El Farol City

Towards new modelling representations of urban mobility

Rafał Kucharski

Jagiellonian University

SONATA BIS Grant Interview

COeXISTENCE

Rafał Kucharski - Transportation Scientist

Transportation Conbtributions:

- Methods (`MaaSSim`)
- Tools (`RouteRL`)
- Algorithms (`ExMAS`)
- ...

in top journals and conferences

Continuous funding:

- ERC StG (PD TU Delft)
- NCN Opus + IDUB (comeback)
- HE (SUM Project)
- ERC StG $\rightarrow$ AAAS Meeting 26

Emerging brand:

- Leading and unique in CEE.
- Growing in size and quality.

Interdisciplinary:

- Computer Science
- Machine Learning
- Maths
- Optimization
- Sociology/Psychology

El Farol

- Physics/Complex Systems

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Classic problem: revisited

Which:
road,tramway,bike-lane
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The Current Paradigm:

Macroscopic Equilibrium Based Models
(*Nash* → *Wardrop*)

This makes forecasting rigorous and practical:

Compare two equilibria (current vs future) and measure the impact.

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Problem

How to improve a transport system?

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Reality: Human behaviour

we (the travellers) are neither perfectly informed, rational, homogeneous, nor deterministic.

Quite contrary, we are:

biased, vary in taste, use habits, beliefs, incomplete information, and argue with friends over which route is the best.

Issue:

1. there are detailed agent-based models,
2. we know that our behaviour is complex (not Nash),
3. empirical data suggests that the observed systems are not in equilibria

why SOTA remains macroscopic?

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Why hasn't the shift happened yet?

Long standing, and growing gap between:

- state-of-the-art microscopic agent-based models (more detailed and nuanced)
- and state-of-the-practice macroscopic equilibrium models.

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- **Problem:** Missing longitudinal observations of learning trajectories. We see the what (flows) but not the how (sequences of decisions over weeks).
- **Solution:** Unique access to **Telecom traces** to observe long-term individual routing strategies in known contexts.

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- **Framework:** Simulation framework missing to move from single-behaviour models to diverse, heterogeneous populations.
- **Experiments:** Not enough experimental data to understand models.

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- **Problem:** Non-deterministic simulations are often dismissed as unstable or chaotic.
- **Solution:** Developing **Physics-inspired measures** to quantify stability, stationarity, and convergence in non-equilibrium systems.

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El Farol City

Virtual city of heterogenous, diverse agents - digital twin on which optimal policy actions may be identified.

Bridging the gap

Hypothesis 1

Urban mobility, (like El Farol Bar Classical Game Theory Puzzle) is a complex system of heterogeneous individuals.

Despite microscopic variability ($\sim$ chaos), it yields a state that is macroscopically stable, quantifiable, and predictable.

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Macroscopic equilibrium models can be replaced by families of trained agent populations.

For models which are more realistic, responsible, detailed, robust, meaningful and applicable (also in ML).

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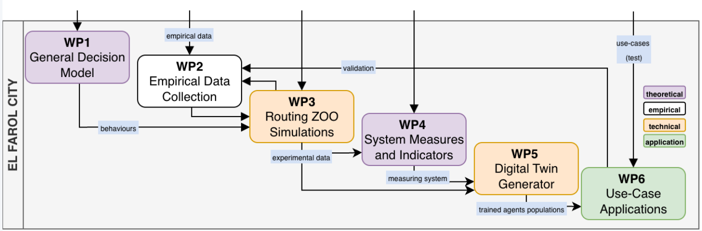
Work plan

- **WP1 (Theory)**
- **WP2 (Data)**
- **WP3 (Simulation)**
- **WP4 (Measures)**
- **WP5 (Tool)**
- **WP6 (Application)**



WP1: General Decision Model

Objective:

Create a unified mathematical representation of urban mobility behavior.

Unify proposed models and identify missing phenomena:

- non-deterministic choices
- subjective perception,
- taste variations,
- bounded rationality,
- indifference bands,
- inertia,
- habitual choices,
- real-time information,
- guidance (GoogleMaps),
- exploration
- ...

Learning (update perceived cost)

$$\overline{C}_{i,\tau,k} \leftarrow \begin{cases} \overline{C}_{i,\tau-1,k} & \text{if } a(i,\tau-1) \neq k \\ \overline{C}_{i,\tau-1,k} & \text{if } \left|\overline{C}_{i,\tau-1,k} - \hat{C}_{i,\tau,k}\right| \leq \gamma_C \\ (1-\alpha_0)\overline{C}_{i,\tau-1,k} + \alpha_0\, \hat{C}_{i,\tau,k} & \text{otherwise} \end{cases}$$

- update only for chosen action k
- bounded rationality: ignore small surprises $\leq \gamma_C$
- learning rate α_0 controls adaptation

Decision / Act (noisy utility + inertia + exploration)

$$U_{i,\tau,k} = \beta\, \overline{C}_{i,\tau,k} + \varepsilon_{i,\tau,k} \qquad \varepsilon_{i,\tau,k} = w_i \varepsilon_i + w_{ik}\varepsilon_{ik} + w_{ik\tau}\varepsilon_{ik\tau}$$

$$a(i,\tau) = \begin{cases} a(i,\tau-1) & \text{if } \Delta\overline{C} \leq \gamma_u \\ \begin{cases} \arg\max_k U_{i,\tau,k} & \text{w.p. } 1-\delta_{i,\tau} \\ \text{random } k & \text{w.p. } \delta_{i,\tau} \end{cases} & \text{otherwise} \end{cases}$$

- β scales sensitivity to perceived costs
- γ_u inertia / indifference threshold
- δ exploration probability

WP2: Empirical Data Collection

The Data Breakthrough:

Longitudinal day-to-day routing datasets from cellular traces.

- `Orange` **Partnership:** Resolved legal (GDPR), corporate, and technical hurdles for access .
- **Calibration:** Fitting the WP1 model to sequences of observed real-world choices.
- **Extension:** Possibly complemented by SmartCard data from London (TfL), Washington (WMATA), Geneva, ...

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78aef455-75ed-4087-86a4-20081e93a1a7	5	20.10.2025	17:00-17:30	38	Grid_102726

Orange

Sample data of 1000 agents received from Trójmiasto - more to follow (within `COeXISTENCE`)

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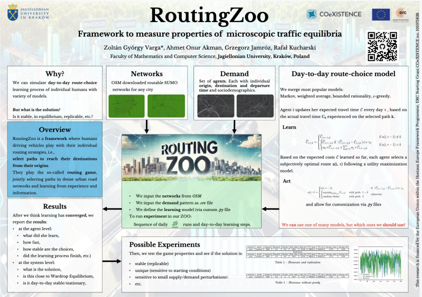
WP3: RoutingZOO Simulations

Routing ZOO:

simulation platform where virtual drivers experiment with routing strategies to navigate from origins to destinations in dense urban networks.



1

Experimental scheme

Extensively replicated expreriments with various population compositions and realizations, with many realized learning trajectories and (in)stabilities.

HPC computations

We will need dozens of CPUs to build extensive expiermental data to properly understand the system.

We have it @ lab lavel → GMUM @ UJ → PL Grid

[1] `https://github.com/COeXISTENCE-PROJECT/RoutingZoo`, presented @TRB Washington 2025

WP4: System Measures and Indicators

How can we describe and measure the macroscopic order of the microscopic system?

Individuals' state (micro):

- utility, travel time, travel cost, comfort
- reliability, regret, logsum
- training efficiency, exploration, entropy

Macrostate (KPIs):

- system-wide performance (pax-h, fuel, CO_2, delays)
- variability, stability, equity (Gini)
- stationarity, ergodicity
- replicability, Lyapunov exponent, roboustness (Perturbation Tests)

Measures

Category	**Typical measures**
State	Mean, variance, entropy, distributions
Dynamics	Autocorrelation, Lyapunov, phase transitions
Performance	Throughput, delay, reward
Equity	Gini index, Jain's index, variance
Coordination	Mutual information, synchronization
Robustness	Sensitivity, recovery time
Complexity	Entropy, predictability

Challenge

Transfer knowledge from complex system physics to agent-based models of complex social systems.
PostDoc + PhD + scentific commitee

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WP5: Digital Twin Generator

Family of pre-trained agent populations realistically reproducing given mobility situation.

Digital Twin Generator:

A reusable tool to generate pre-trained agents' populations. Combines WP1 (Behavior), calibrated to data (WP2) and trained in RoutingZOO (WP3).

- **Output:** Digital Twins of cities that reproduce observed macroscopic network states.
- **Usability:** Ready-to-use populations for Machine Learning training and bechmarks.

Behavioural Cloning - Generative AI

Possibly extending (generalizing) empirically observed behaviour for out-of-distribution cases[a] with autoencoder architecture(?)

[a] probably not enough data to train reliably

ML contribution:

Potentially bridging the gap to scale ML applications in transportation science domain

Like:

- PettingZOO
- OpenSpiel
- Football RL players (FIFA)
- DeepMind Melting Pot

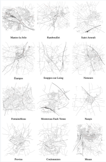
WP6: Use Case Applications

Testing El Farol framework against standard equilibrium forecasts.

Toy network tests first

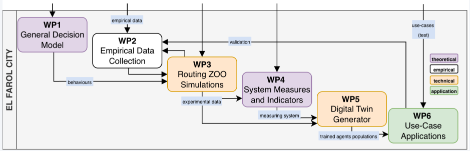
- For a set of pre-trained populations (WP5)
- of agents applying various behavioural models (WP1)
- of macroscopic measures (WP4)
- meeting the empirical observations (WP2),
- trained in `RoutingZOO` (WP3)

let's analyze how we predict impact of generic network interventions (new road, road-closure) across 26 cities.



Feedback Loop:

we iterate back to WP1–WP5 until satiasfactory results



Toward real cases:

- Krakowski Model Transportowy UM Kraków,
- Model Transportowy Aglomeracji Warszawskiej UM Warszawa,
- Pasażerski Model Transportowy CPK.

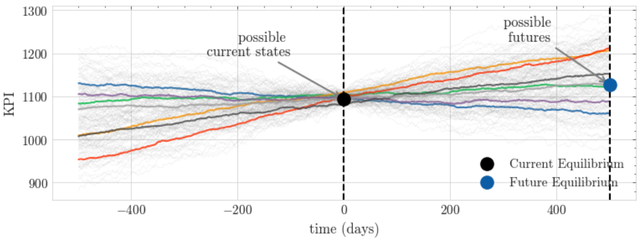
Objective

Replace static equilibrium based methods in practical use-cases

Possible new paradigm for modelling-aided policy interventions in transport systems.

State-of-the-practice

Build the road for which the new Equilibrium State yields maximal performance.



El Farol City

For a family of trained agent populations, yielding diverse represenations of currently observed state, run a replicated probabilistic simulations towards the new state. Observe the family of realized trajectories and assess their performance.

Significance

Decisions on evolutions (or revolutions) of our transport systems (efficiency of public money spendings) shall be based on solid and sound analytical analyses, with realistic and detailed simulations.

Bottom line: We have no tools to shift us towards sustainable and efficient transport systems without ideology bias.

Summary

Risks, team building and contribution.

Physics and Transportation

Breakthroughs:

- Gravity Model (1959)
- Traffic flow (fluids, LWR, 1955)
- Pedestrian Flows (Helbing Social Force Model 1995)
- . . .

Risks

Risk	Mitigation Strategy
Scientific: Models fail to converge or stabilize.	Strong Scientific Committee (Prof. Watling, Prof. Flotterod). Focus on defining "invariance regions" rather than strict convergence. Leverage Complex System Expert knowledge.
Data Access: Legal changes block Telecom data.	Business model already verified. Fallback to public smart-card datasets (TfL/Washington) via partners.
Computational Load: Simulations are prohibitive.	Using existing Lab infrastructure + GMUM UJ server room + PLGrid access.
Team Building: Difficulty recruiting Physics experts.	Strong brand of the Lab (ERC, NCN). Competitive environment at UJ Math/CS Faculty.

Team

excelling in Complex Systems

experts at PD + PhD level

build a team to bridge Complex System & Transportation.

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El Farol City

A new modelling paradigm for the era of sustainable mobility.

Problem: Static models cannot capture behavioural complexity of multi-agent social system of urban mobility.

Significance: We make policy decision (build/close) based on oversimplified models.

Challenge: Data, Tools, Measures

Method: Models, Data, Simulation, Analysis

Risk: Mixed low-hanging fruits, large experiments and fundamental challenges of complex systems.

Impact: Potentially sound and long-lasting at moderate risk.

Thank You!

www.rafalkucharskilab.pl

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