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

- Public transport agency
- Mobility providers
- Customers
- Policy makers
- Municipality
- Automotive and tech developers
Takeaways for the 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**
- Public transport agency
  - Dynamic pricing
  - Service refinement
- Mobility providers
  - Dynamic pricing
  - Operational strategies (Rebalancing, service)
- Customers
  - Travel decisions: When? How? Where?
- Municipality

**Monthly**
- Public transport agency
  - Dynamic pricing
  - Service refinement
  - Fleet adjustments
- Mobility providers
  - Dynamic pricing
  - Operational strategies (Rebalancing, service)
  - Fleet adjustments
- Customers
  - Travel decisions: When? How? Where?
- Municipality

**Yearly**
- Public transport agency
  - Price plans
  - Service refinement
  - Fleet adjustments
- Mobility providers
  - Price plans
  - Fleet sizes & composition
  - Service design
  - Logistics
- Customers
- Municipality
  - Regulations
  - Taxes and incentives
  - Geographical restrictions

**Every five years**
- Public transport agency
  - Price plans
  - Infrastructure investments
  - Service design (routes, ...)
- Customers
  - Where to live?
  - Where to work?
  - Demand profile evolution
- Mobility providers
  - Fleet sizes & composition
  - Tax incentives
  - Service design
  - Long-term investments
- Municipality
  - Regulations
  - Taxes and incentives
  - Public contracts
  - Infrastructure investments
Interactions happening on a daily basis

Public transport agency
- Dynamic pricing
- Service refinement

Municipality

Mobility providers
- Dynamic pricing
- Operational strategies (Rebalancing, service)

Customers
- Travel decisions: When? How? Where?
Interactions happening on a monthly basis

**Public transport agency**
- Dynamic pricing
- Service refinement
- Fleet adjustments

**Mobility providers**
- Dynamic pricing
- Operational strategies
  (Rebalancing, service)
- Fleet adjustments

**Customers**
- Travel decisions:
  When? How? Where?

**Municipality**
-
Interactions happening on a yearly basis

Public transport agency

- Price plans
- Service refinement
- Fleet adjustments

Customers

- Travel decisions: When? How? Where?
- Plans subscriptions

Mobility providers

- Price plans
- Fleet sizes & composition
- Service design
- Logistics

Municipality

- Regulations
- Taxes and incentives
- Geographical restrictions

Customers

- Travel decisions: When? How? Where?
- Plans subscriptions

Mobility providers

- Price plans
- Fleet sizes & composition
- Service design
- Logistics

Public transport agency

- Price plans
- Service refinement
- Fleet adjustments

Municipality

- Regulations
- Taxes and incentives
- Geographical restrictions
Interactions happening on a 5-years basis

- **Public transport agency**
  - Price plans
  - Infrastructure investments
  - Service design (routes, ..)

- **Mobility providers**
  - Fleet sizes & composition
  - Service design
  - Long-term investments

- **Customers**
  - Where to live?
  - Where to work?
  - Demand profile evolution

- **Municipality**
  - Regulations
  - Taxes and incentives
  - Public contracts
  - Infrastructure investments

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- **Municipality**
  - Regulations
  - Taxes and incentives
  - Public contracts
  - Infrastructure investments

- **Customers**
  - Where to live?
  - Where to work?
  - Demand profile evolution

- **Public transport agency**
  - Price plans
  - Infrastructure investments
  - Service design (routes, ..)
We focus the exposition on the yearly time horizon

**Daily**

- **Public transport agency**
  - Dynamic pricing
  - Service refinement

- **Mobility providers**
  - Dynamic pricing
  - Operational strategies (Rebalancing, service)

- **Customers**
  - Travel decisions: When? How? Where?

- **Municipality**

**Yearly**

- **Public transport agency**
  - Price plans
  - Service refinement
  - Fleet adjustments

- **Mobility providers**
  - Price plans
  - Fleet sizes & composition
  - Service design
  - Logistics

- **Customers**
  - Travel decisions: When? How? Where?
  - Plans subscriptions

- **Municipality**
  - Regulations
  - Taxes and incentives
  - Geographical restrictions

**Monthly**

- **Public transport agency**
  - Dynamic pricing
  - Service refinement
  - Fleet adjustments

- **Mobility providers**
  - Dynamic pricing
  - Operational strategies (Rebalancing, service)

- **Customers**
  - Travel decisions: When? How? Where?

- **Municipality**

**Every five years**

- **Public transport agency**
  - Price plans
  - Infrastructure investments
  - Service design (routes, ...)

- **Mobility providers**
  - Fleet sizes & composition
  - Service design
  - Long-term investments

- **Customers**
  - Where to live?
  - Where to work?
  - Demand profile evolution

- **Municipality**
  - Regulations
  - Taxes and incentives
  - Public contracts
  - Infrastructure investments
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**)

Formally:
- The municipality chooses an **action** from the set $\Gamma_0$
- The mobility service providers choose a **reaction** to the action of the municipality:

$$\gamma_j : \Gamma_0 \rightarrow \bigcup_{\gamma_0 \in \Gamma_0} U_j(\gamma_0)$$
Game formulation

- **Payoffs:** To each player we associate a payoff function:
  \[ U_j : \Gamma_0 \times \Gamma_1 \times \ldots \times \Gamma_N \to \mathbb{R} \]
  \[ \langle \gamma_0, \gamma_1, \ldots, \gamma_N \rangle \mapsto U_j(\gamma_0, \gamma_1, \ldots, \gamma_N). \]

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

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

  where the subscript \(-j\) represents all players but \( j \).

- We can compute equilibria via **backward induction**
We consider the city of Berlin, including:

- **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:
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
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

Looking for equilibria of the sequential game
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.
- 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: