Post-Wardropian Urban Mobility Games with Connected Autonomous Vehicles

findings and outlook for future

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Playing Urban Mobility Games With Autonomous Vehicles

Agenda

- Autonomous Vehicles AD 2026
  Waymo and others
- Research Gap
  What are we missing?
- Methodology
  How to look into the future?
- Findings
  What we found?
- Insights
  What's next?

machine-dominated dystopia

or

synergy of human-machine COeXISTENCE

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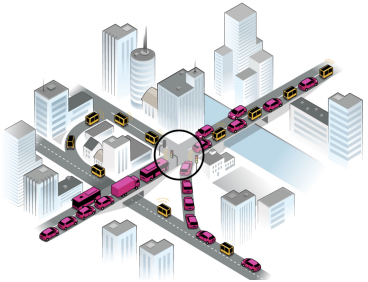
Autonomous Vehicles AD 2026 - where we are?

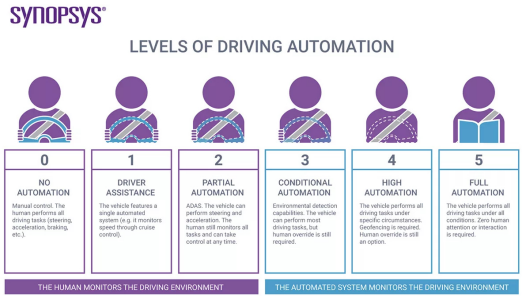


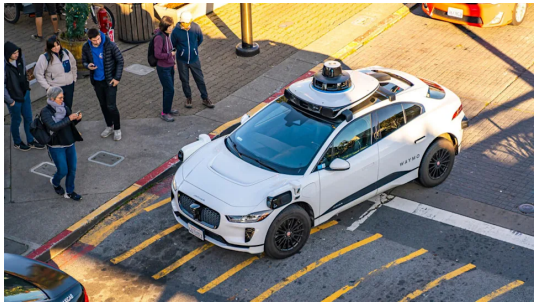
Connected autonomous vehicles

CAVs

Autonomous car

a car that is capable of travelling without human input





Autonomous Vehicles

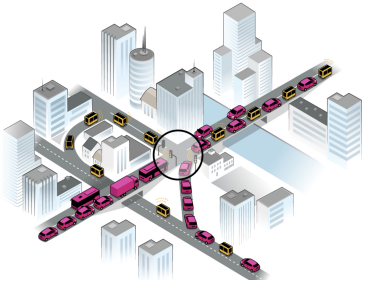
AD 2026

Summary: Unprecendented progress in AV capabilities, operations, safety, and reliability.

The Analogy: We are currently teaching the machine how to walk (avoiding obstacles, following rules).

The Success: You can be driven.

Research Gap



CAV

decision maker

Autonomy

Now the focus is on making them capable to drive

but the challenge is even bigger beyond that

Decisions

Now CAVs are 3yo kids and we teach them how to walk and not to get lost. The real problems come when they are teenagers and they start making decisions

The Research Gap

Gap

What will be the impact of collective actions of **Autonomous Vehicles** on the:

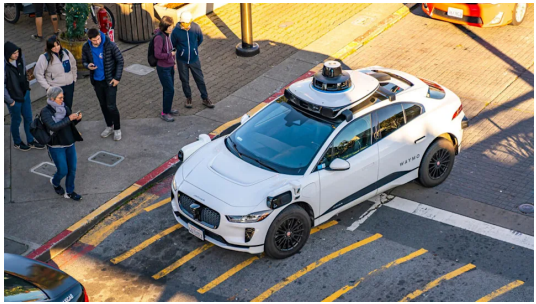
1. individuals
2. transport systems
3. cities
4. extrnal (environment, equity, accesibility).

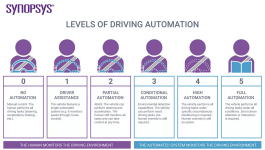
Advantages

not digital-twins

Machines (unlike humans):

- are designed to behave optimally, i.e. use all the data and computational power to make optimal decisions;
- can collaborate, i.e. share information and cooperatively reach synergy;
- may understand human behaviour: predict it and anticipate our decisions;
- are automated and thus controllable by design;





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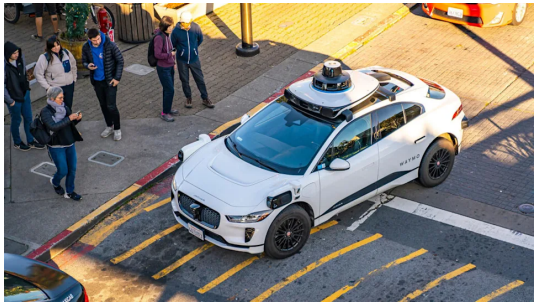

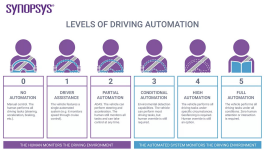

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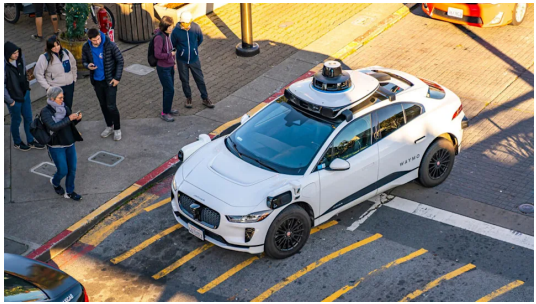

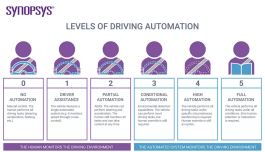

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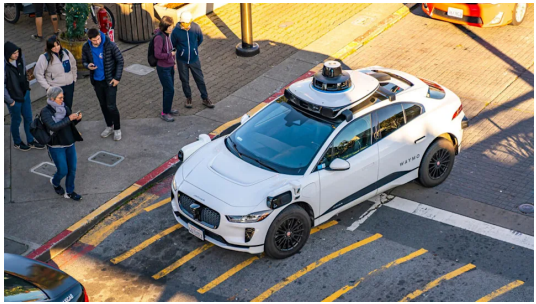
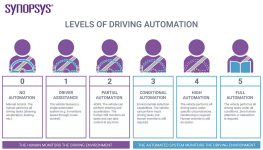
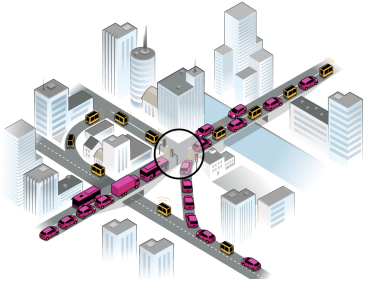


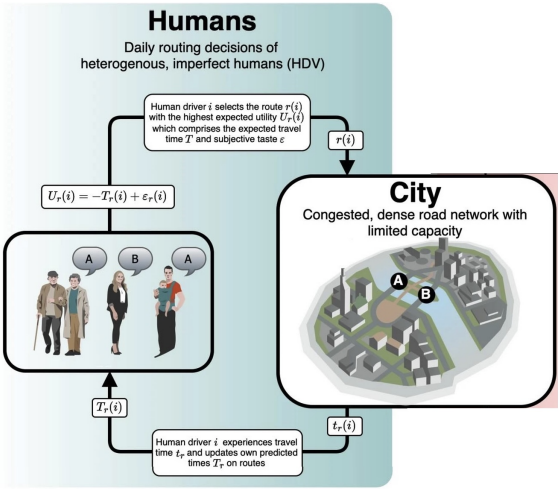


Methodology



The Urban Routing Game

Day-to-day repeated route-choice problem aka morning rush hour



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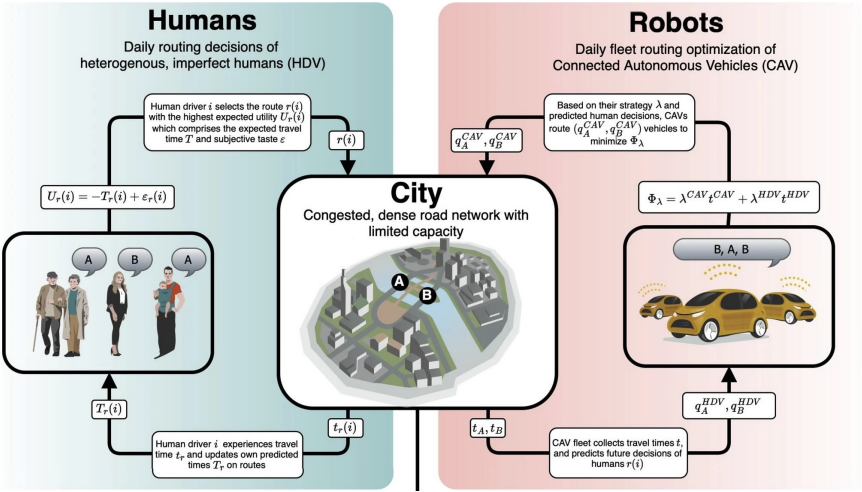


The COeXISTENCE Framework

We create a multi-agent virtual environment to simulate the daily-repeated Urban Routing Game on limited resource (capacity) between:

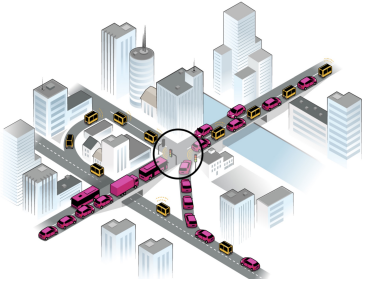
Human Drivers (HDVs): choosing subjectively optimal route for themselves based on experience ($\sim$ Nash Equilibrium).

Machine Fleets (CAVs): Can follow any strategy, from purely selfish to collectively optimized.

Tools used:

- Transportation Science (Traffic Assingment, Traffic Flow Models)
- Game Theory (Nash vs. System Optimum).
- Machine Learning (Reinforcement Learning (RL) for fleet routing)
- Agent-Based Modelling (Large-scale urban network simulations).
- Assessment (Equity, Welfare, Efficiency, Sustainability, Inclusiveness).

Findings



Team

credits

Big thanks to the team:

- Onur Akman
- Anastasia Psarou
- Grzegorz Jamroz
- Michał Hoffman
- Zoltan Varga
- Pawel Gora
- Łukasz Gorczyca
- Michal Bujak
- Sylwia Polak
- ...

General

alarming

Studying the simplest two-route bottleneck macroscopic network, we discover[1] that:

- The choices of CAVs that replace a given share of HDVs differ significantly from the choices of the remaining HDVs.
- In different scenarios the average travel time of both HDVs and CAVs may increase or decrease.
- If the fleet of CAVs applies the selfish strategy, it may improve its collective travel time at a cost to human drivers when the share of CAVs is small.

[1] Jamróz, G., Akman, A. O., Psarou, A., Varga, Z. G. & Kucharski, R. Social implications of coexistence of CAVs and human drivers in the context of route choice. *Scientific Reports* **15,** 6768 (2025).

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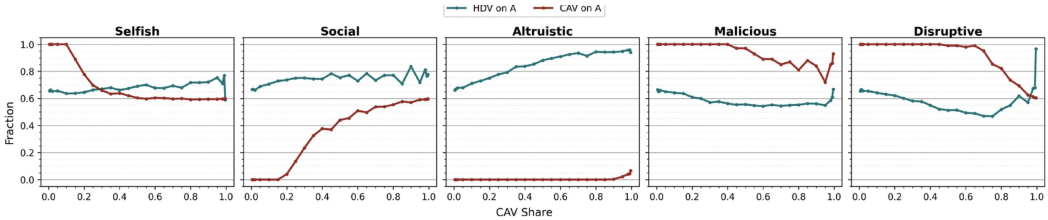
Different choices

Studying the simplest of the two-route bottleneck macroscopic network, we discover[2] that

The choices of CAVs (blue-ish) that replace a given share of HDVs (brown-ish) differ significantly from the choices of the remaining HDVs.

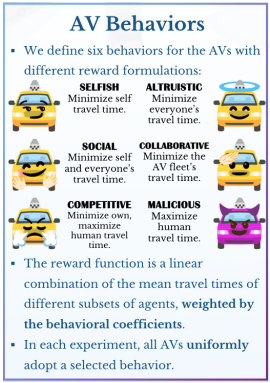


it depends on the market share (x-axis) and the strategy (panels).

[2] Jamróz, G., Akman, A. O., Psarou, A., Varga, Z. G. & Kucharski, R. Social implications of coexistence of CAVs and human drivers in the context of route choice. *Scientific Reports* **15,** 6768 (2025).

Fleet strategy controls the overall system performance

alarming[3]



Defining the objective of fleet operations (presumably different from human behaviour) drivers the system performance.

- Humans:

$$U_i \approx \gamma^i \, t_i + \varepsilon$$

- Machines:

$$U_i = \gamma^i \, t_i + \gamma^{\text{CAV}} \, T_F + \gamma^{\text{HDV}} \, T_{\text{HDV}}$$

[3] Akman, A. O., Psarou, A., Varga, Z. G., Jamróz, G. & Kucharski, R. Impact of collective behaviors of autonomous vehicles on urban traffic dynamics: A multi-agent reinforcement learning approach. *arXiv preprint arXiv:2509.22216* (2025).

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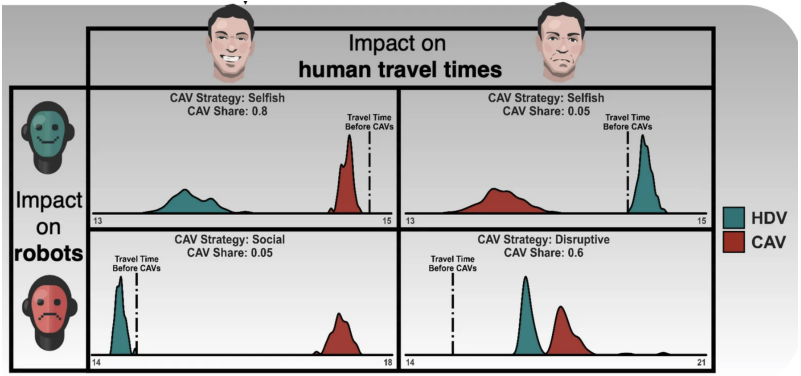
alarming

In different scenarios the average travel time of both HDVs and CAVs may increase or decrease[4].



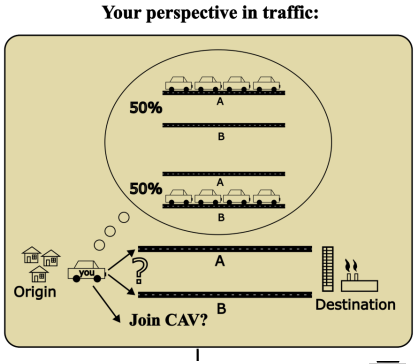
[4] Jamróz, G., Akman, A. O., Psarou, A., Varga, Z. G. & Kucharski, R. Social implications of coexistence of CAVs and human drivers in the context of route choice. *Scientific Reports* **15,** 6768 (2025).

Disequilibrating is a good strategy to maximise fleet market share

alarming

What to expect from a capitalist, big-tech players?[5]

- A fleet operator seeking market share may benefit from controlled chaos.
- **Travel-time oscillations** can be predictable for the operator, but not for humans.
- Frustration can push drivers to switch to the fleet.
- Presumably amplified when multiple fleets compete aggressively.



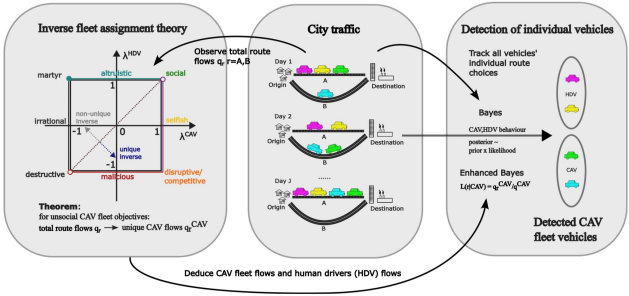
[5] Jamróz, G., Kucharski, R. & Watling, D. Market share maximizing strategies of CAV fleet operators may cause chaos in our cities. *arXiv preprint arXiv:2512.03524* (2025).

Unsocial fleet behaviours can be detected.

promising

- Can we infer **fleet flows** on routes given totals + fleet size/behaviour?
- Can we **identify fleet vehicles** from repeated route-choice observations?

Finding: detection/identification is feasible for antisocial fleet objectives[6].

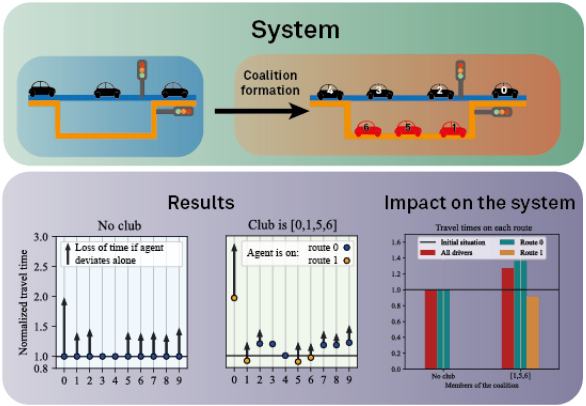


[6] Jamróz, G. & Kucharski, R. Detection of coordinated fleet vehicles in route choice urban games. Part I. Inverse fleet assignment theory. *arXiv preprint arXiv:2506.22966* (2025).

CAVs may form exclusive clubs

alarming[7]

- CAVs can break away from Nash equilibrium by coordinating as a coalition.
- Coalitions reduce their travel times.
- With limited road capacity, faster arrivals for the coalition come at the expense of others.
- Coalitions remain efficient only up to a size ⇒ exclusive clubs.
- CAV elite? Premium users of public space?



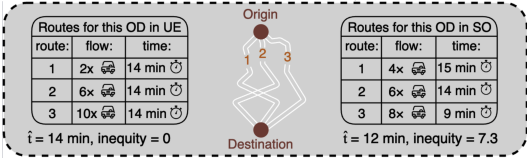
[7] Kucharski, R., Psarou, A. & Descormier, N. Equilibria in routing games with connected autonomous vehicles will not be strong, as exclusive clubs may form. *arXiv preprint arXiv:2510.12862* (2025).

Traffic can be both optimal and fair with CAVs

promising

We may break the long term dychotomy between Optimality and Fairness (Nash Equilibrium)[8]

- With compliant CAV routing, **system-optimal** assignment becomes attainable.
- System optimum is **unfair**.
- Wardrop Cyclical Equilibrium via day-to-day cycles.
- Cycles **equalize average travel times** across travelers (fairness) while keeping **daily path flows optimal** (efficiency).
- In Barcelona 670 vehicle-hours of Price-of-Anarchy are eliminated daily



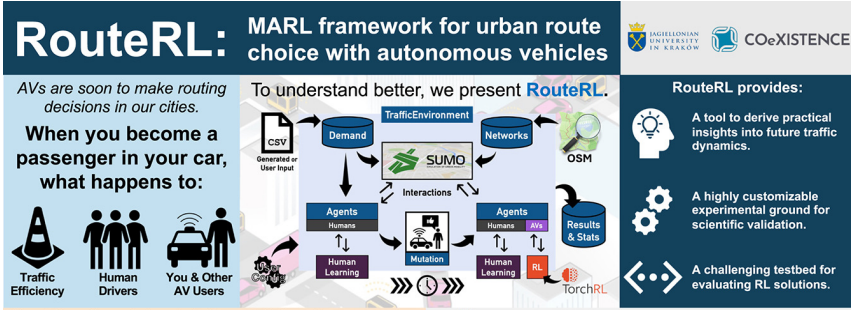
[8] Hoffmann, M., Bujak, M., Jamróz, G. & Kucharski, R. Wardropian Cycles make traffic assignment both optimal and fair by eliminating price-of-anarchy with Cyclical User Equilibrium for compliant connected autonomous vehicles. *arXiv preprint arXiv:2507.19675* (2025).

How to include state of the art Machine Learning in the loop?

tool

```
pip install routerl
```

RouteRL: MARL framework for urban route choice with autonomous vehicles



Ahmet Onur Akman*, Anastasia Psarou*, Łukasz Gorczyca, Zoltán György Varga, Grzegorz Jamróz, Rafał Kucharski

This research is financed by the European Union within the Horizon Europe Framework Programme, ERC Starting Grant number 101075838: COeXISTENCE.

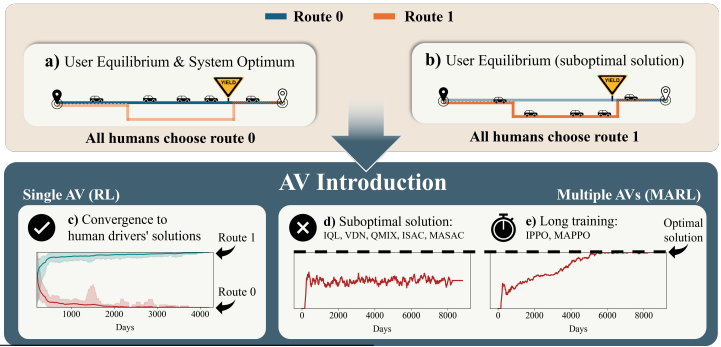
9

[9] Akman, A. O., Psarou, A., Gorczyca, Ł., Varga, Z. G., Jamróz, G. & Kucharski, R. RouteRL: Multi-agent reinforcement learning framework for urban route choice with autonomous vehicles. *SoftwareX* **31**, 102279. ISSN: 2352-7110. doi:https://doi.org/10.1016/j.softx.2025.102279 (2025).

State-of-the-art RL algorithms fail even on trivial routing tasks.

alarming

Reinforcement Learning seems to be best suited for this task, naturally fitting candidate for this repeated (episodes), non-differentiable, non-stationary problem[10].
(which already won in GO, Starcraft and breakthourgh in AlfaFold).



Reinforcement Learning

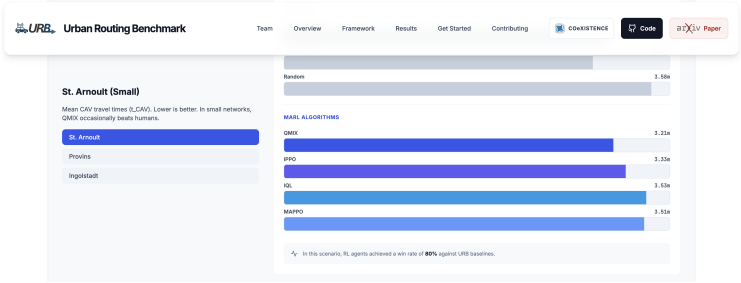
Even in a trivial setting(e.g., two routes, small fleet), only few state-of-the-art RL methods reach optimal routing reliably.

[10] Psarou, A., Kucharski, R. *i in.* Autonomous vehicles need social awareness to find optima in multi-agent reinforcement learning routing games. *AAMAS 2026, short paper* (2026).

The ML community shall compete to develop efficient algorithms

tool/benchmark www.urbenchmark.com

- URB (Urban Routing Benchmark)[11] for fleet routing with MARL. With: multiple real-world networks + demand, predefined tasks, baselines, metrics.
- Goal: **standardize evaluation** and build a **leaderboard** for progress.
- In future: Monitor and verify algorithms used by fleets (?)



[11] Akman, A. O., Psarou, A., Hoffmann, M., Gorczyca, Ł., Kowalski, Ł., Gora, P., Jamróz, G. & Kucharski, R. URB - Urban Routing Benchmark for RL-equipped Connected Autonomous Vehicles. *NeurIPS 2025*. eprint: https://doi.org/10.48550/arXiv.2505.17734 (2025).

It is better to be a good socially aware CAV than selfish

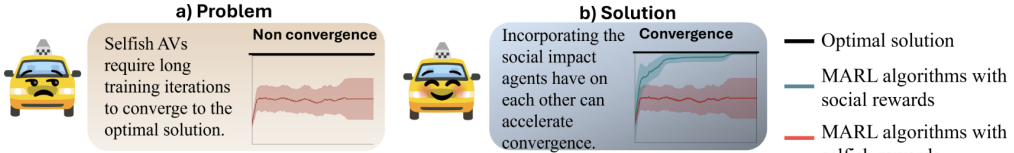
promising

Let's make CAVs care also for others:

- Adding social awareness in rewards (e.g., marginal-cost-based imact on the system) can improve learning[12].

$$\frac{\partial T'}{\partial a_i}$$

- Effect: **reduced training time** and more reliable convergence.
- Impact: can benefit both system-wide performance and individual agents.



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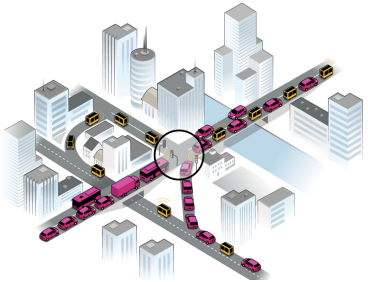
Conclusion



COeXISTENCE

framework to discover how machine intelligence may take-over our urban mobility and how to avoid it

URBAN MOBILITY = **SUPPLY** + **DEMAND** + **INTELLIGENT MACHINES**

sustainability
efficiency

infrastructure

people

COeXISTENCE

anticipate
demonstrate
resolve

paradigm shift in urban mobility

Insights

Things can always get worse

- Delegating strategic decisions to CAVs (effectively to big-tech) will have consequences.
- It may change our cities.
- Making them better or worse.
- . . . inclusive or exclusive.
- Harsh battlefield with *winner takes it all* competition (remember Uber?)

Call for action

We need to report this, understand, simulate, demonstrate and get ready before it comes.

The policymakers shall look ahead and prepare our public spaces into what's coming.
Society needs to participate, before exploited.

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- Delegating strategic decisions to CAVs (effectively to big-tech) will have consequences.
- It may change our cities.
- Making them better or worse.
- . . . inclusive or exclusive.
- Harsh battlefield with *winner takes it all* competition (remember Uber?)

Call for action

We need to report this, understand, simulate, demonstrate and get ready before it comes.

The policymakers shall look ahead and prepare our public spaces into what's coming.
Society needs to participate, before exploited.

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COeXISTENCE

Future of cities with autonomous vehicles.

Thank you for your attention,

welcome to discuss

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STOP WAR