Ride-sharing, congestion, departure-time and mode choices: A social optimum perspective

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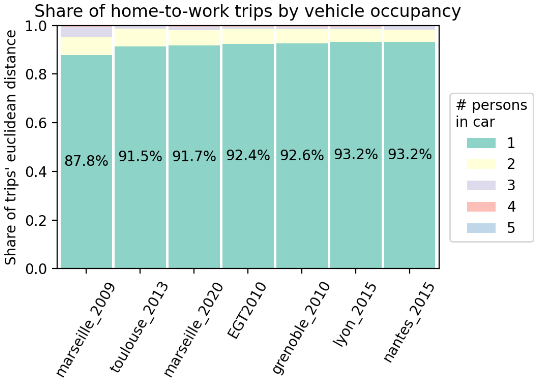
Motivation

- **Ride-sharing:** multiple passengers traveling in the same direction share a vehicle
- Expected effect: $\nearrow$ vehicle occupancy $\longrightarrow$ $\searrow$ car vehicle-kilometers
- High potential: In 2010, in Île-de-France, car drivers are traveling alone for 92.4 % of the distance of the home-to-work trips inc. intermediate stops (60.5 % for non-work purposes)



Motivation

	Benefits	Costs
Individual	Split fuel and other expenses	Temporal / spatial mismatch, inconvenience
Social	$\searrow$ congestion, $\searrow$ CO_2, $\searrow$ local pollutants, $\searrow$ noise	Infrastructure (pick-up / drop-off zones)

- Government intervention is required (network effects, negative externalities)
- Example policies:
  - **Financial incentives** to drivers (100 € bonus in France)
  - **High-occupancy vehicle (HOV) lanes** (e.g., Boulevard Périphérique in Paris)

Contributions

Research questions:

- How to optimally match drivers and passengers?
- What is the social surplus potential?

Contributions:

- Methodology to find the socially optimal match between passengers and drivers in large-scale scenarios
- Application to Île-de-France with METROPOLIS2

	Benefits	Costs
Individual	**Split fuel** and other expenses	**Temporal / spatial mismatch, inconvenience**
Social	↘ **congestion**, ↘ $\mathbf{CO_2}$, ↘ local pollutants, ↘ noise	Infrastructure (pick-up / drop-off zones)

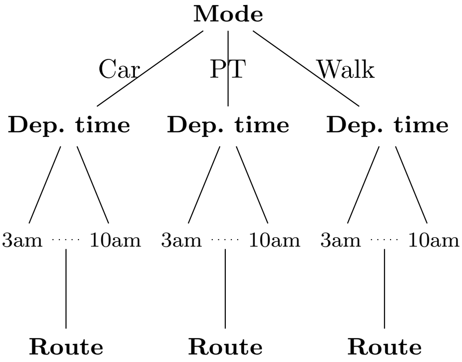
Similar papers

	Obj. function	Time	Congestion	Network
Delle Site, de Palma, Ghoslya (2022)	social costs	static	exogenous	Sioux Falls
Sun, Wu, Chen (2022)	$\sim$ individual costs	dynamic	microscopic	Chattanooga
de Palma, Stokkink, Geroliminis (2022)	individual costs	dynamic	bottleneck	single road
de Palma, Javaudin, Stokkink, Tarpin-Pitre (2024)	individual costs	dynamic	bottleneck	Île-de-France
This paper	social costs	dynamic	bottleneck	Île-de-France

Outline

Settings

- Home-to-work trips in the morning
- Agents select a travel mode, departure time, and route
- No ride-sharing in the baseline scenario
- Travel modes: car (as a driver), public transit (PT), walking



Preferences

Generalized cost with mode m at departure time t^d:

$$C^m(t^d) = \underbrace{\alpha_m \cdot \mathrm{tt}^m(t^d)}_{\text{Travel cost}} + \underbrace{\beta \cdot [t^* - t^a]^+ + \gamma \cdot [t^a - t^*]^+}_{\text{Schedule-delay cost}} + \underbrace{F^m}_{\text{Fuel}},$$

- $\mathrm{tt}^m(t^d)$: travel time with mode m at departure time t^d
- $t^a = t^d + \mathrm{tt}^m(t^d)$: arrival time
- α_m: mode-specific value of time
- β, γ: penalties for early and late arrival
- t^*: desired arrival time
- F^m: fuel cost (only for car)

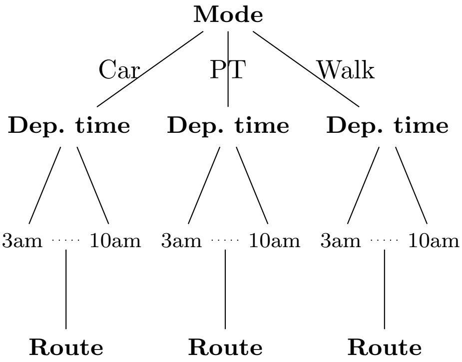
Choice models

- **Route choice:** fastest time-dependent path (car), least-cost path (PT), or shortest path (walk)
- **Departure-time choice:** Multinomial Logit

$$t^d = \arg\min_t [C^m(t) - \eta(t)]$$

- **Mode choice:** Multinomial Logit

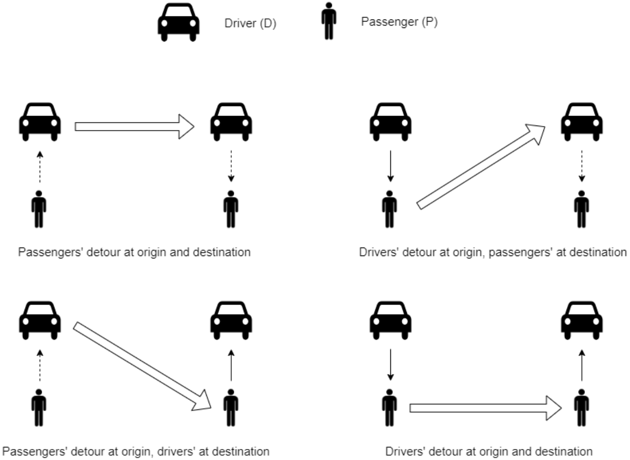
$$m = \arg\min_m [C^m - \varepsilon^m]$$



Ride-sharing system

- System coordinated by a social planner with full information
- Participants to the system can be matched as RS driver, matched as RS passenger, or keep traveling alone
- RS drivers select their departure time and route (conditional on the detour)
- The social planner chooses the pick-up and drop-off locations of each match

Detour scenarios



Ride-sharing social cost

When agent i is matched as RS driver with passenger j as RS passenger:

- Cost of driver i is:

$$C_{i,j}^{\text{Driver}} = \alpha_{\text{Driver}} \cdot \text{tt}_{i,j}^{\text{Driver}} + \beta \cdot [t_i^* - t^a]^+ + \gamma \cdot [t^a - t_i^*]^+ + F_{i,j}^{\text{Driver}} + \eta_i(t^d) + \varepsilon_i^{\text{Driver}}$$

- Cost of passenger j is

$$C_{i,j}^{\text{Pass}} = \alpha_{\text{Pass}} \cdot \text{tt}_{i,j}^{\text{Pass}} + \alpha_{\text{Walk}} \cdot \text{wt}_{i,j}^{\text{Pass}} + \beta \cdot [t_j^* - t^a]^+ + \gamma \cdot [t^a - t_j^*]^+ + \eta_j(t^d) + \varepsilon_j^{\text{Pass}}$$

- Total social cost is:

$$C_{i,j} = C_{i,j}^{\text{Driver}} + C_{i,j}^{\text{Pass}} + E_{i,j}$$

  with $E_{i,j}$ cost of CO_2 emissions

Social planner optimization

Optimization program of the social planner:

$$\min_X \sum_{i,j} C_{i,j} X_{i,j}$$

subject to the constraints

$$\sum_j X_{ij} = 1, \quad \forall i$$

$$X_{ij} \in \{0, 1\}, \quad \forall i, j$$

- $X = (X_{i,j})$: matching matrix where $X_{i,j} = 1$ when i is a driver with j as passenger and $X_{i,i} = 1$ when i travels alone
- $C_{i,j}$: total social cost of matching i with j, with $C_{i,i}$ = total social cost of i traveling alone

Social planner optimization

Remarks:

- A driver can share their ride with at most one passenger
- The role of agents (driver, passenger, alone) are not pre-assigned but optimized endogenously by the social planer
- A match between i and j is feasible only if

$$C_{i,j} \leq C_{i,i} + C_{j,j}$$

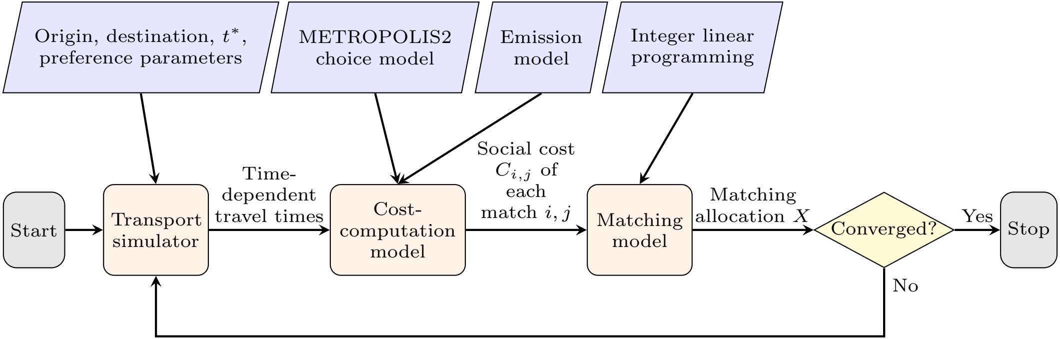
  i.e., Pareto-improving transfers can be implemented so that no agent is worse off

Outline

Endogeneity

- The optimization problem can be solved using standard integer linear programming techniques
- Endogeneity problem: social costs $C_{i,j}, \forall i, j$ are treated as fixed but they depend on congestion levels which are shaped by matching decisions X

Iterative framework



Transport simulator

METROPOLIS2 (Javaudin and de Palma, 2024):

- Population of agents with a chain of **point-to-point trips**
- Mode, departure-time and route decisions
- Endogenous congestion with dynamic link-level bottlenecks (mesoscopic simulator)
- Some agents can have fixed modes → matching decisions can be forced

Cost-computation model

For each feasible pair i, j and each detour scenario:

- driver i's selected departure time and route are computed through METROPOLIS2
- passenger j's walking time is computed through routing on the pedestrian network
- CO_2 emissions and fuel consumption are computed with METRO-TRACE (Le Frioux et al, 2024) based on link-level speeds and agent-level vehicle characteristics

The total social cost $C_{i,j}$ of the pair i, j is the minimum cost over all detour scenarios.

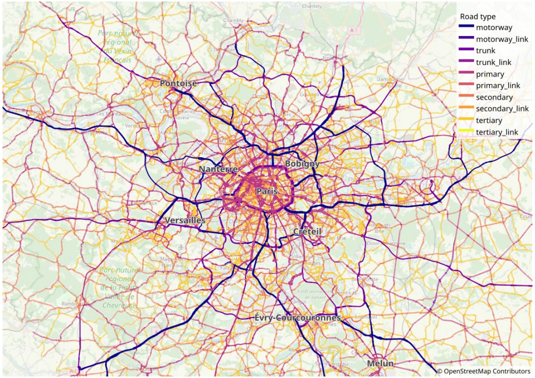
Matching model

- Integer linear program
- PuLP Python library
- Output of the model: matches $X = (X_{i,j})$

Outline

Simulation setup

- Île-de-France region
- Road and pedestrian network from OpenStreetMap
- Public transit schedule from Île-de-France Mobilités (GTFS)
- Synthetic population with activities and trips from Hörl and Balac (2021)
- Morning period from 3 a.m. to 10 a.m.
- 10 % re-scaling: 629k agents, 819k trips
- Four-step calibration process (Javaudin, 2024)



Parameters

Parameter	Value
α_{Car}	10 €/h
α_{Walk}	10 €/h
α_{PT}	8 €/h
α_{Driver}	10 €/h
α_{Pass}	10 €/h
β	5 €/h
γ	5 €/h
Walking speed	4 km/h
Fuel cost	1.8 €/L
CO_2 emission cost	200 €/t

Ride-sharing scheme assumptions

- Participants to the system are:
  - Car drivers in the baseline scenario
  - Direct trip from home to work
  - Additional 40 % probability
- Final share of participants: 13.2 % of simulated population
- A pair i, j is *feasible* if:
  - j's origin is within 5 km of i's origin
  - j's destination is within 5 km of i's destination
  - j's baseline departure time is within 20 min of i's baseline departure time

Main results

About 30 % of participants are matched either as a RS driver or RS passenger

	Baseline	**Ride-sharing**	**Change**
Car trips	2.06 M	1.95 M	−5.2 %
Vehicle-kilometers	30.70×10^6 km	30.54×10^6 km	−0.5 %
Time lost in congestion	209 526 h	200 455 h	−4.3 %
Fuel consumption	1.943×10^6 L	1.938×10^6 L	−0.2 %
CO_2 emissions	6167 t	6155 t	−0.2 %

⇒ The potential of ride-sharing is small

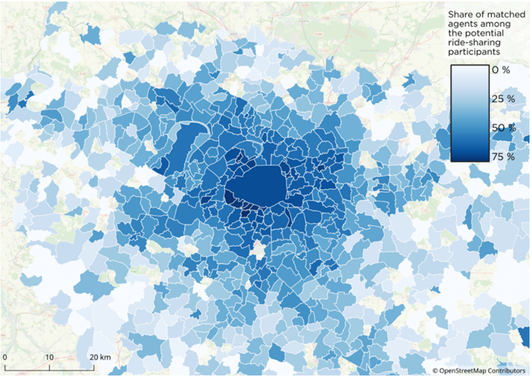
Mode switch

From \To	Walking	Car Driver	Public transit	Car Passenger	Total
Walking	31.8	·	·	·	31.8
Car Driver	·	30.7	·	2.0	32.7
Public transit	·	0.3	35.1	·	35.4
Total	31.8	31.0	35.1	2.0	100.0

$\Rightarrow$ Rebound effect: 15 % of car share reduction is "absorbed" by switches from public transit (54 % of vehicle-kilometers!)

Spatial distribution

Participants are more likely to be matched when living in densely populated areas

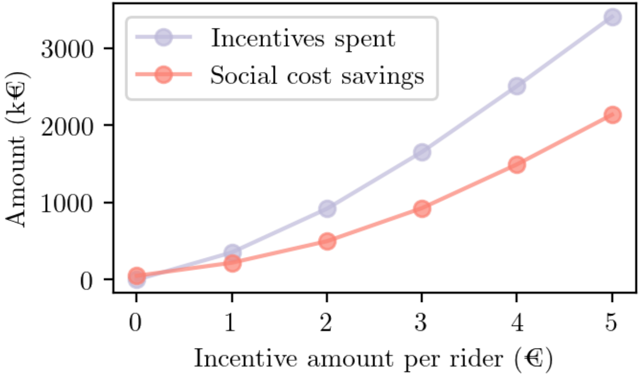


Ride-sharing incentive

Incentive amount	0€	1€	2€	3€	4€	5€
Car share	31.0 %	30.3 %	29.6 %	29.0 %	28.5 %	28.1 %
Ride-sharing share	4.0 %	5.6 %	7.3 %	8.8 %	10.0 %	10.8 %
Incentives spent (k €)	0	354	920	1,656	2,510	3,409
Social cost savings (k €)	51	220	499	928	1,495	2,139
Car VKT (10^6 km)	30.54	30.32	30.15	29.96	29.75	29.52
Time lost in congestion (10^3 hour)	200.5	195.9	191.4	187.7	184.2	182.0
CO_2 emissions (t)	6155	6097	6084	6046	5996	5955
Mean walking distance (m)	590	610	650	680	710	730

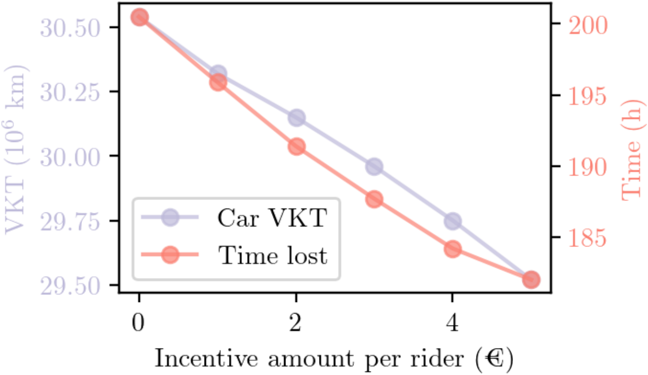
$\Rightarrow$ Offering incentives increase the number of matches found (up to 82 % of the theoretical maximum)

Ride-sharing incentive



⇒ The cost of incentives increases faster than the improvement in social surplus

Ride-sharing incentive



⇒ Car vehicle-kilometers and time lost in congestion decrease about linearly with the incentive amount

PT fare subsidy

	Baseline	1 € RS incentive	−0.15 € PT fare
Policy cost (k €)	0	354	343
Social cost savings (k €)	0	220	550
Car share	32.7 %	30.3 %	32.2 %
PT share	35.4 %	35.1 %	36.3 %
Car VKT (10^6 km)	30.70	30.32	30.29

⇒ A reduction of PT fare can achieve larger social benefits than ride-sharing incentives with similar cost

Outline

Take-away

- Methodology for large-scale evaluation of a ride-sharing system with:
  - temporal matching (scheduling preferences)
  - location-based spatial matching (~~zones~~)
  - socially optimal matching (inc. CO_2)
  - endogenous congestion
- Application to Île-de-France:
  - With 13.2 % of participants: 2.0 % RS passengers; vehicle-kilometers $\searrow$ 0.5 %
  - Ride-sharing incentives are more expensive than the improvement in benefits
  - Subsidizing ride-sharing is worse than subsidizing PT

Future directions

- Local pollutants
- Arbitrary pick-up / drop-off locations
- Drivers with 2+ passengers
- Multi-hop ride-sharing
- Intermodality ride-sharing + PT
- Evening peak (round trips)
- HOV lanes

Thank you