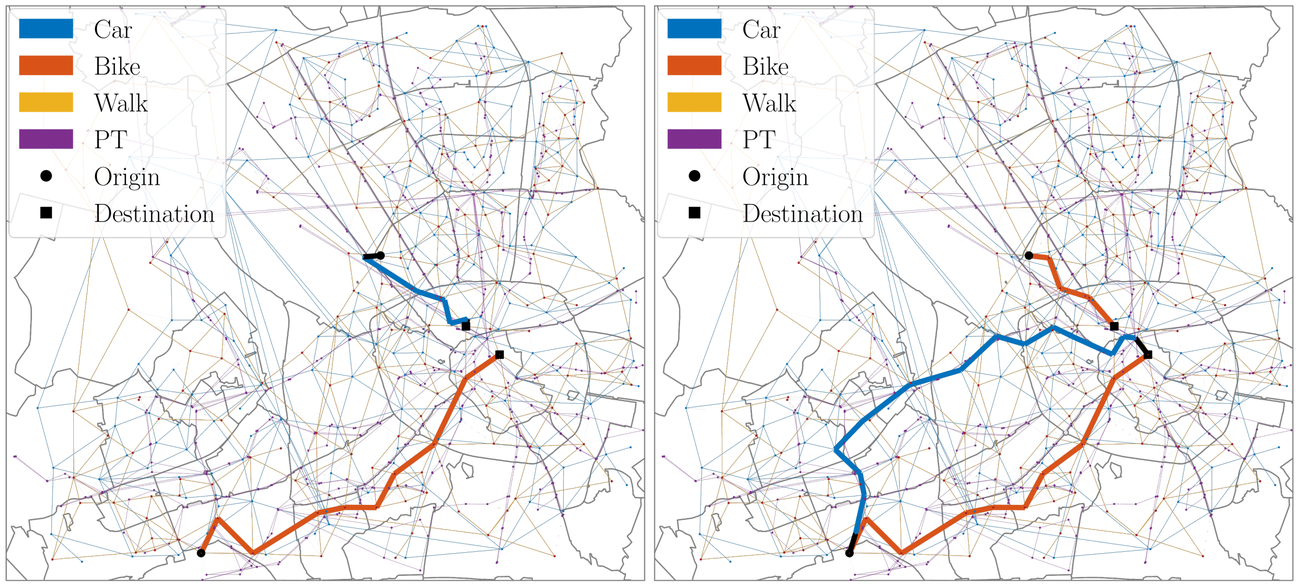




But wait, this bike-path may not be accessible...

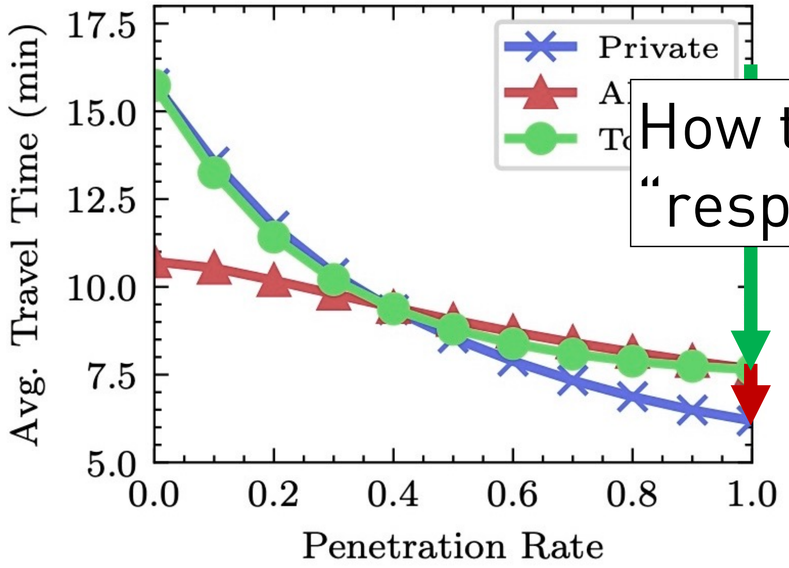
In practice, we could **realize** maximum **commute sufficiency** with **turn-taking** mechanisms...

Salazar, Betancur Giraldo, Paparella, Pedroso, "On Accessibility Fairness in Intermodal AMoD Systems", IFAC CTS, 2024
[1] Arentze, Timmermans, "A Learning-based Transportation Oriented Simulation System", TRPB, 2004
[2] Rasouli, Kim, Yang, "Albatross IV: from Single Day to Multi Time Horizon Travel Demand Forecast", TRB, 2018

Need some kind of turn taking mechanism…

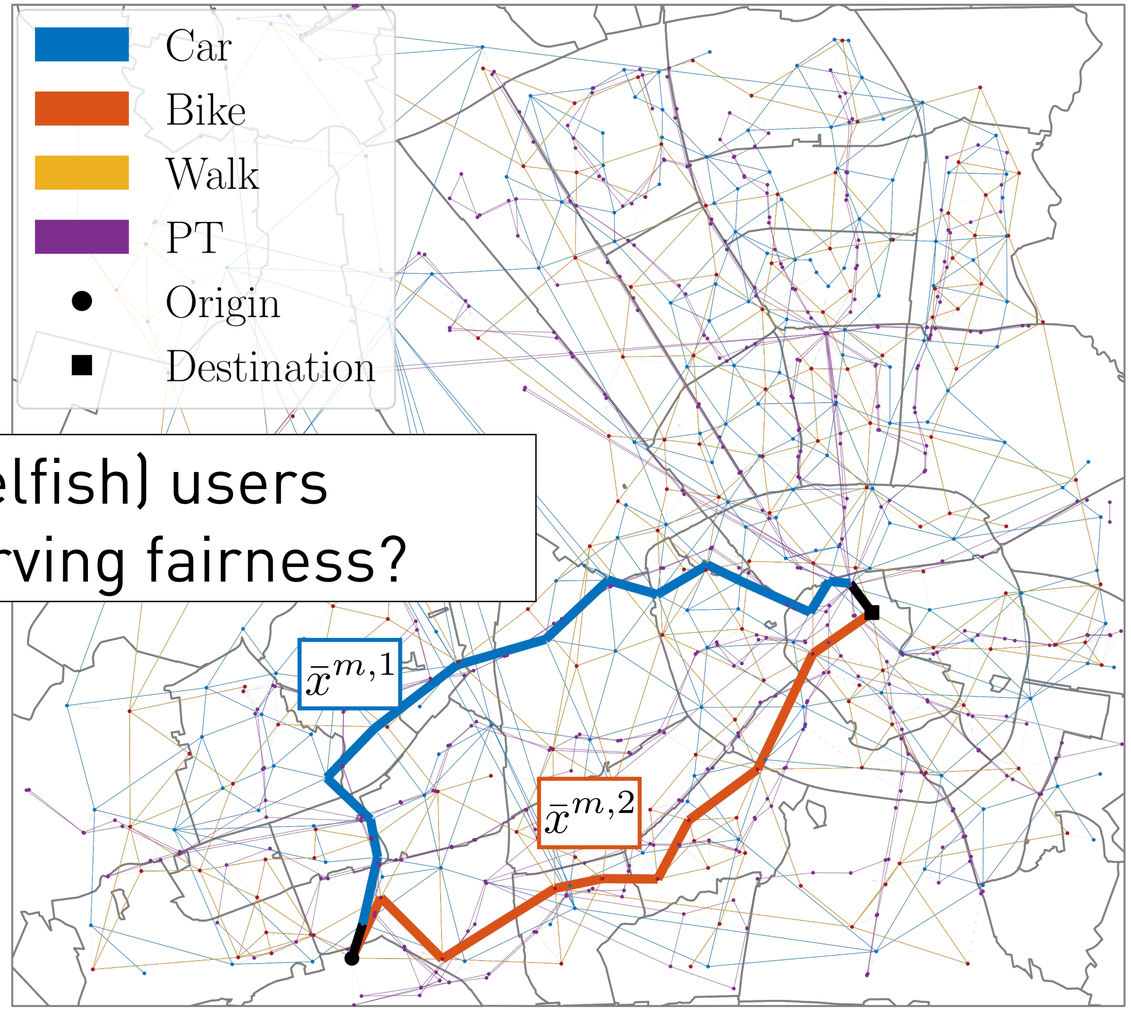
When on a rush, go **faster**
And when less on a rush go **slower**
On average achieve accessible travel time…

Wait, we had a similar problem with the previous I-AMoD problem as well!



How to ensure that (selfish) users "respect turns" preserving fairness?

Dilemma: it is better to be selfish if others are not!



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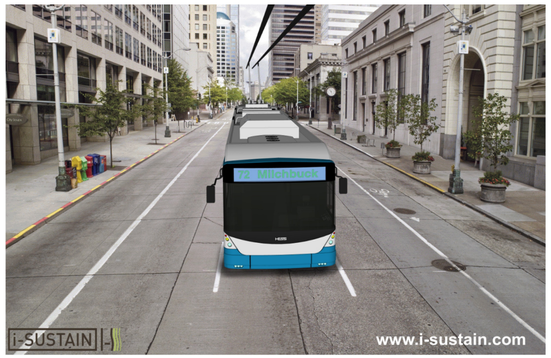
Incentive Schemes for Sustainable Mobility

=

Sacrifice?



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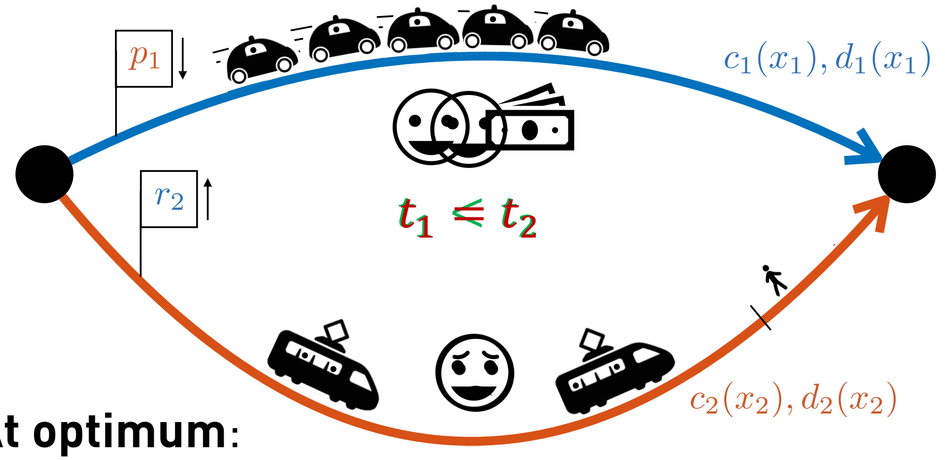


At optimum:
some users fast (arc 1) and some slow (arc 2)

So more users use arc 1, which gets congested and as slow as arc 2

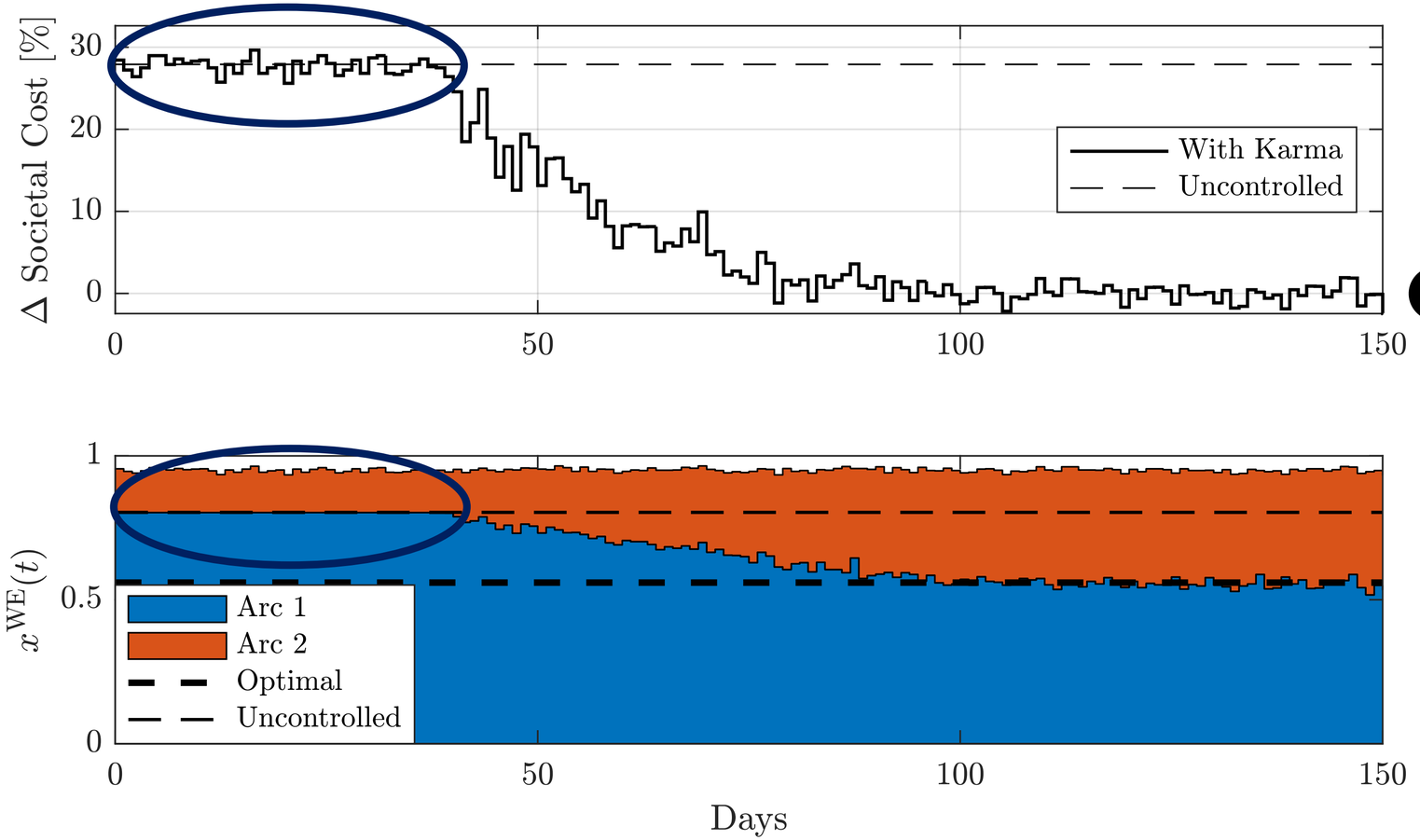
One solution: **monetary tolls** on **arc 1**
Yet they **discriminate** w.r.t. income: unfair!

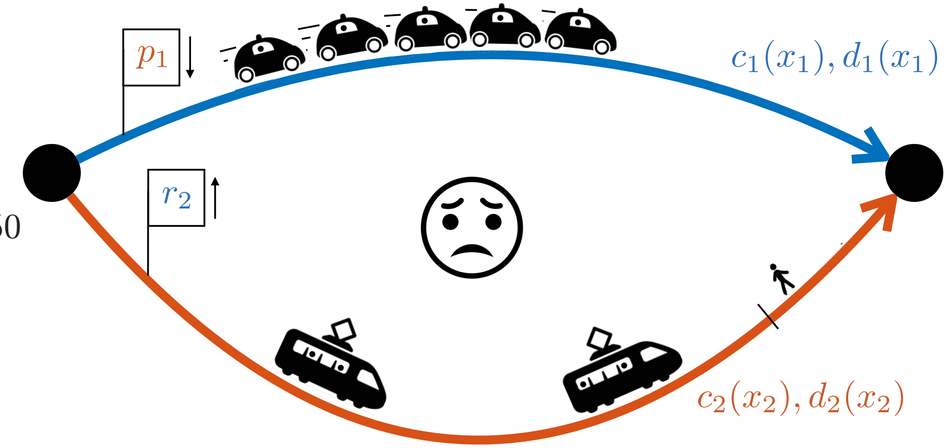
Use **artificial currencies** (points) instead:
Pay points on arc 1 and receive points on arc 2

Salazar, Paccagnan, Agazzi, Heemels, «Urgency-aware Optimal Routing in Repeated Games through Artificial Currencies», ECC, European Journal of Control, 2021

It works!

Theorem V.1: $\lim_{t\to\infty} x^{\mathrm{WE}}(t) = x^\star$





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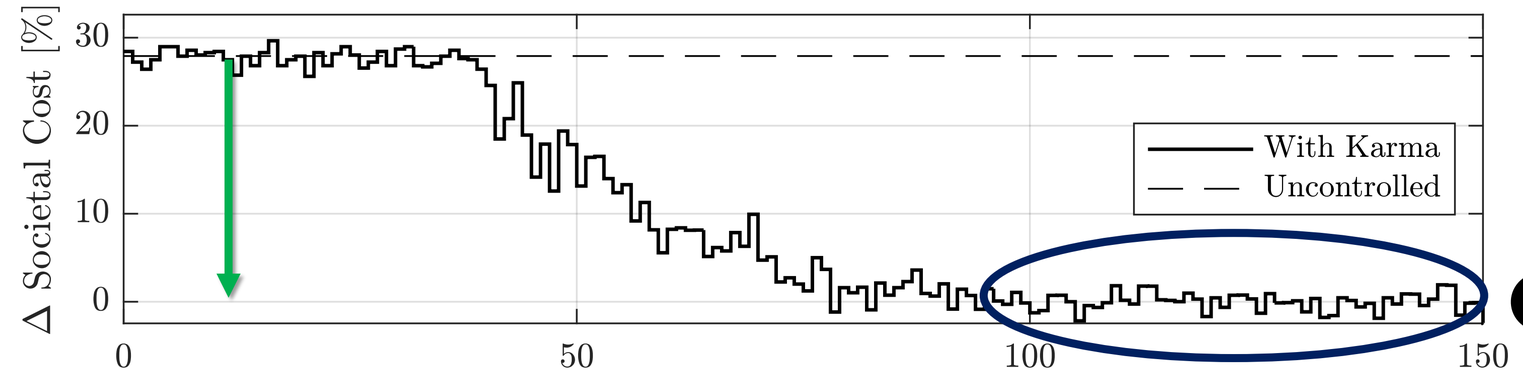
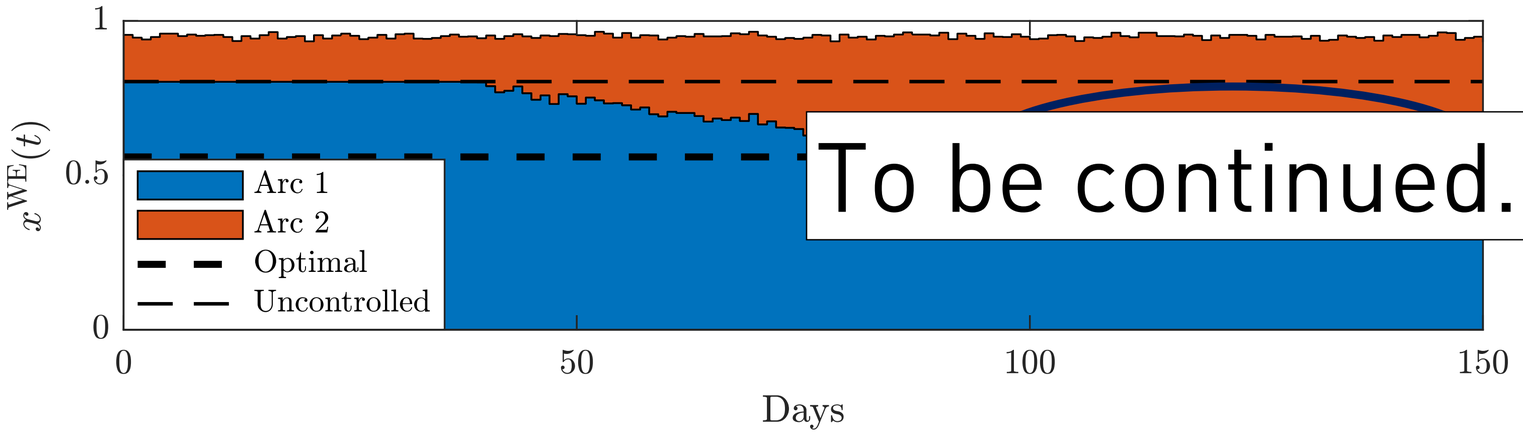
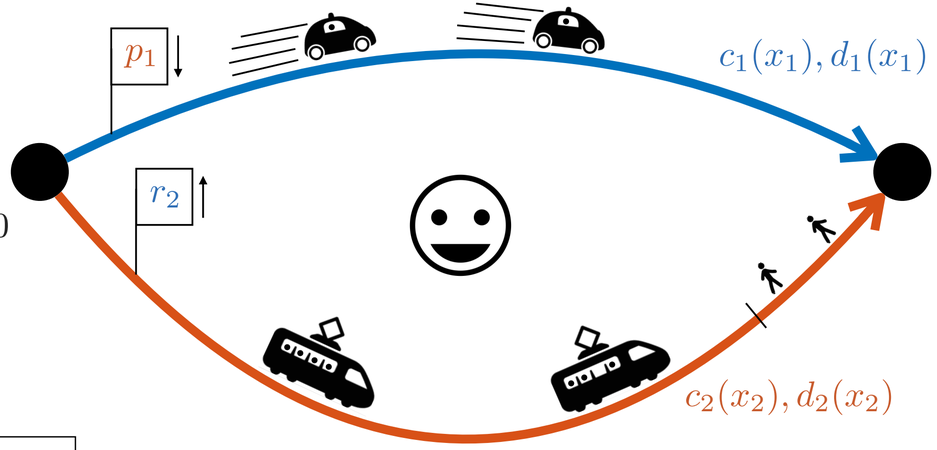




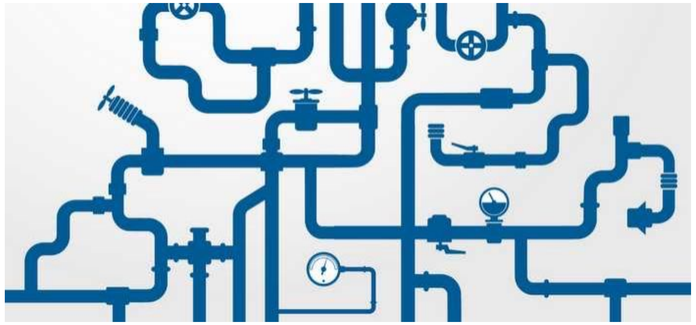
To be continued...



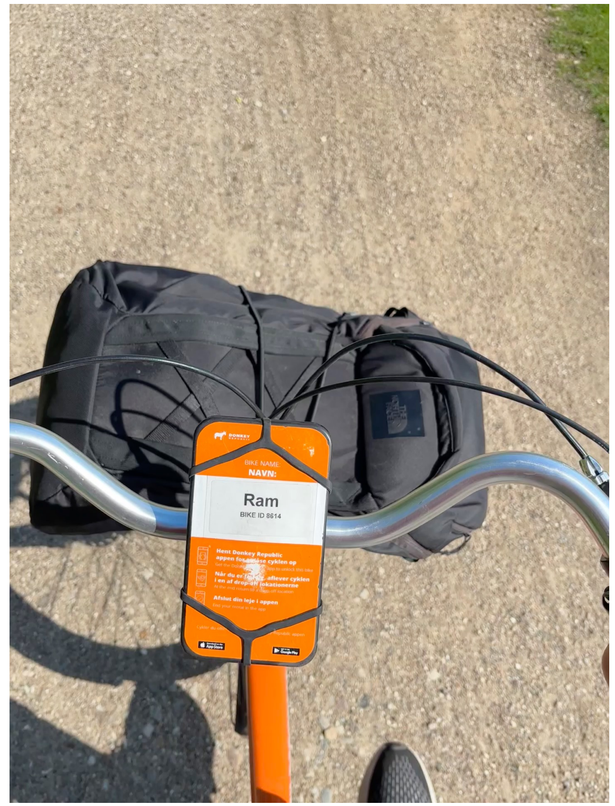
Crucially, everyone is still **free** to **choose** when to go fast and when to go slow!

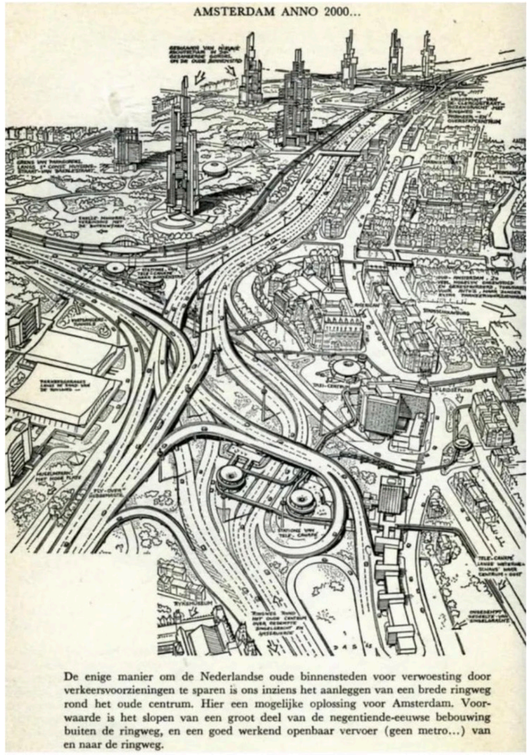
Salazar, Paccagnan, Agazzi, Heemels, «Urgency-aware Optimal Routing in Repeated Games through Artificial Currencies», ECC, European Journal of Control, 2021

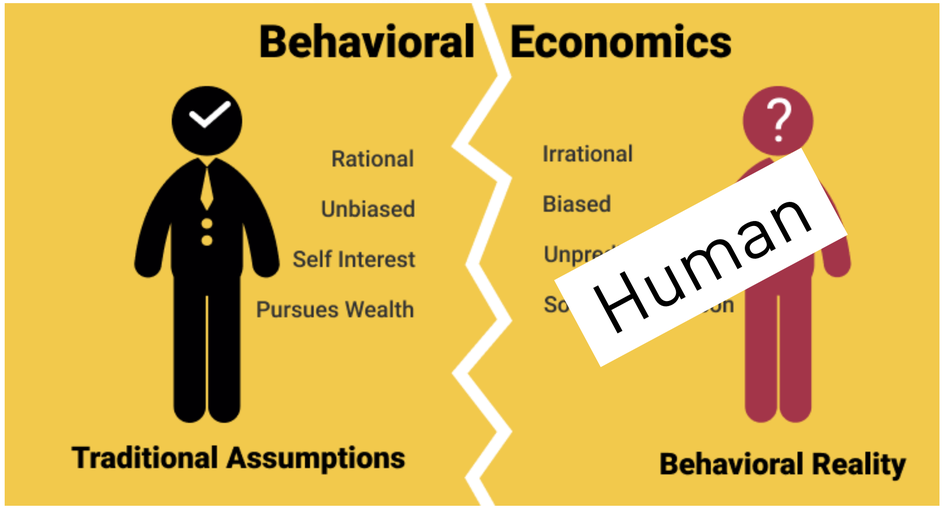
A Change of Perspective? Question the Questions?



Flows of selfish, disconnected particles to be optimized…







From technology-driven to needs-driven future?

LEARNING FROM THEIR MISTAKES

A project by @sustainableAMS & @schlijper

LEARNING FROM THEIR MISTAKES

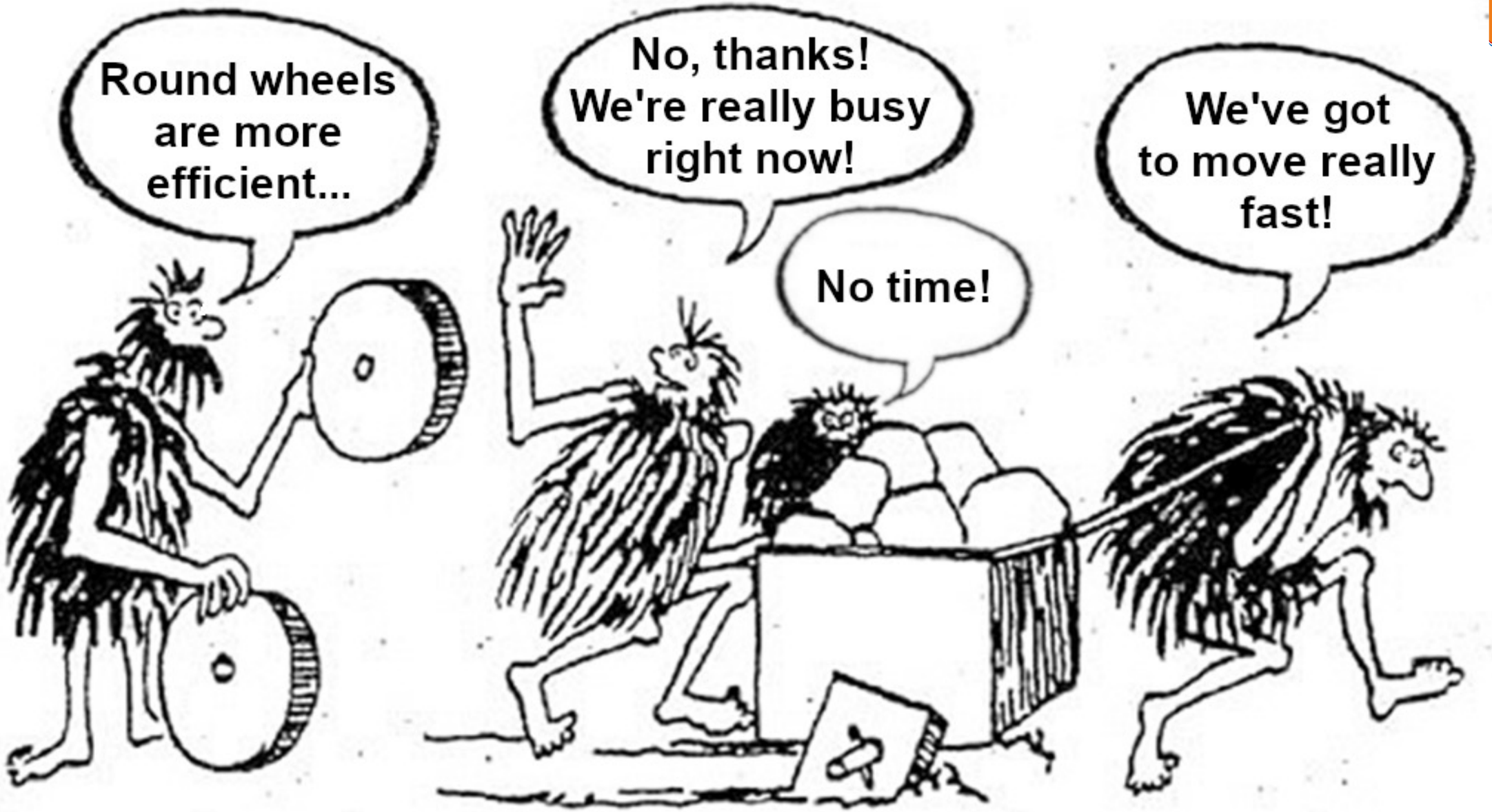
Dutch Cycling Embassy

Dutch Cycling Embassy

Dutch Cycling Embassy
Credits Chris Bruntlett


DUTCH
CYCLING
EMBASSY
Dutch Cycling Embassy


PELOTON


Round wheels are more efficient...
No, thanks! We're really busy right now!
No time!
We've got to move really fast!

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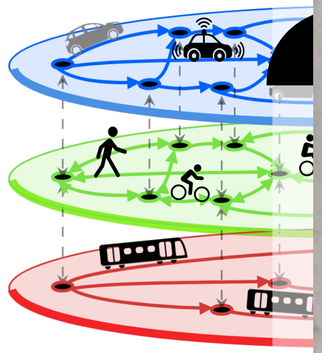

Acknowledgements: colleagues and students, and sponsors

"Before being engineers, you are first and foremost humans"

us as a **visitor**!

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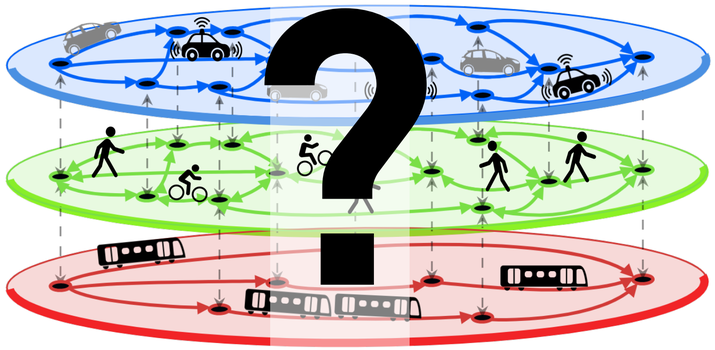
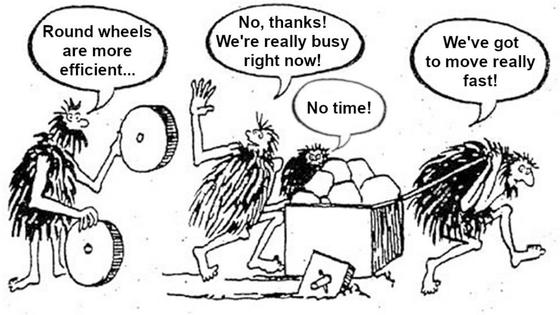


SCAN ME



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