Game Theory to Study Interactions between Mobility Stakeholders

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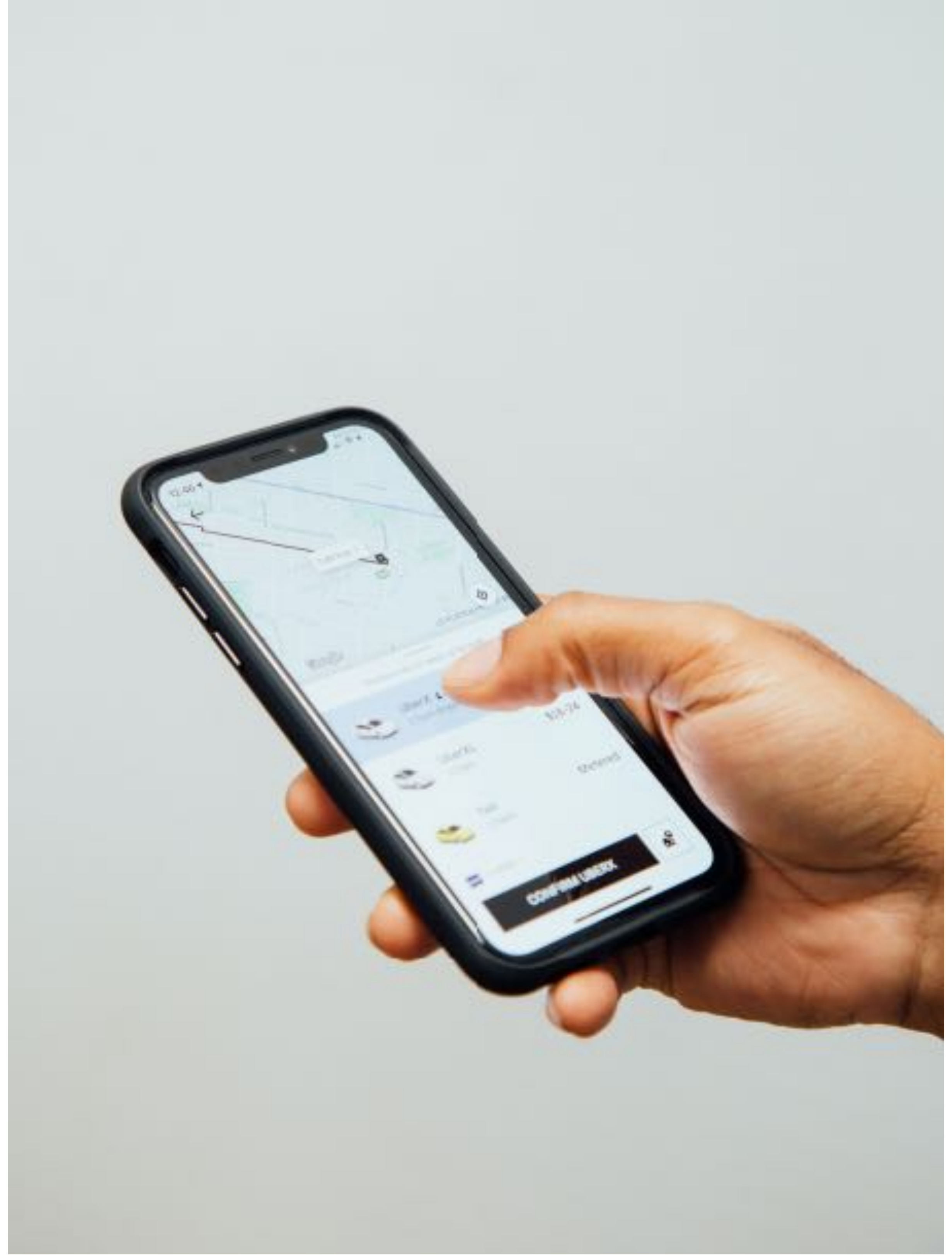
Mobility systems are under pressure



Travel demand is increasing and **travel needs** are changing

55% of the population resides in cities. By 2050, the proportion is expected to reach 68%

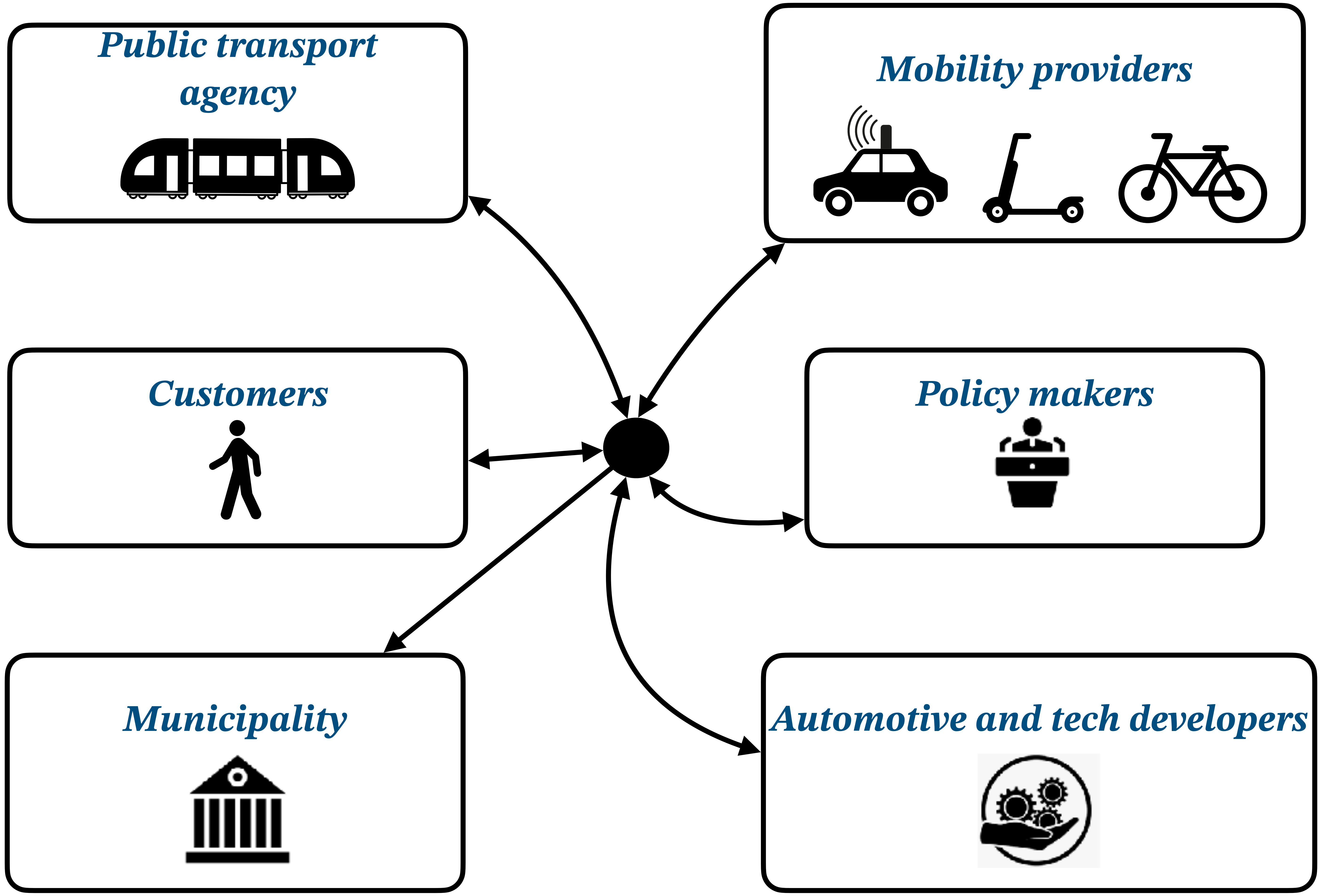
The rise of private **mobility service providers** exploiting **public resources** entangles current **regulation schemes**

Ride-hailing has increased by 1,000% in NYC from 2012 to 2019

Transportation systems need to meet global **sustainability goals**

Cities are responsible for 60% of greenhouse emissions, 30% of which produced by transportation (in US)

Mobility systems are very complex socio-technical systems



Takeaways for the talk

- **Takeaways** of this talk**:**
  - We provide a **formal** way to model **interactions** between stakeholders of the **mobility ecosystem**
  - We show how one can **formulate and solve** a **sequential game** involving **heterogeneous decision domains**
  - The proposed approach is very **flexible** and can be adapted to **multiple scenarios**
  - We **instantiate** the proposed techniques in the **real world case study of Berlin**
  - Our framework can produce **actionable information** and can **assist** stakeholders in **decision processes**

Public sector view

Questions

How to meet sustainability goals while accommodating urbanization?

How to define public investments for the next 50 years ?

How to guarantee quality of life?

How to handle private companies which exploit public resources?

Tools

Policies and regulations

Public transit pricing

Incentive and taxation systems

Private sector view

Questions

Larger demands: which new business models?

How to react to government rules?

What do the customers want?

In which technology should we invest?

Tools

Pricing

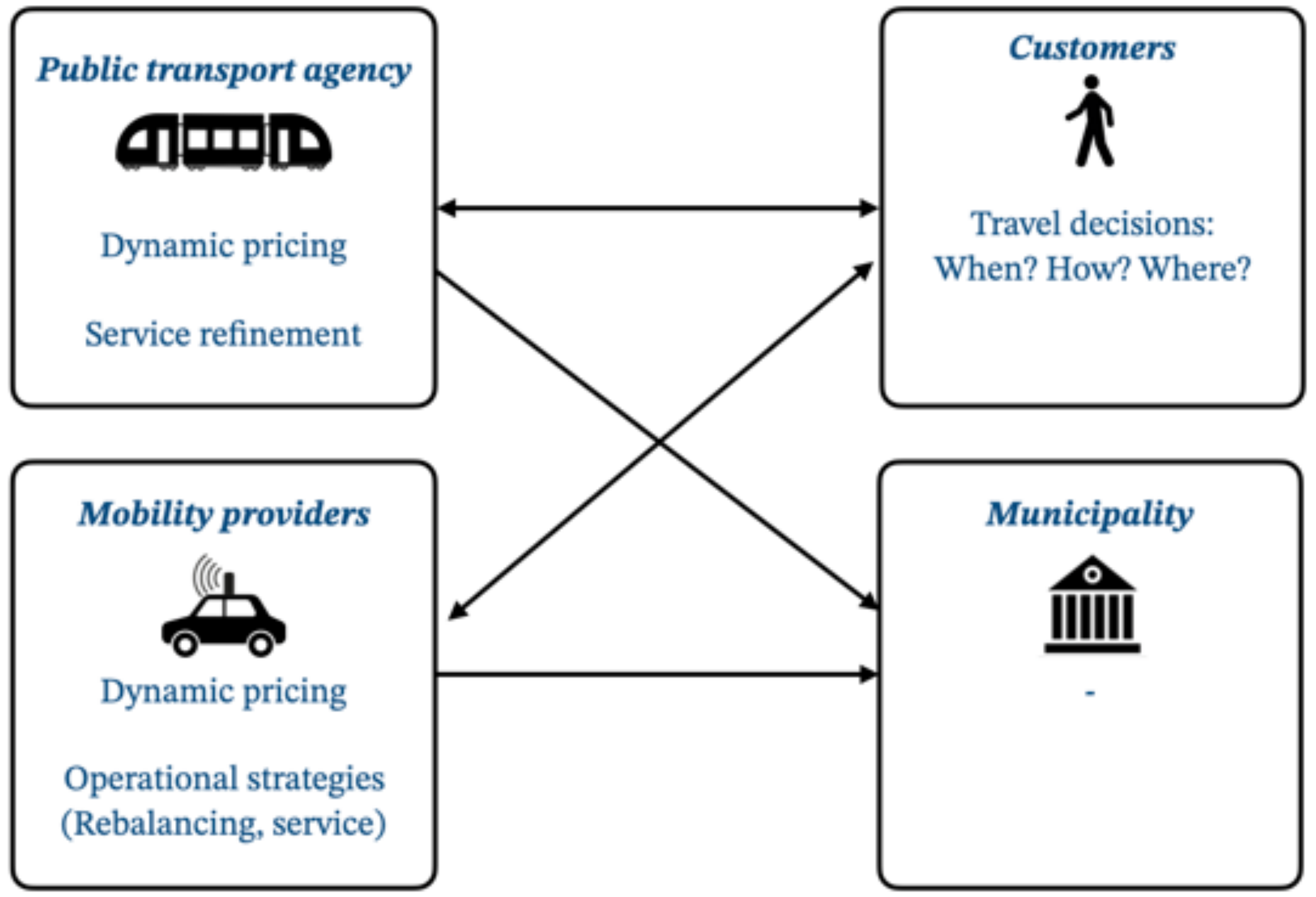
Service design

Fleet sizes

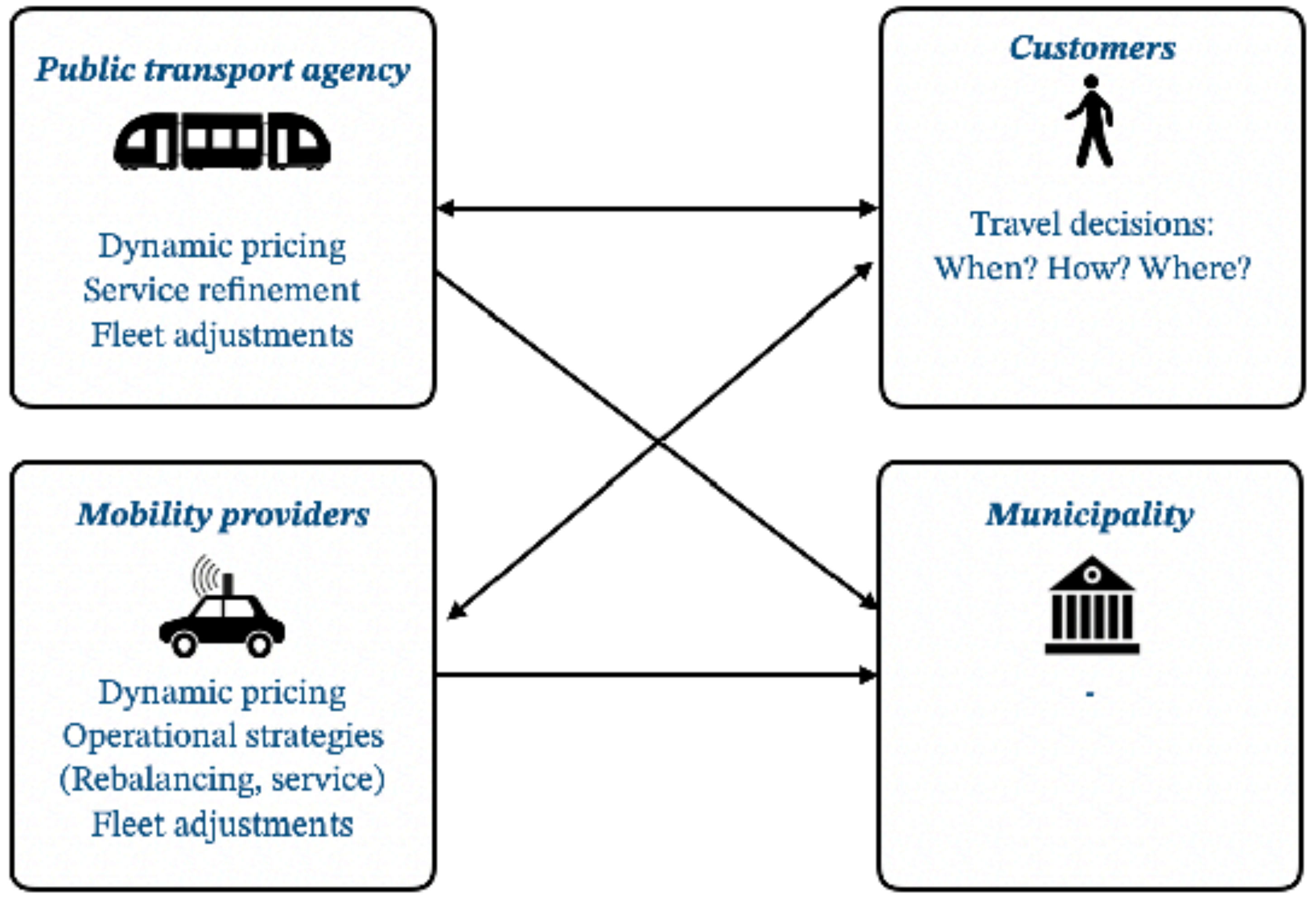
Fleet compositions

Interactions between stakeholders are characterized by different time horizons

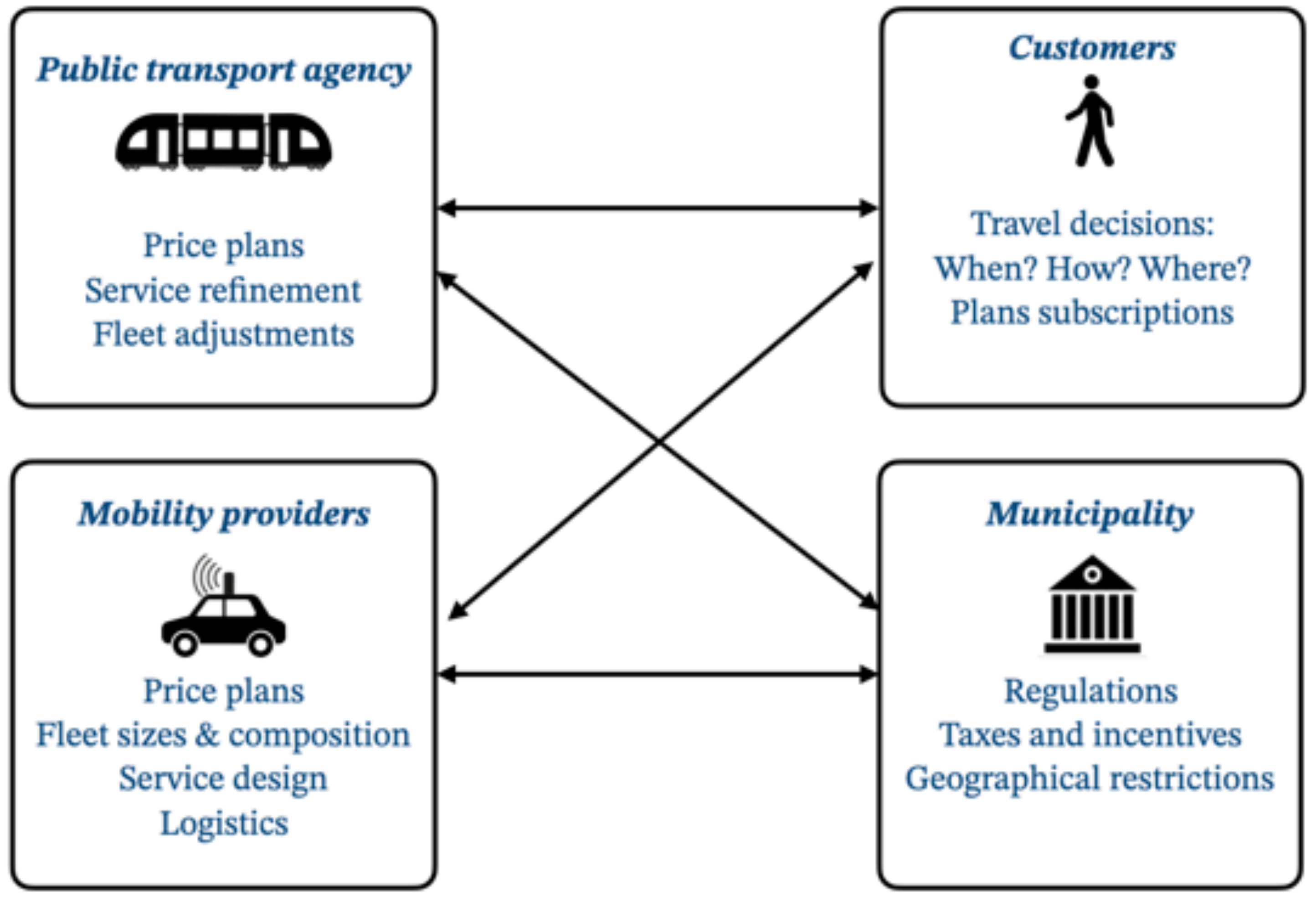
Daily



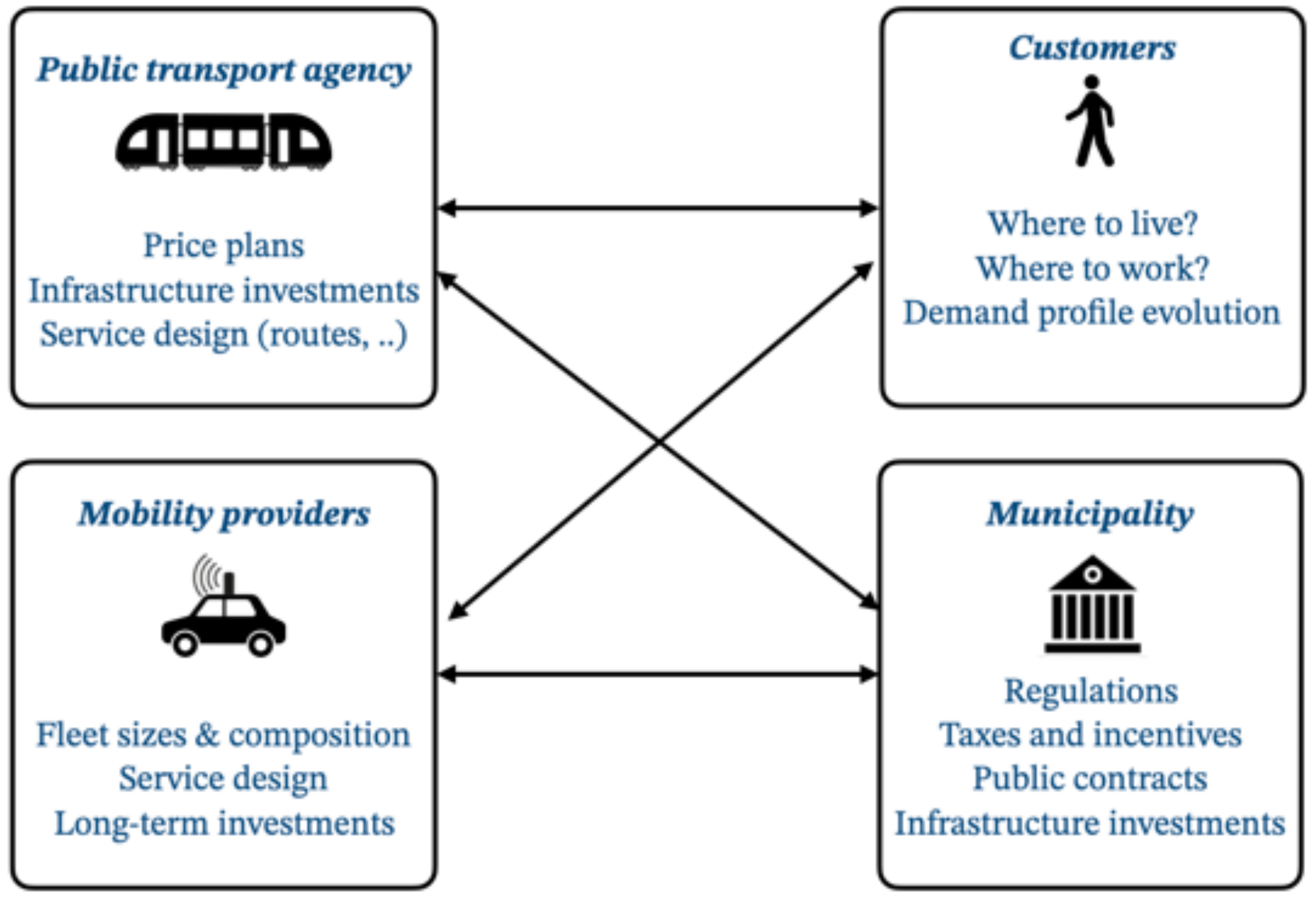
Monthly



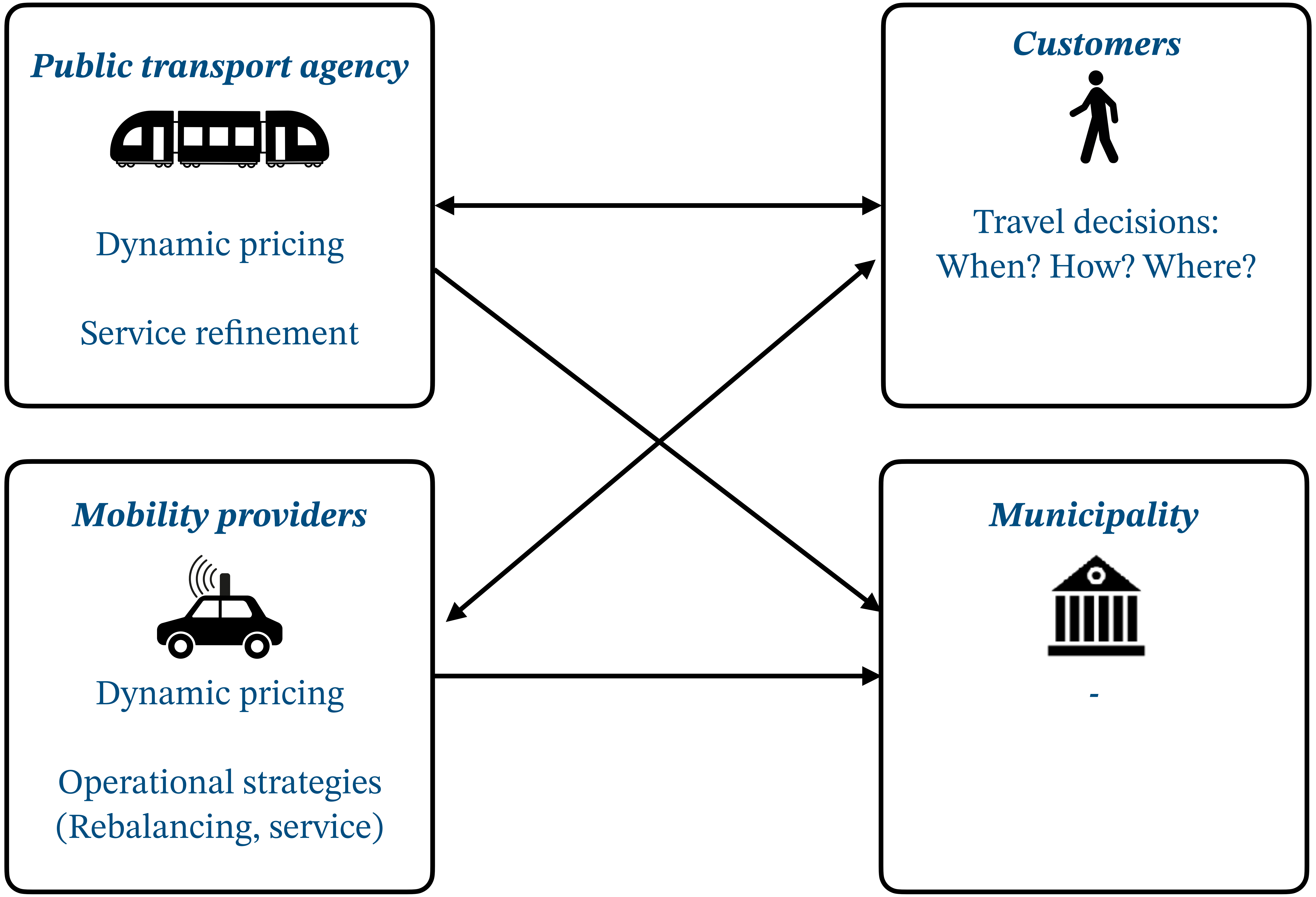
Yearly



Every five years

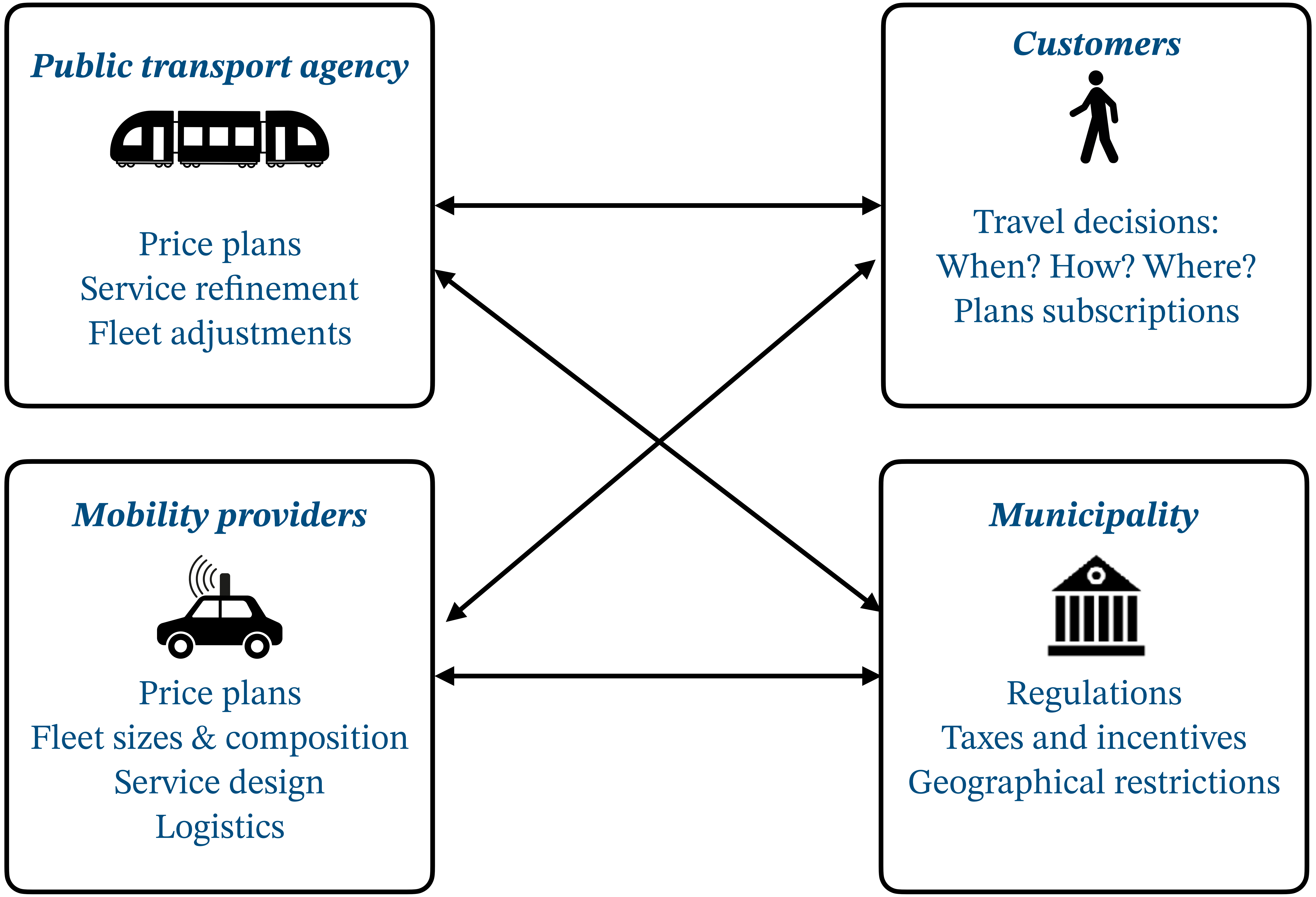


Interactions happening on a daily basis

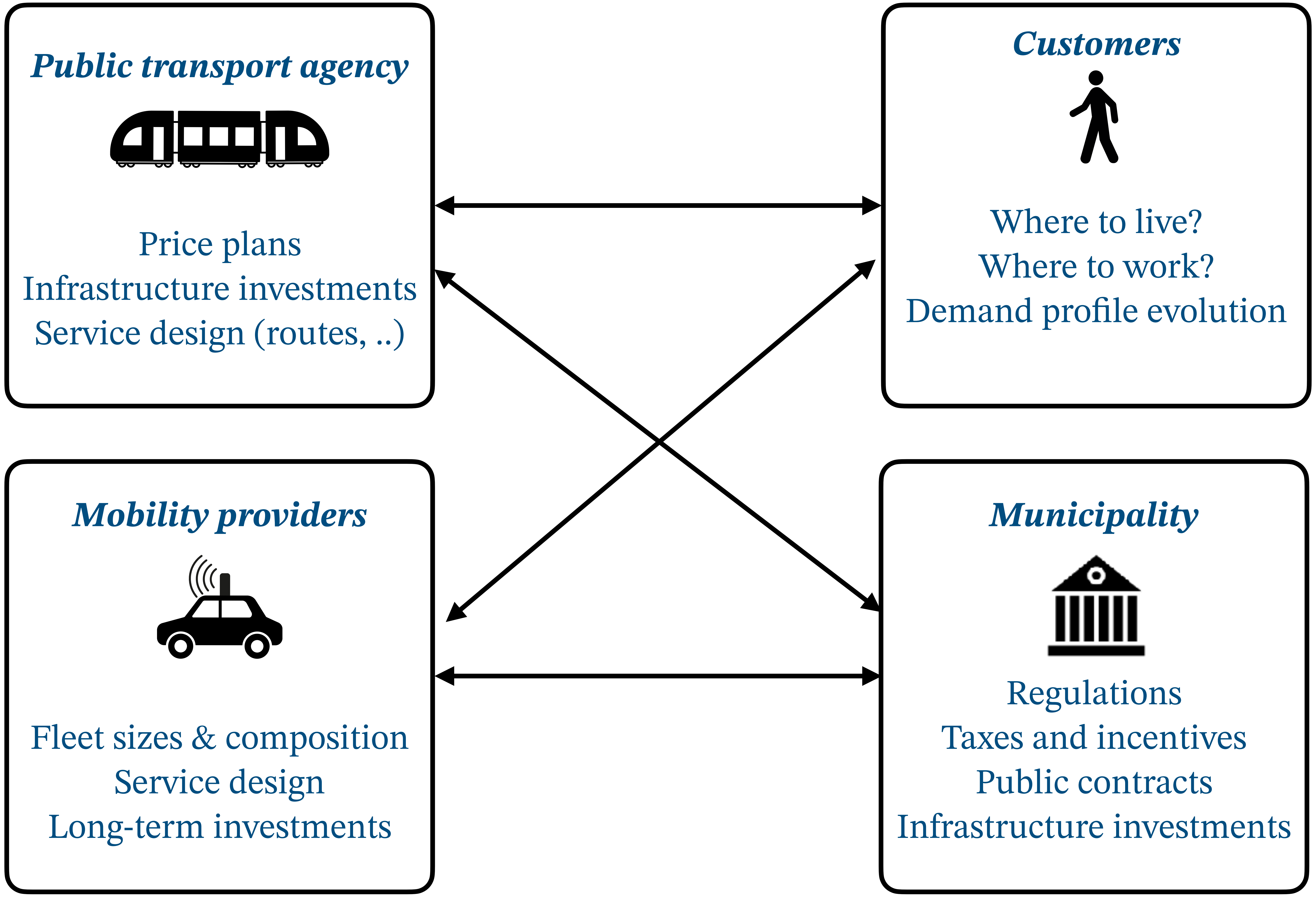



Interactions happening on a monthly basis
Public transport agency
Dynamic pricing
Service refinement
Fleet adjustments
Customers
Travel decisions:
When? How? Where?
Mobility providers
Dynamic pricing
Operational strategies
(Rebalancing, service)
Fleet adjustments
Municipality
-

Interactions happening on a yearly basis

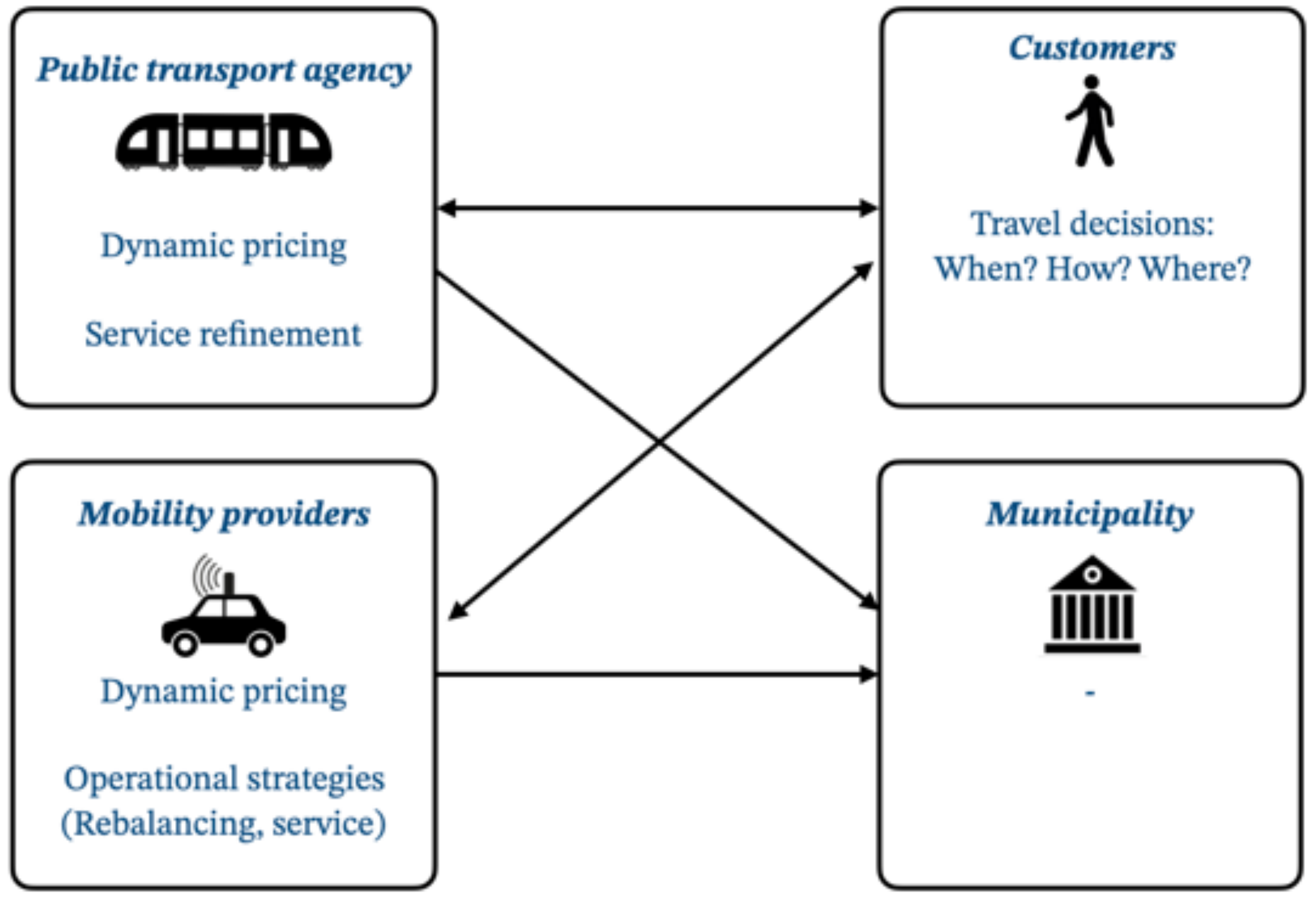


Interactions happening on a 5-years basis

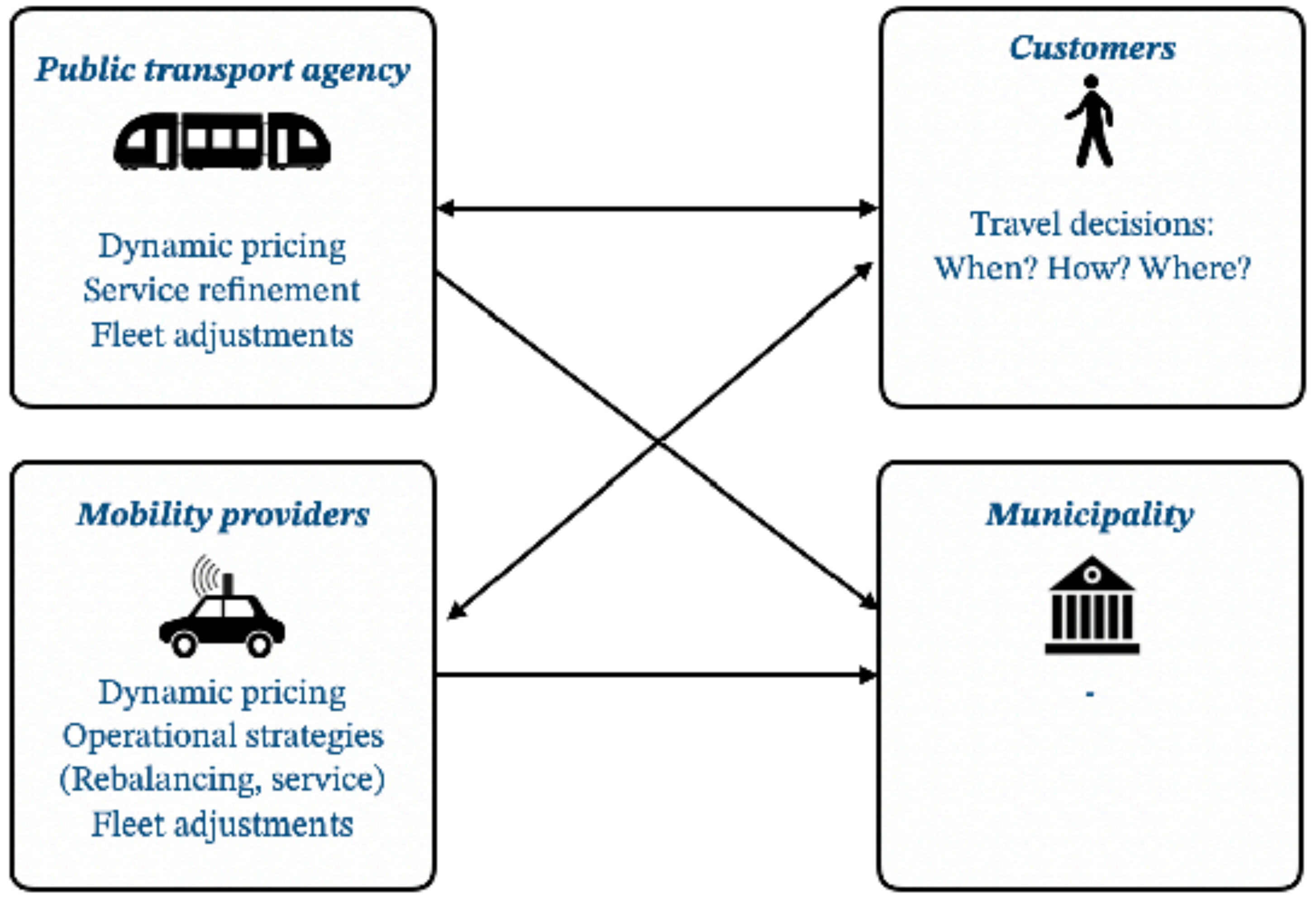


We focus the exposition on the yearly time horizon

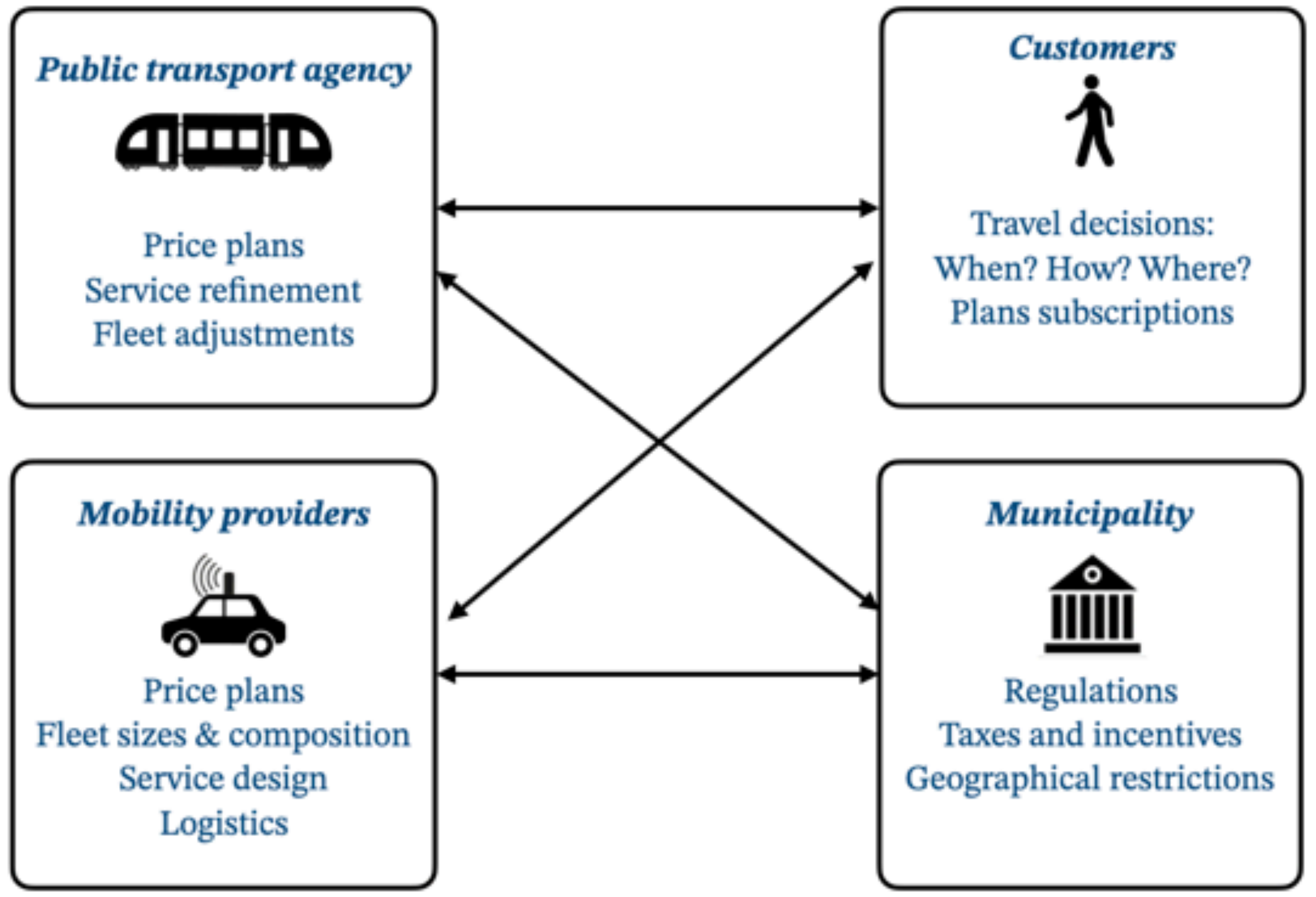
Daily



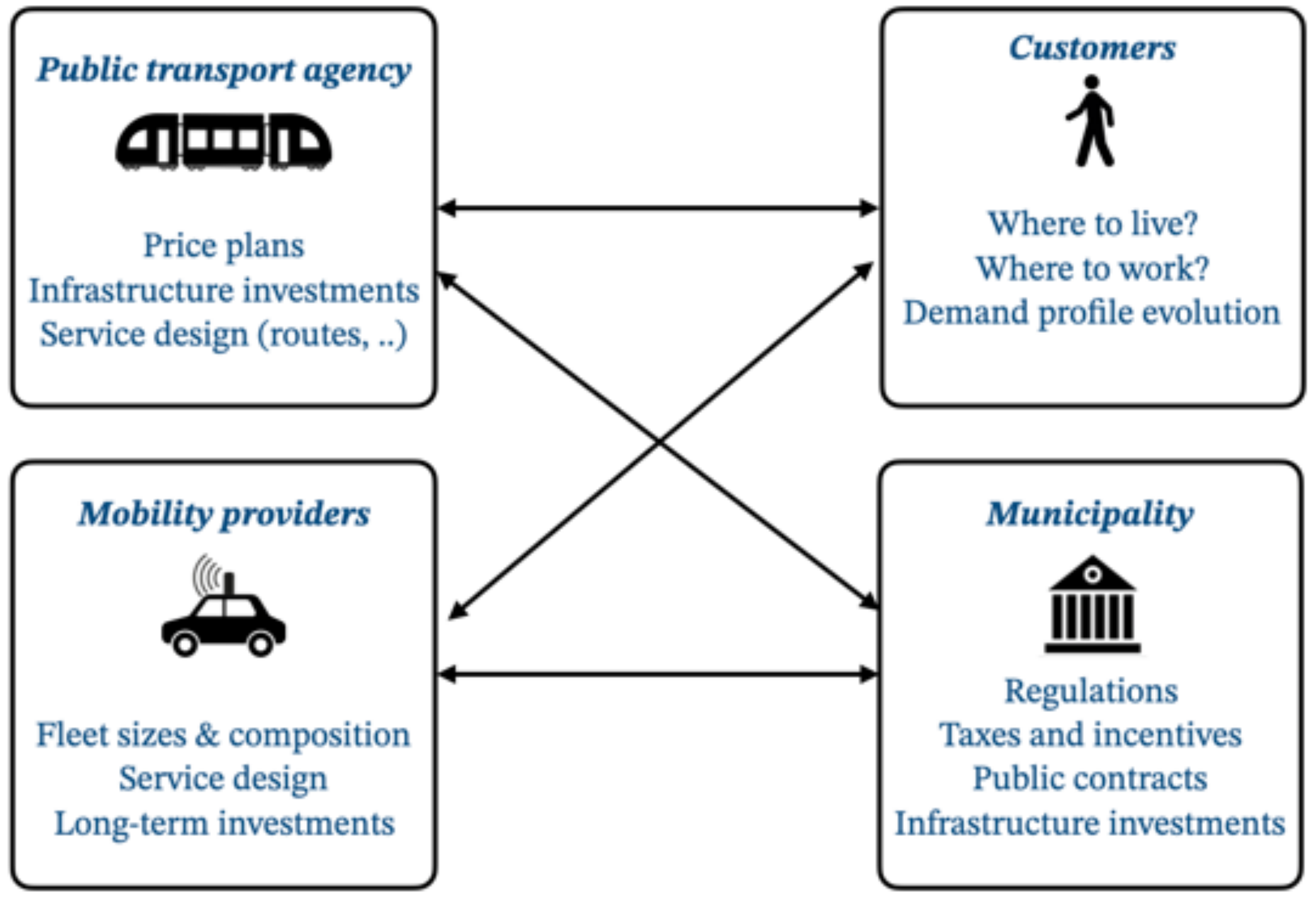
Monthly



Yearly



Every five years



Game formulation

- We model **sequential** interactions as a **game**:
  - The **municipality** plays **first** (e.g., by choosing public transport **prices**, **taxes**)
  - The **mobility service providers** interact **simultaneously** after the municipality (e.g., by choosing **prices**, **fleet sizes**)
  - Customers react accordingly (e.g., by choosing their **trip**)

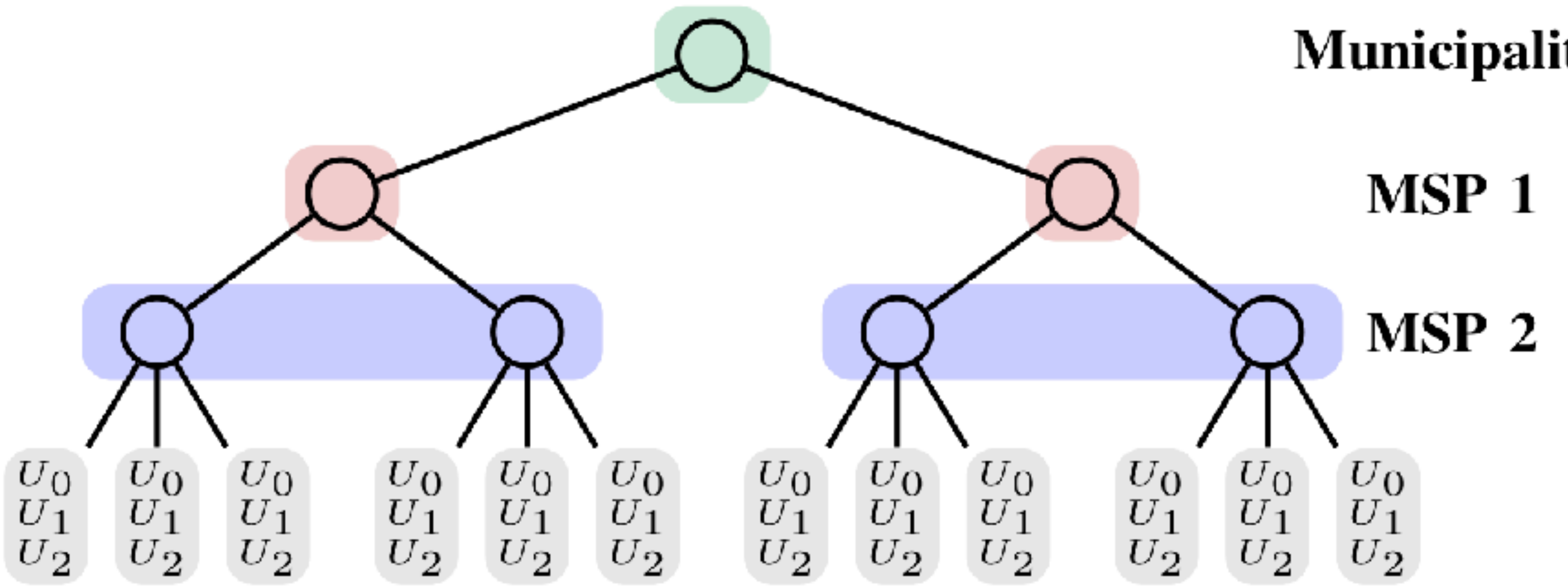
PT prices and type

Taxes (distance-based, empty miles)

Vehicle types

Fleet sizes

Price structures



- Formally:
  - The municipality chooses an **action** from the set Γ_0
  - The mobility service providers choose a **reaction** to the action of the municipality:

$$\gamma_j : \Gamma_0 \rightarrow \bigcup_{\gamma_0 \in \Gamma_0} \mathcal{U}_j(\gamma_0)$$

Game formulation

- **Payoffs:** To each player we associate a **payoff** function:

$$\begin{aligned} U_j \; : \; & \Gamma_0 \times \Gamma_1 \times \ldots \times \Gamma_N \to \mathbb{R} \\ & \langle \gamma_0, \gamma_1, \ldots, \gamma_N \rangle \mapsto U_j(\gamma_0, \gamma_1, \ldots, \gamma_N). \end{aligned}$$

- For instance,
  - **Municipalities** want to **minimize** emissions and **maximize** social welfare.
  - **Mobility service providers** want to **maximize** profit or return on investment (ROI).

- The payoff depends on a **low-level model** of the mobility system (e.g., a **simulator**)

- **Equilibrium:** a tuple of strategies is an equilibrium of the game if **no agent** is willing to **unilaterally deviate** from its strategy:

Definition (Equilibrium). The tuple $\langle \gamma_0^*, \gamma_1^*, \ldots, \gamma_N^* \rangle \in \prod_{i \in \{0, \ldots, N\}} \Gamma_i$ is an *equilibrium* of the game if for all players $j \in \{0, \ldots, N\}$:

$$U_j(\gamma_j^*, \gamma_{-j}^*) \geq U_j(\gamma_j, \gamma_{-j}^*), \forall \gamma_j \in \Gamma_j,$$

where the subscript $-j$ represents all players but j.

- We can compute equilibria via **backward induction**

Hands on: case study

- We consider the city of **Berlin**, including:

Municipality

Actions:

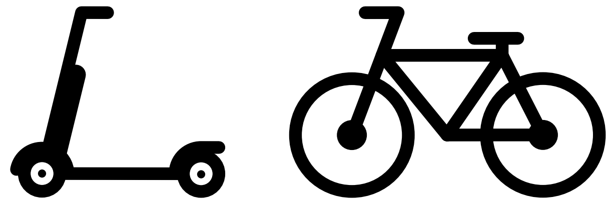
- *Short-distance PT price*
- *Long-distance PT price*
- *Cutoff distance*
- *Distance-based tax for AVs*
- *Distance-based tax for* ***empty*** *AVs*

AMoD operator

Actions:

- *Propulsion*
- *Automation level*
- *Fleet size*

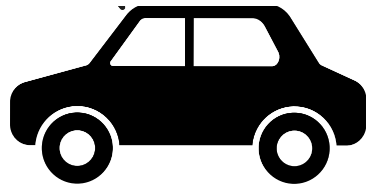
Micro-mobility operator



Actions:

- *Base price*
- *Mileage-dependent price*
- *Vehicle type*

Taxi company



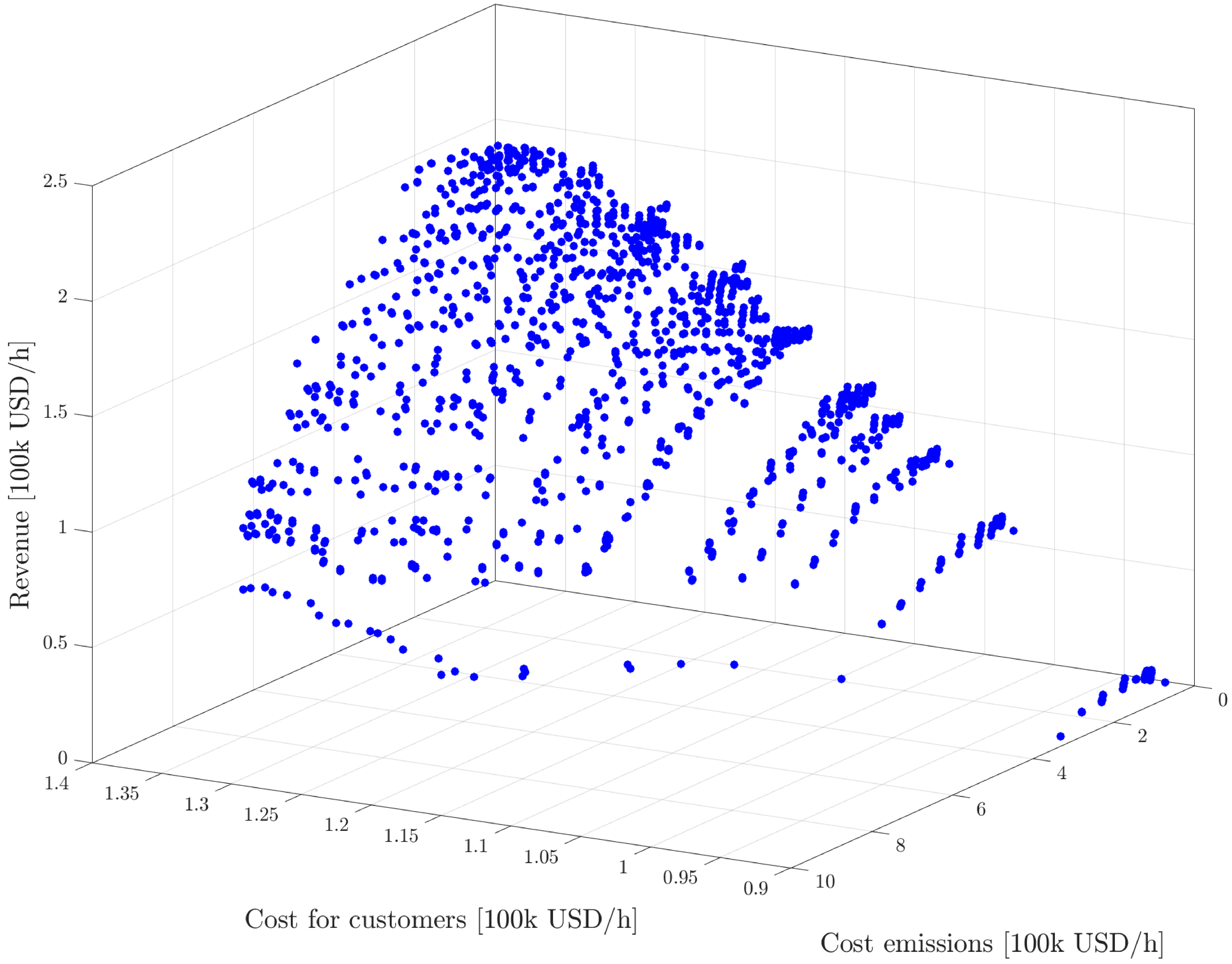
Actions:

- *Base price*
- *Mileage-dependent price*

- Customers choose options by **minimizing** their **cost** (including **fare** and monetary **value of time**)
- We consider 129,560 **real travel requests** and explicitly account for **congestion effects**
- We derive **vehicle-related parameters** and **costs** from **catalogues** and **official reports**

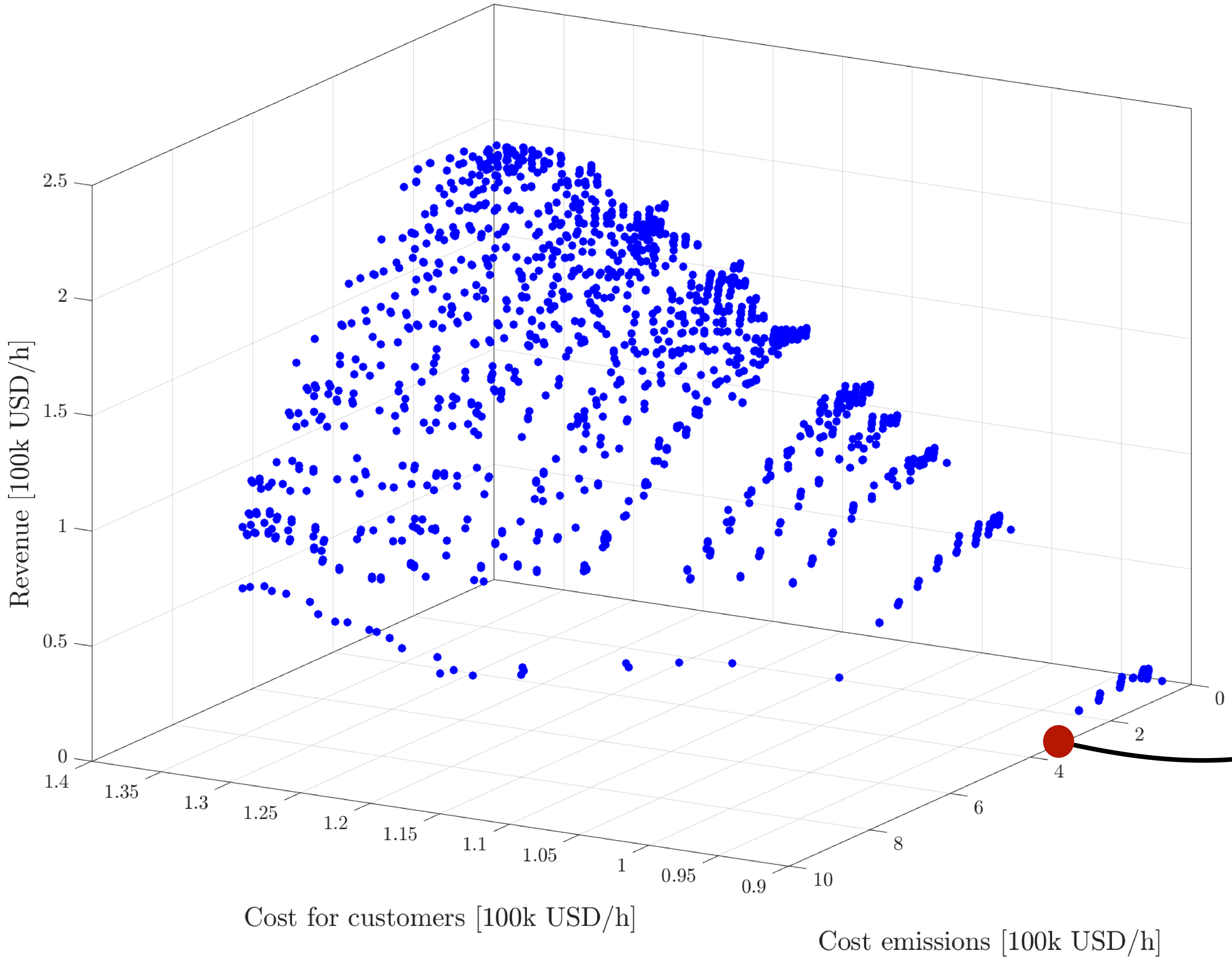
Looking for equilibria of the simultaneous game between MSPs

- First, we compute **equilibria** of the **simultaneous** game between MSPs:



Looking for equilibria of the sequential game

- We then compute the **equilibria** of the **sequential game**
- The **objective** of the **municipality** is pure *political* matter. For each choice, we produce **actionable information:**



Customers-oriented City

AMoD:
5,000 AVs, ICEV
Micromobility:
E-scooters, with fares:
- Base: 1.20 USD
- Variable 1.21 USD/mile

Municipality:
Public transit fares:
- SDP: 0 USD
- LDP: 0 USD

Taxes:
- 0 USD/mile both on full and empty vehicles

Looking for equilibria of the sequential game

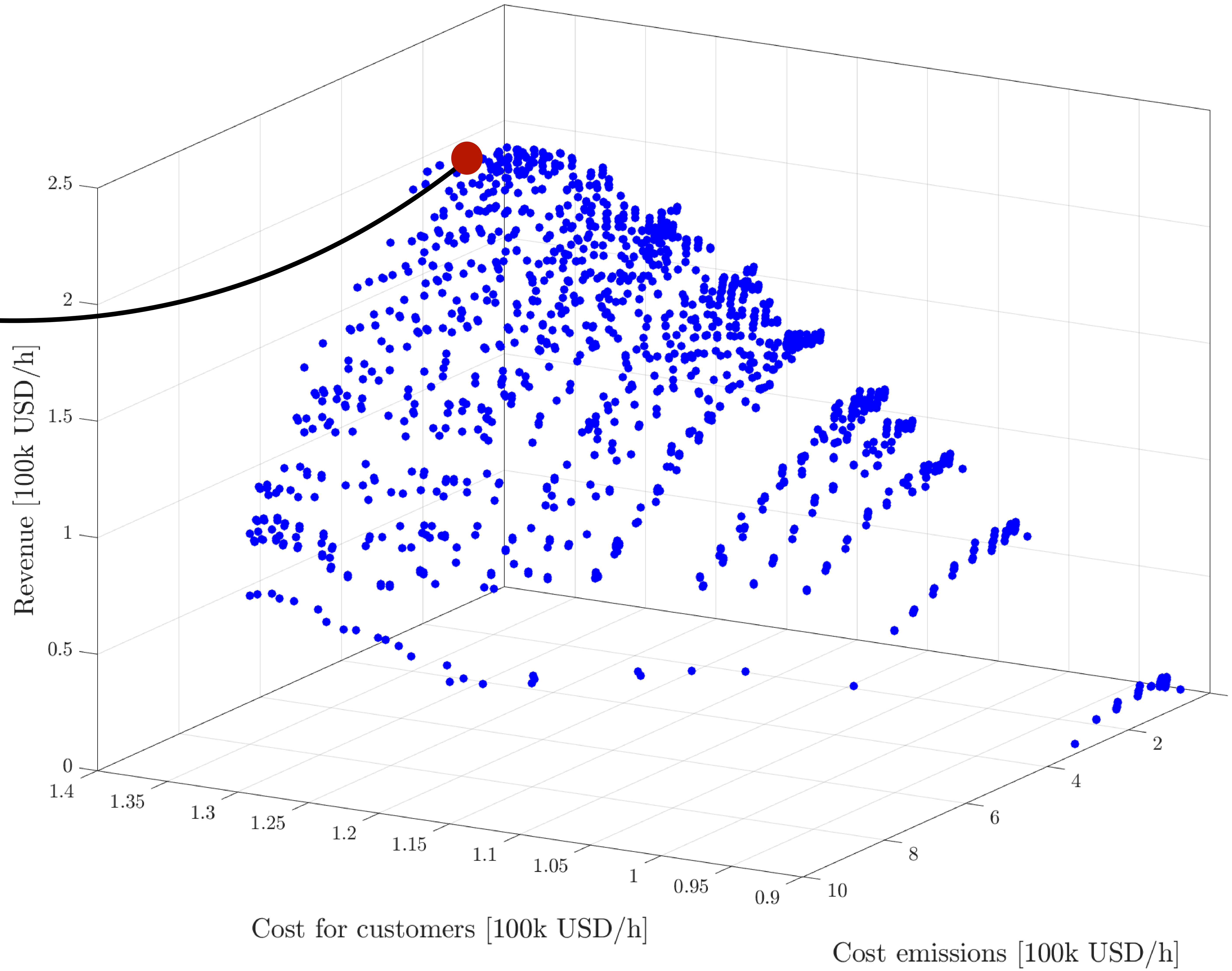
- We then compute the **equilibria** of the **sequential game**
- The **objective** of the **municipality** is pure *political* matter. For each choice, we produce **actionable information:**

Revenue-oriented City

AMoD:
5,000 AVs, ICEV
Micromobility:
E-scooters, with fares:
- Base: 1.20 USD
- Variable 0.96 USD/mile

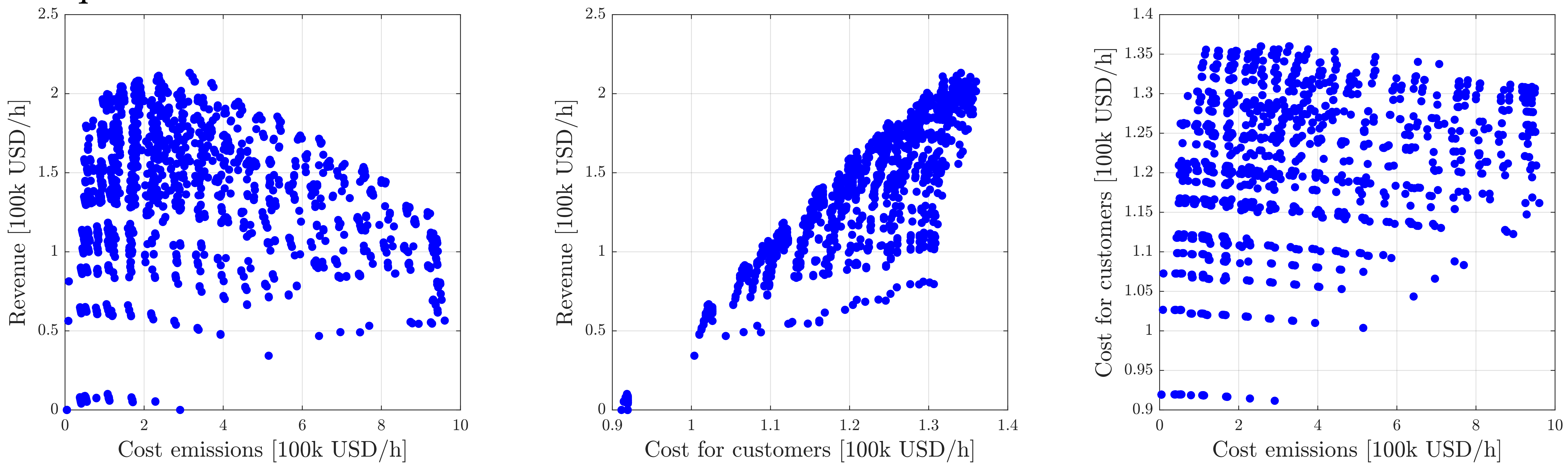
Municipality:
Public transit fares:
- SDP: 3 USD
- LDP: 5 USD
- Cutoff: 1.55 miles

Taxes:
- 1.28 USD/mile both on full and empty vehicles

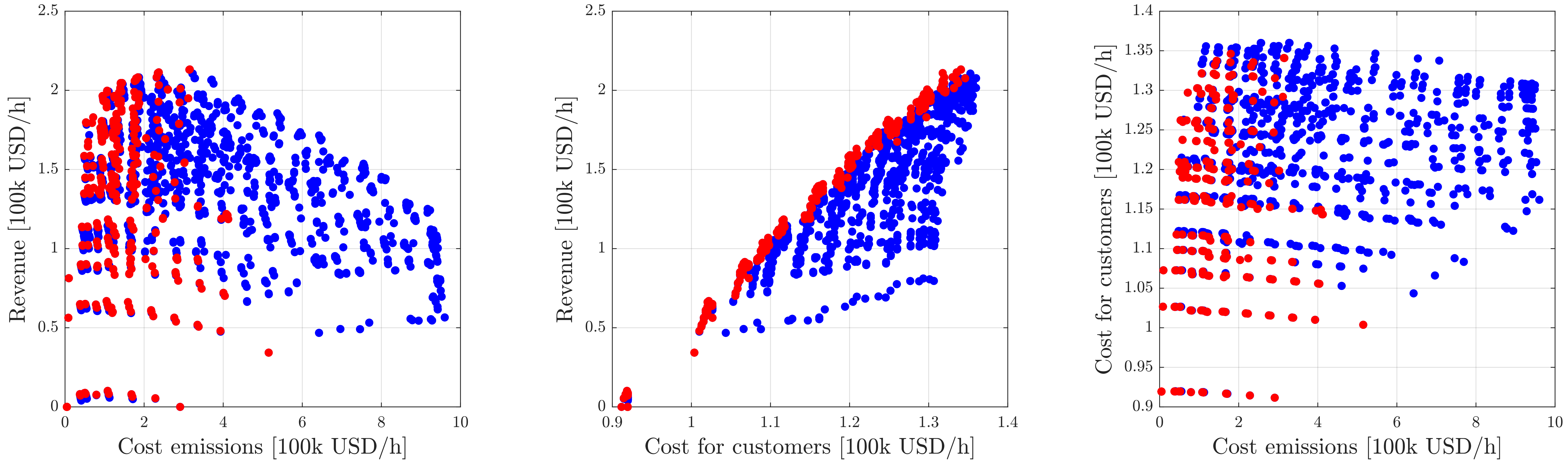


We can analyze equilibria and determine dominating ones

- We can **project** the equilibria:

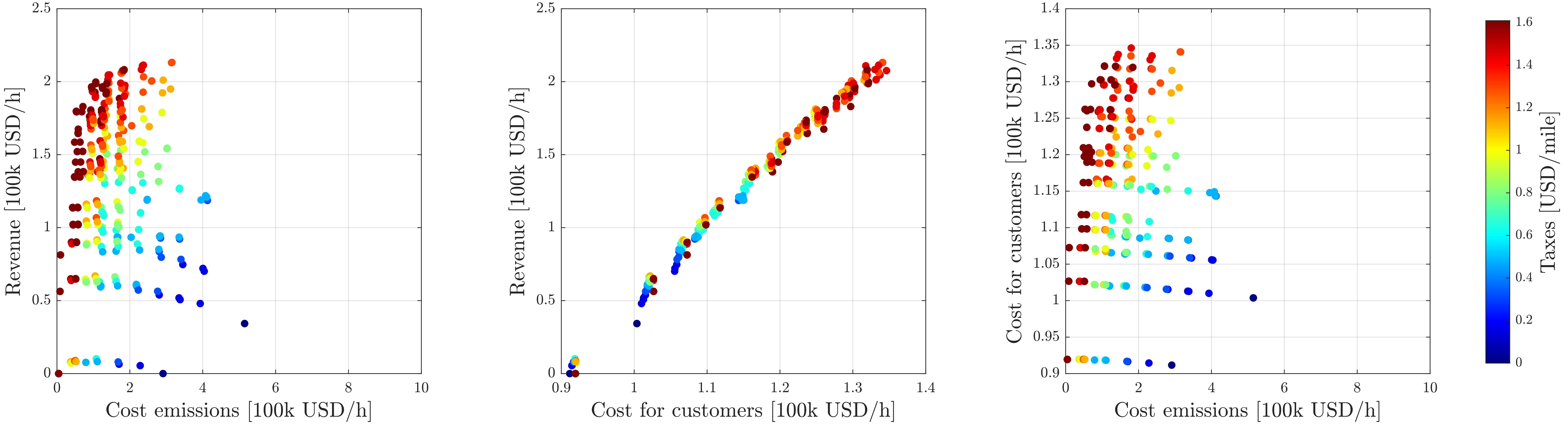


- We can identify **dominating equilibria** (in **red**):

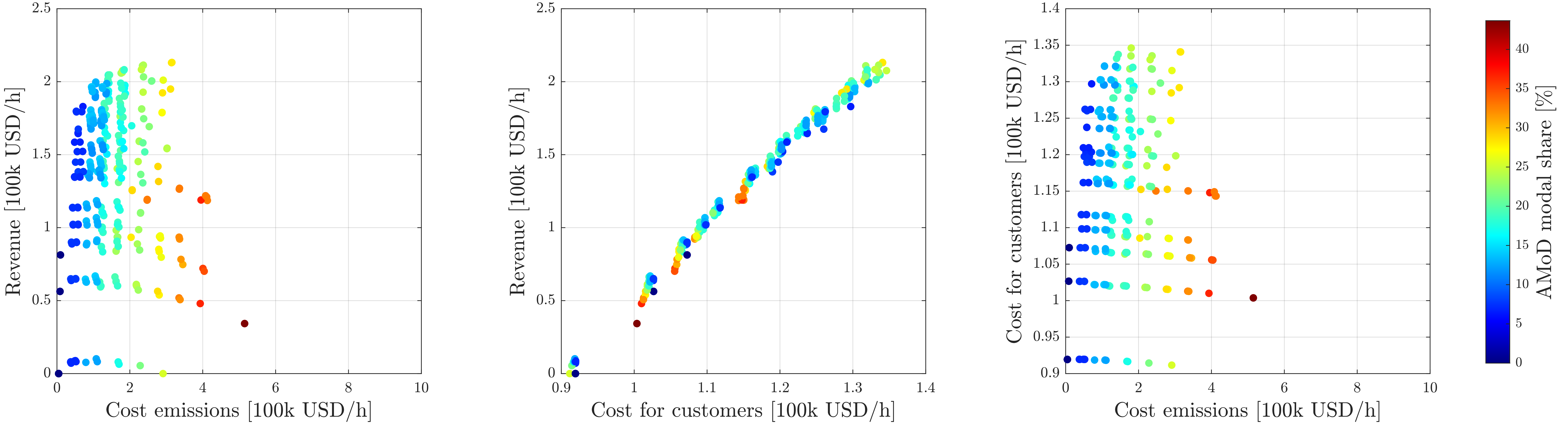


We can study effects of interventions and system metrics

- We can study effects of **interventions** (e.g, **taxes**):



- We can study **system metrics** (e.g., **modal share**):



Takeaways

- We provide a **formal** way to model **interactions** between stakeholders of the **mobility ecosystem**
  We model interactions all the way from **municipalities** to **customers**, through **mobility providers**
- We show how one can **formulate and solve** a **sequential game** involving **heterogeneous decision domains**
  We optimize the choice of **prices** and **taxes**, as well as the choice of **fleet sizes** and **compositions**
- The proposed approach is very **flexible** and can be adapted to **multiple scenarios**
  We characterize interactions depending on the chosen **time horizon**
- We **instantiate** the proposed techniques in the **real world case study of Berlin**
  We show how the approach **scale** up to **real** scenarios
- Our framework can produce **actionable information** and can **assist** stakeholders in **decision processes**
  We can **compute equilibria**, look at their **details**, and identify **trends**

Conclusion

- **Outlook:**
  - We would like to instantiate our framework for various **low-level models of the mobility system**
  - We would like to model interactions happening at **different time scales**
  - We would like to apply our methodology to **similar problem settings** (e.g., marine shipping market)

- **References:**

  - **Zardini**, **Lanzetti**, Guerrini, Frazzoli, and Dörfler, *Game Theory to Study Interactions between Mobility Stakeholders*, 2021.
  - **Lanzetti**, Schiffer, Ostrovsky, Pavone, *On the Interplay between Self-driving cars and public transportation*, 2021.
  - **Zardini**, **Lanzetti**, Pavone, and Frazzoli, *Analysis and Control of Autonomous Mobility-on-Demand Systems: A Review,* 2021.
  - **Zardini, Lanzetti**, Censi, Frazzoli, and Pavone, *Co-Design to Enable User-Friendly Tools to Assess the Impact of Future Mobility Solutions*, 2020

Check out the paper: