PhD Thesis

Development of a Dynamic Transport Simulator for Policy Evaluation: Applications to Ride-Sharing and Low Emission Zone in Paris

presented by

Lucas Javaudin

under the supervision of

André de Palma

at

THEMA, CY Cergy Paris Université

PhD Defense · December 9, 2024

Context: Challenges and Policies in Transportation

Challenge	Example policies
Road accidents → injuries / deaths	Speed limit reduction
Road congestion → productivity loss / stress	New infrastructure
Air pollution → chronic diseases / deaths	Low emission zone
CO_2 emissions → climate change	Subsidies for electric cars
Noise pollution → health issues	Limited traffic zone

The Difficulty of Evaluating Transport Policies

Example: Speed limit decrease on the *Boulevard Périphérique* from 70 km/h to 50 km/h

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  - departing earlier
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  - ↘ noise
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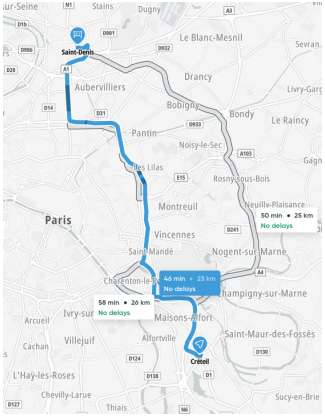
  - ↘ congestion
- **Other impacts:** ↗ traffic on other roads & ↗ public-transit occupancy → rebound effect



10:14 → 11:00

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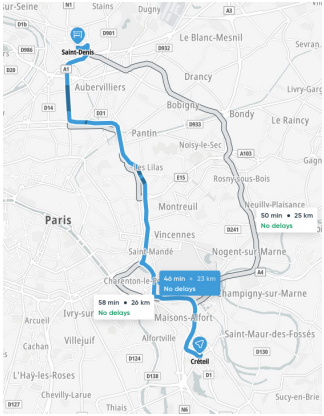

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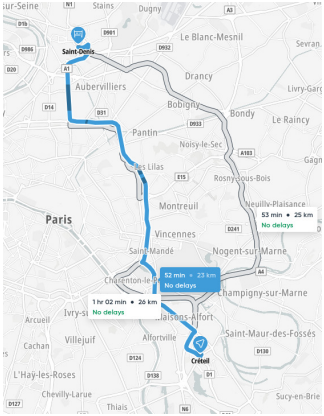

10:08 → 11:00

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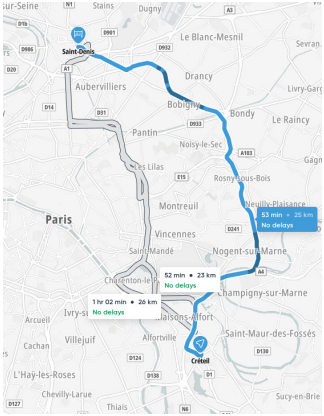

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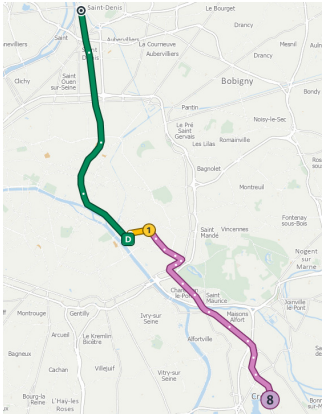

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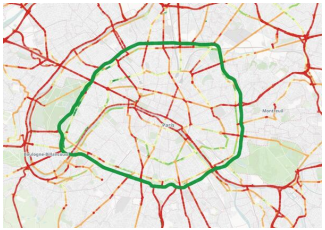

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Transport simulations

- Tools that simulate the **travel decisions** (e.g., mode, departure time, route) and associated **outcome** (e.g., congestion, air pollution) of a **population traveling** on a **transport infrastructure** (e.g., roads, public-transit lines)
- **Various categories:** aggregated vs agent-based; static vs dynamic; macroscopic vs mesoscopic vs microscopic
- In this thesis: **agent-based dynamic mesoscopic simulators**

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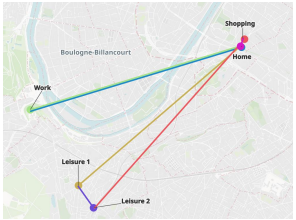

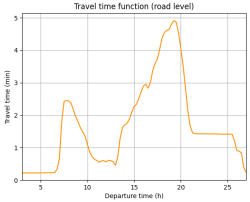

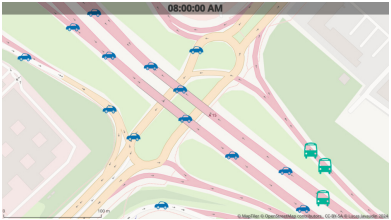

METROPOLIS1/2 Simulators

- Two simulators used in the thesis:
  - **METROPOLIS1:** C++ simulator developed around 1997 by André de Palma, Fabrice Marchal, Yurii Nesterov *[Chapter 1]*
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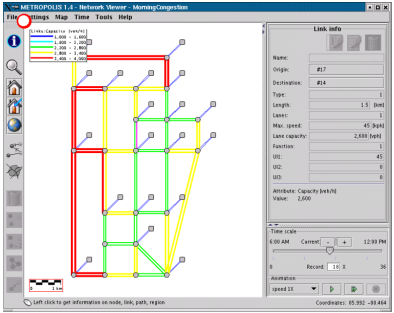

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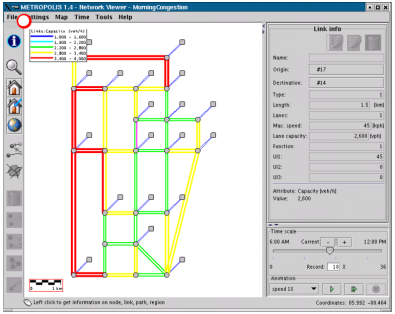
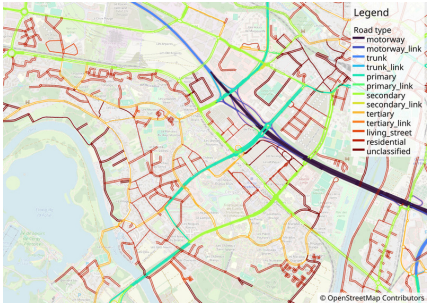


METROPOLIS: Input

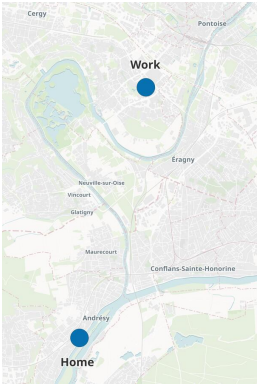
Road network



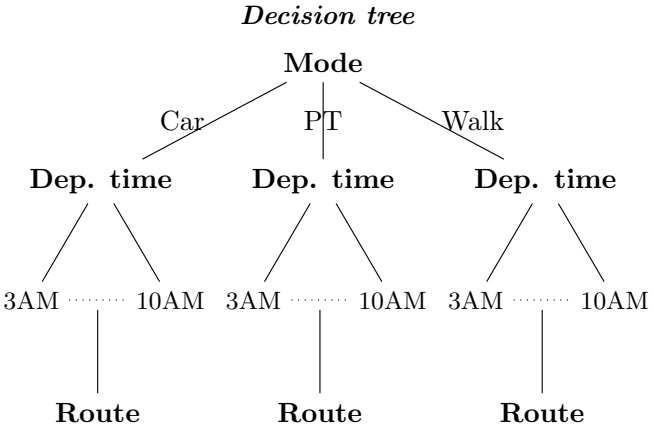
Population of **agents**

Gender	Man
Age	35
Owns a car	Yes
Has driving license	Yes

Activity	Work
Desired start time	09:00
Duration	8 h 30 min



METROPOLIS: Demand Model (1/5)

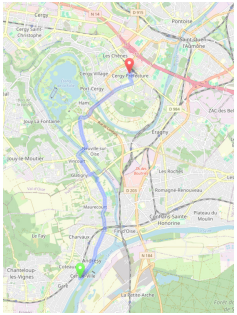


METROPOLIS: Demand Model (2/5)

Mode options

Walking

- Travel time: 2 h 4 min
- Utility: −23.85 €



Public transit

- Travel time: 26 min
- Utility: −7.29 €

Car

- Travel time: 17 to 18 min
- Utility: −8.76 €

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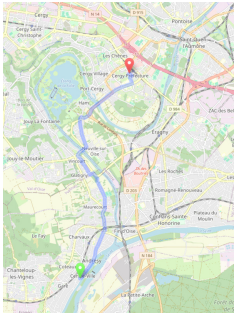

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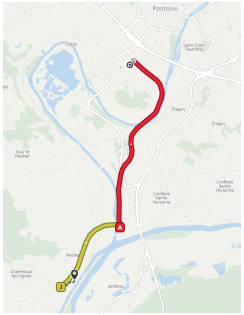

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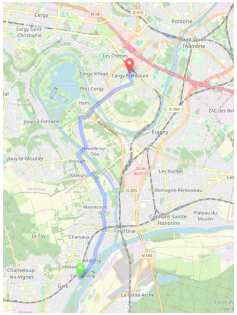

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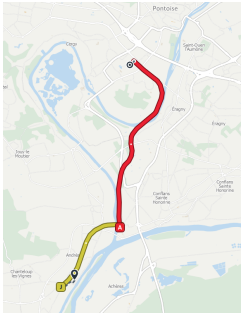

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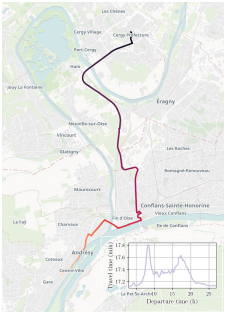

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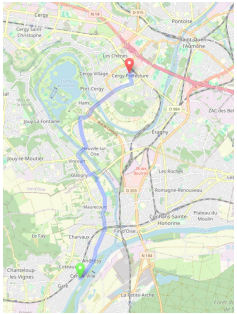

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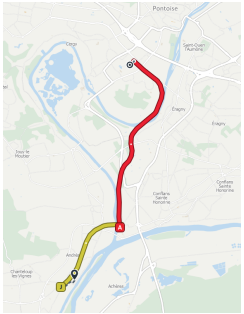

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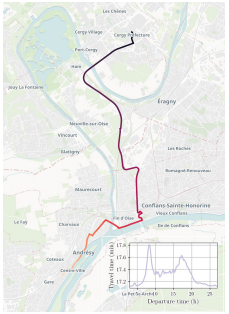

METROPOLIS: Demand Model (3/5)

Mode choice

Mode	Utility	Probability
Walking	$-23.85\,€$	$0\,\%$
Public transit	$-7.29\,€$	$81\,\%$
Car	$-8.76\,€$	$19\,\%$

Probabilities are derived from a **Multinomial Logit model**

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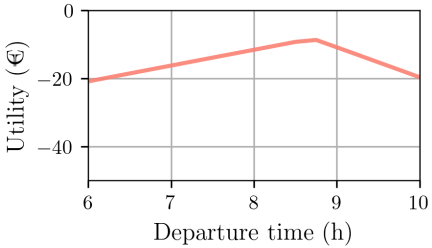
Chosen mode (random) → Car

METROPOLIS: Demand Model (4/5)

Departure-time choice

Utility as a function of departure time



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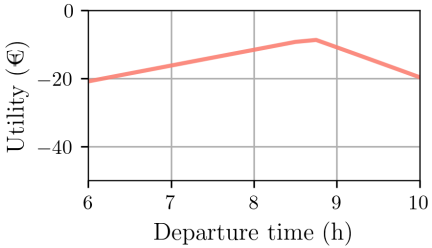
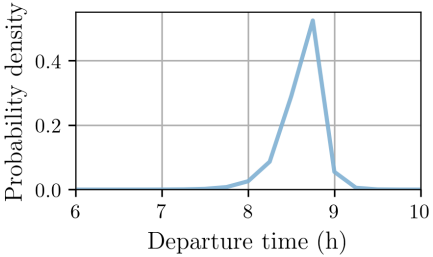


Probability of departure time selection



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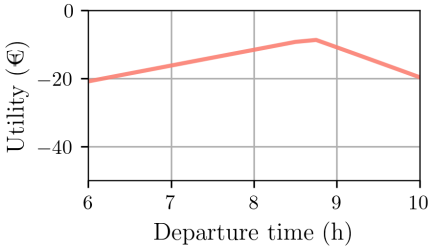

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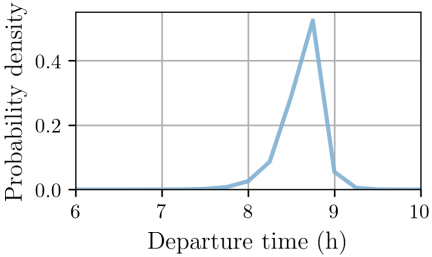

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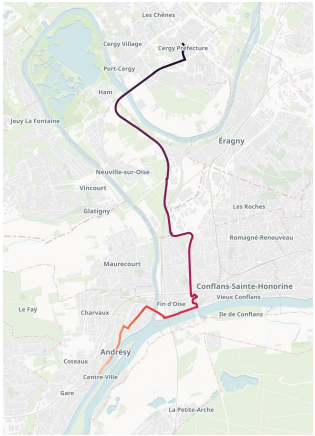
Chosen departure time (random) → 8:42:16

METROPOLIS: Demand Model (5/5)

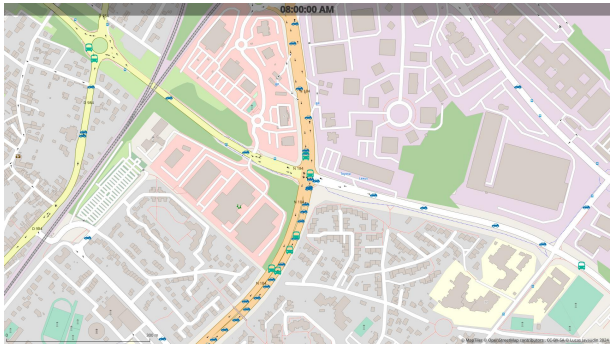
Route choice

Fastest route given mode (car), departure time (8:42:16), and anticipated congestion



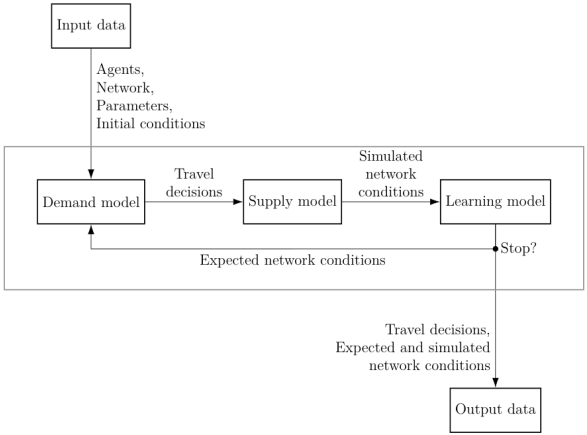
METROPOLIS: Supply Model

Road trips are simulated; congestion occurs when too many cars are taking the same roads



METROPOLIS: Overview

Iterative process



Plan of the thesis

Chapter 1 **Ride-sharing** with inflexible drivers in the Paris Metropolitan area
With André de Palma, Patrick Stokkink & Léandre Tarpin-Pitre

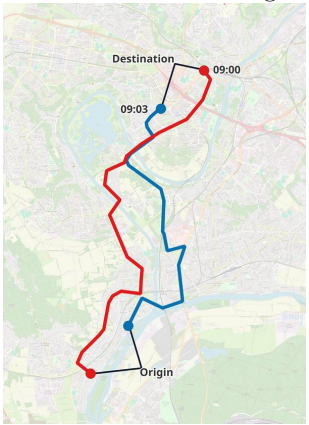
Chapter 2 **METROPOLIS2:** Bridging theory and simulation in agent-based transport modeling
With André de Palma

Chapter 3 Impact of **low emission zones** on spatial and economic inequalities using a dynamic transport simulator
With André de Palma

Motivations

- **Ride-sharing** (or carpooling): 2+ individuals share a car for their trip
- **Benefits:** ↗ vehicle occupancy ⇒ ↘ vehicle-kilometers ⇒ ↘ congestion & CO_2
- **Challenges:** spatial & temporal matching, requires a critical mass
- **Research question:** What is the potential of ride-sharing with optimal matching and inflexible drivers?

Without ride-sharing



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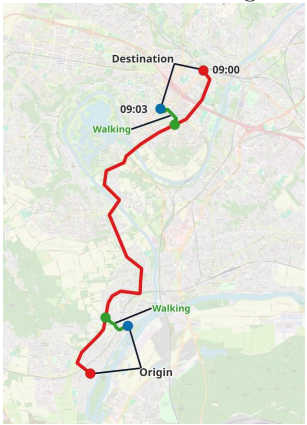

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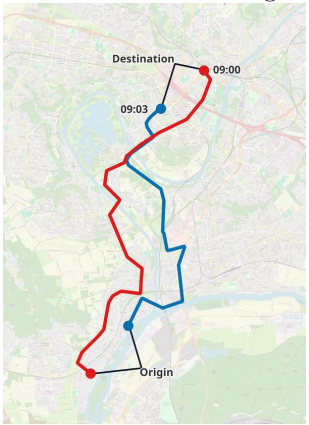

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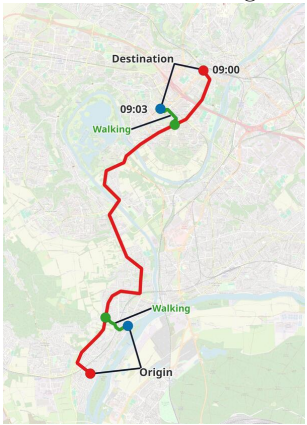

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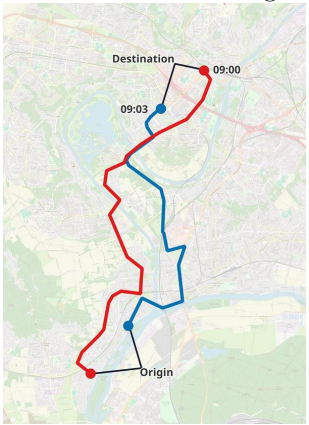
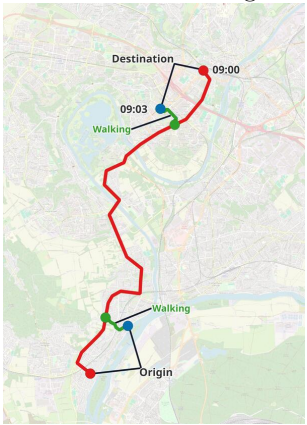


With ride-sharing



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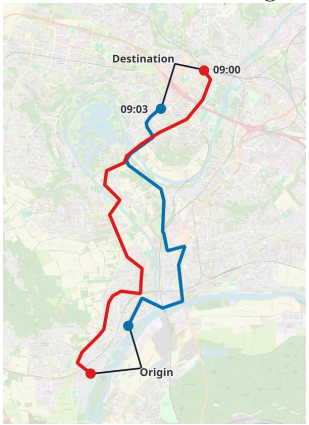
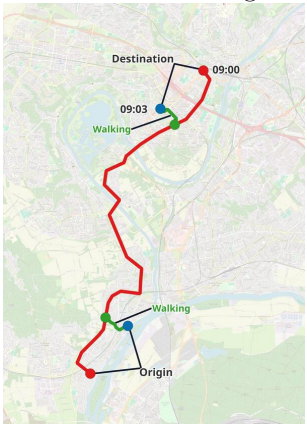


With ride-sharing



Methodology

- **Inflexibility assumption:** drivers keep the same route and departure time
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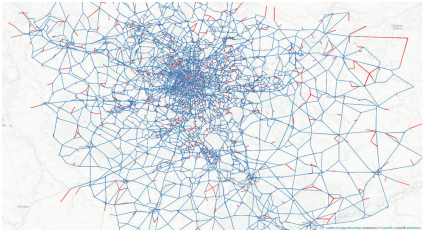

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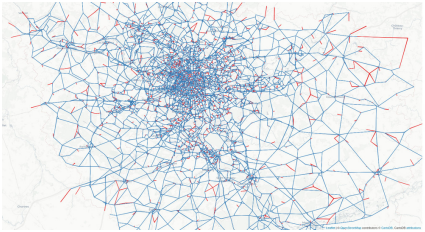

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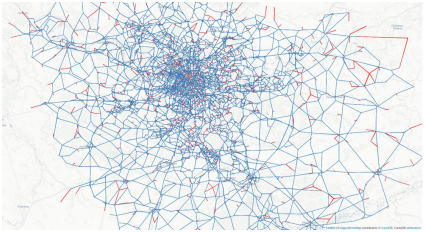

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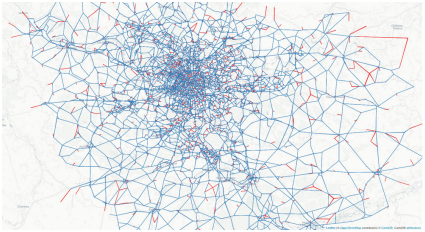

Results

- With 30 % **of population willing to participate:**
  - 3.3 % of ride-sharing passengers
  - Car share: 74.5 % → 72.4 %
  - Vehicle-kilometers & CO_2 emissions: ↘ 1.9 %
- With up to 2 **passengers per car:** 4.2 % of ride-sharing passengers
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Desirable (missing) features of transport simulators:

- Flexible mode choice model
- Fully heterogeneous preferences
- Trip chaining
- Point-to-point trips
- Bottleneck congestion

Contributions:

- Development of a new transport simulator: **METROPOLIS2**
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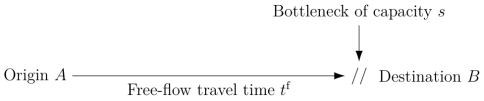

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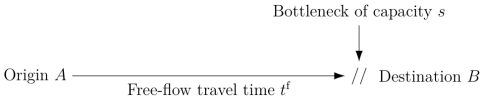

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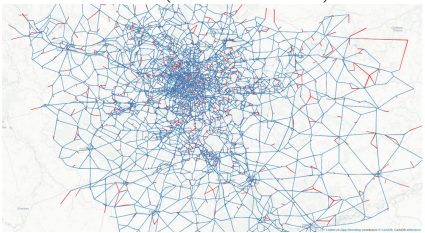


Methodology

Main features of METROPOLIS2:

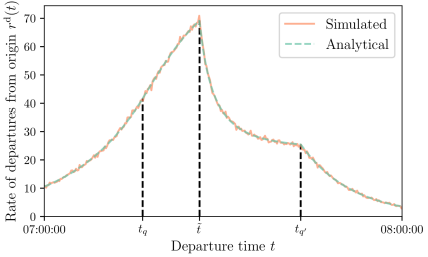
- Trip chaining
- Point-to-point trips
- Mode, departure time, and route choice
- "Generalized alpha-beta-gamma" utility
- Bottleneck queues
- Varying vehicle types

Tools:

- Rust language
- Discrete-choice models
- Inverse transform sampling
- Time-dependent many-to-many contractions hierarchies
- Event-based model

Results

- **METROPOLIS2 vs theory:**
  - Results well replicated when number of agents and breakpoints large enough
  - Convergence more difficult when closer to the deterministic model



Departure rate METROPOLIS2 vs analytical results

- **METROPOLIS2 vs METROPOLIS1:**
  - Similar results
  - Faster
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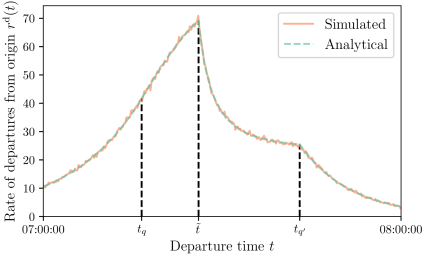

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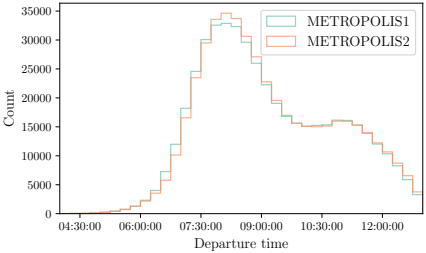

Convergence METROPOLIS1 vs METROPOLIS2

Motivations & Contributions

- **Definition:**
  - **Low Emission Zone (LEZ):** area of a city restricted from entry for the most polluting vehicles
- **Motivations:**
  - Solution to improve air quality in cities
  - Controversial: disproportionately penalize low-income households?
- **Contributions**
  - Methodology to **simulate** and **calibrate** large-scale simulation with METROPOLIS2 [Ziemke et al., 2019]
  - Methodology to **evaluate** public policies [Durrmeyer and Martinez, 2022; Bou Sleiman, 2023]
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- **Scope** of the simulation:
  - Île-de-France region
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  - Five modes (car driver, car passenger, public transit, bicycle, walking)
- Four-step **calibration methodology:**
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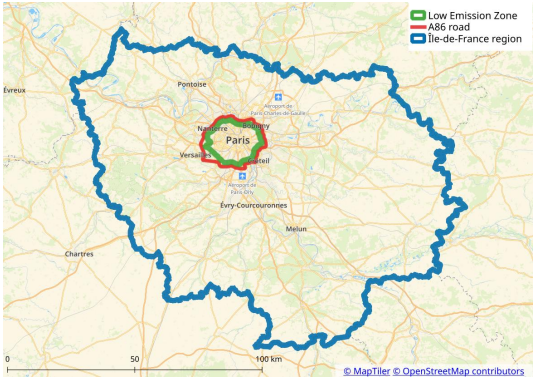

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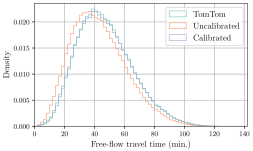

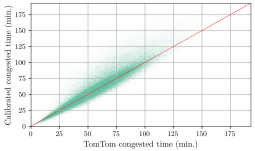

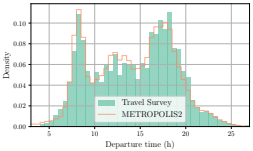

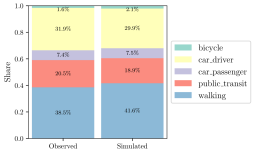

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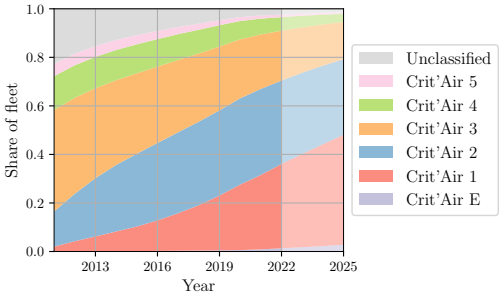
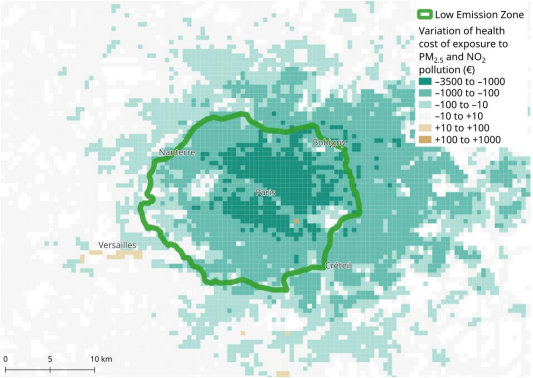


Results

- **Global impact:**
  - Car mode share: 36.6 % → 34.7 %
  - Vehicle-kilometers −3.9 %
  - $PM_{2.5}$ emissions −7.6 %
  - $PM_{2.5}$ premature deaths −13.0 %
- **Individual impacts:**
  - Evenly distributed health benefits
  - Significant disparities in distribution of travel surplus
  - Losers: banned car owners traveling inside the LEZ



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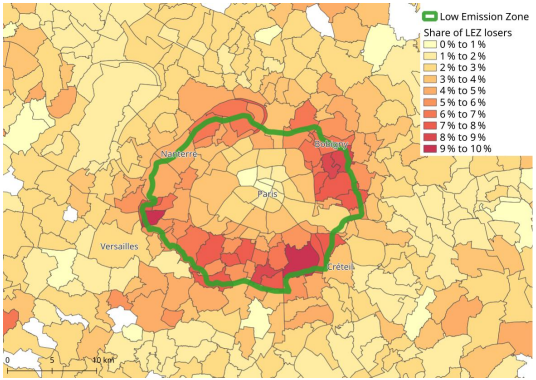
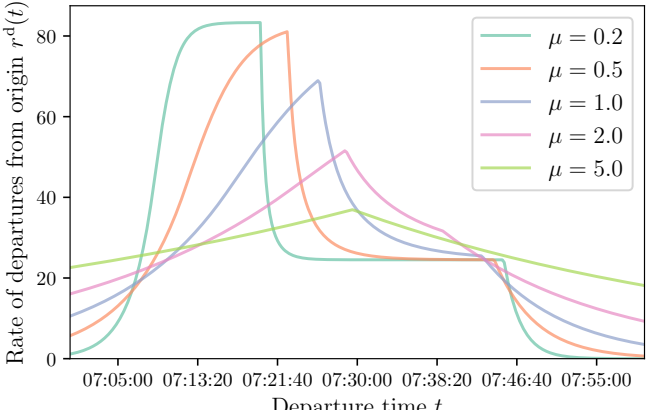
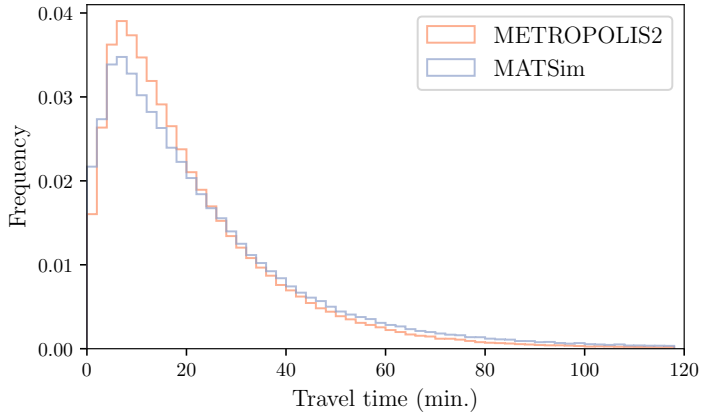


Thank you

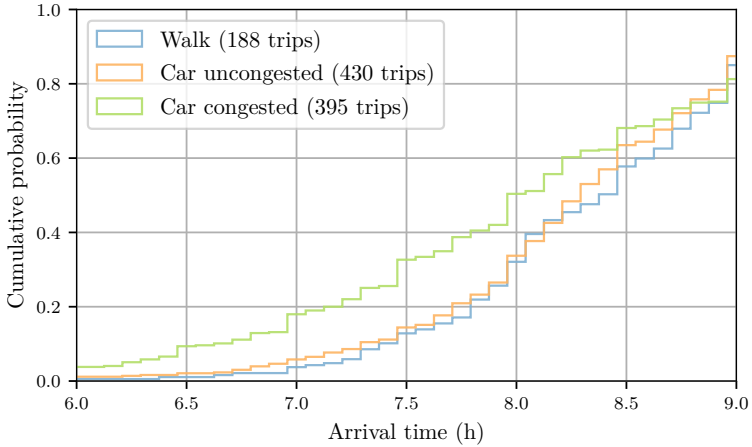
Departure rate as a function of μ (analytical model)



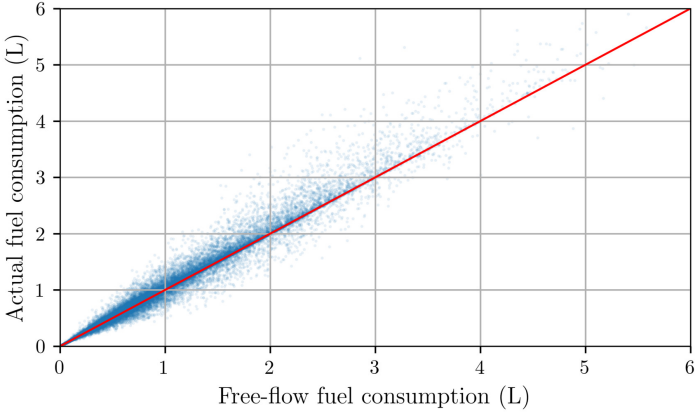
MATSim vs METROPOLIS2 travel time distribution



Arrival time distribution by mode (Intermediate category, EGT 2010)



Free-flow vs actual fuel consumption



Public transit flow variation (LEZ)