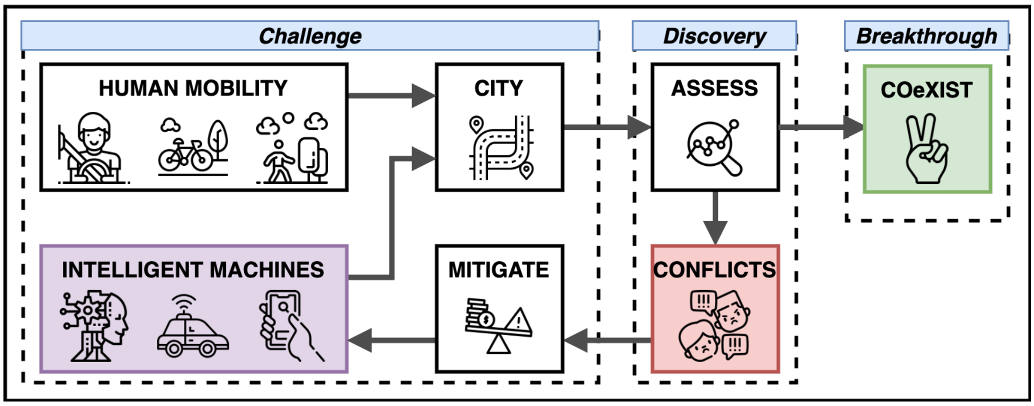
ERC Starting Grant 2022
Research proposal [Part B1]

Playing urban mobility games with intelligent machines. Framework to discover and mitigate human-machine conflicts.

COeXISTENCE

- **Principal investigator (PI):** Rafał Kucharski
- **Host institution:** Jagiellonian University
- **Proposal duration:** 60 months



AI-driven technologies are ready to enter urban mobility. They promise relief to the notoriously congested transport systems in pursuing sustainability goals. Since AI already outperforms humans in the most complex games (chess and Go) it is likely to win the urban mobility games as well, outperforming us e.g. in: route choices (to arrive faster), mode choices (to reduce costs), pricing strategies and fleet management (to increase market shares and profits). Tempting us and policymakers to gradually hand over our decisions to intelligent machines.

The consequences of this ongoing revolution are challenging to predict and largely unknown. While the abundance of previous studies proves the positive potential of AI in urban mobility (from autonomous vehicles via optimal routing up to fleet management), the negative impact is overlooked. Conversely, our scenario of interest is the *machine-dominated urban mobility system, where (collective) decisions of machine intelligence improve system-wide performance, yet at the cost of humans*, now facing e.g. longer travel times, greater monetary costs or being nudged to change natural travel habits into the optimal ones - desired by the machine-centred system.

Such scenarios, however, need to be discovered. To this end, *COeXISTENCE* embarks on the interdisciplinary expedition inside the virtual environment of urban mobility, where machines and humans play the game for limited resources. In the four pre-identified games we will explore the conflict scenarios, demonstrate them on reproducible case-studies, quantify with proposed measures and finally mitigate with a proposed multi-objective reinforcement learning framework, where machines learn to avoid conflicts while simultaneously pursuing their inherently selfish objectives.

Reaching the projects' objectives will be ground-breaking when new phenomena are discovered and lead to breakthrough when they are mitigated - pushing the system towards the synergy of **COeXISTENCE**.

Section a: Extended synopsis

COeXISTENCE is an interdisciplinary experiment in which intelligent machines collectively apply deep reinforcement learning to win with humans in urban mobility games. In the mixed human-machine environment of the future urban mobility they collaborate, anticipate and predict our behaviour to be better in: route choices (to arrive faster), mode choices (to arrive cheaper), pricing strategies and fleet management (to increase market share and profits). In the games for limited resources, this means a negative impact for other players (humans). This research programme aims to 1) experimentally discover human-machine conflicts in the four urban mobility games and then 2) mitigate them with a novel multi-objective reinforcement learning where machines simultaneously learn to be efficient and minimise their externalities. *COeXISTENCE* will shift the paradigm by introducing a so far overlooked phenomenon, discovered on reproducible experiments and successfully mitigated - paving the path towards human-machine synergy in the urban mobility of the future.

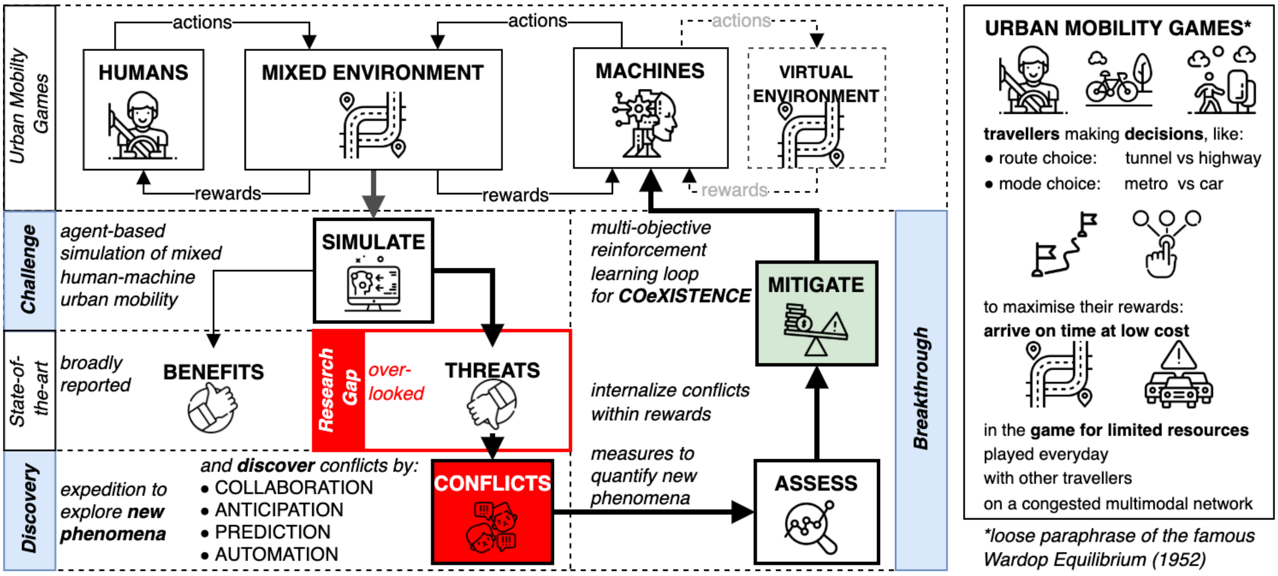


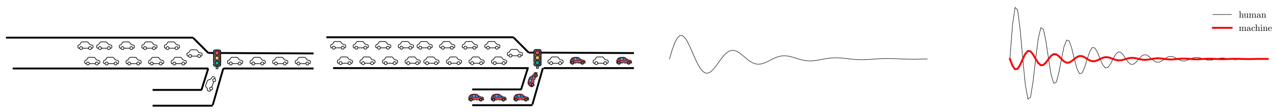
Figure 1: Synthesis: The *Urban Mobility Games* (top) will not be played by humans alone. Intelligent machines – better informed, more precise in calculations and predictions, connected and collaborative, trained within the virtual environment - are entering into the game for limited resources (explained on the right). Simulating such mixed environment is *challenging*, requires interdisciplinary expertise on transport systems, human travel behaviour and machine learning. Studies so far demonstrated how the games benefit from machine intelligence, while potential threats are overlooked. In this project, I pull off the expedition to discover conflicts between humans and machines in the urban mobility game. Within the simulation environment, this project will investigate if the advantages of the machines (*collaboration, anticipation, prediction and automation*) actually result in conflicts. Assessed, quantified and finally mitigated with a new paradigm for multi-objective reinforcement learning.

Promising future: Urban mobility is under increasing pressure in terms of efficiency (notorious congestion and delays) and sustainability (low emissions and externalities). Which stimulates disruptive innovations leveraging on big data and AI breakthroughs[1], pushing the way we travel towards an optimised, data-driven centralised system. The abundance of research demonstrated that a well-designed AI can improve transport system performance. Starting with control algorithms for traffic[2] and public transport[3], via optimal route-guidance[4] up to trip planning[5]. Benefits of *CAVs* (Connected Autonomous Vehicles[6]) were demonstrated on traffic flow[7], intersection capacity[8], traffic safety[9] as well as at the network level (when AI is the decision-maker in the urban mobility game - fig. 1, right) via cooperation[10–12], centralised optimization[13] and deep learning[14].

In parallel, AI-driven machines lately outperformed humans not only in simple, abstract games[15], arcade games[16], action games[17] and Go[18], but also in the cooperative games[19]. It is thus likely that in the near future machines will outperform humans also in urban mobility games.

Overlooked threat: Introducing a class of more efficient (AI-driven) players into the game for limited resources will yield *human-machine conflicts: novel phenomena of profound significance to the future of urban mobility* - the hypothesis that still has to be confirmed. Surprisingly, within overwhelming enthusiasm, criticism is scarce. Whereas in other fields issues of ethics, transparency, explainability and controllability are in the spotlight - in urban mobility they are overlooked. Conflicts are broadly explored at the micro-level of traffic (flow stability, intersection, lane-changing and merging) both among automated vehicles[20] (the famous ethical dilemma[21]) and between humans and machines[22]. Moreover, at the micro-level, apart from selfish also more social, altruistic behaviours were shown applicable for CAVs[23]. Yet at the network level, when machines are decision-makers in the urban mobility games, conflicts remain out of scope. Worryingly, authors demonstrating CAVs' potential often report humans as *suboptimal* and *selfish*[24], or as objects nudged towards the behaviour desired by the system[13] - in contrast to the machines: fully compliant objects allowing to reach system optimum[25].

Conflicts between humans and machines in urban mobility games were not reported yet. There were no simulation studies that show how machines' strategic behaviour in pursuing their objective functions is impacting humans. Consequently, this potential negative impact is missing solid scientific underpinning. Neglecting conflicts not only puts us at risk of deploying potentially malicious AI into our cities but also prevents us from unleashing the full AI potential.



(a) The route-choice game: Network bottleneck (highway narrowed to a single lane). Under the user-equilibrium (left) vehicles queue from the west, while the south inlet is hardly used. Yet when CAVs (red) start making **collaborative** routing decisions (right) they successfully *cheat* adaptive signal control and gain priority from the south. Yielding *conflict by collaboration*: intelligent machines reduce their own waiting times at the cost of the longer queue for humans.

(b) The day-to-day adaptation game: Travellers adapt after a network disruption (e.g. closed bridge). The social system (left) where rational humans adjust their decisions stabilises smoothly after a few days[26]. CAVs learn to anticipate this process and benefit from it (right), presumably at the cost of humans forced to adapt now longer with stronger oscillations, yielding *conflict by anticipation*.

Figure 2: Human-machine conflict scenarios in urban mobility games - illustrative examples.

Conflicts: I identified the following four urban mobility games in which introducing machine intelligence may lead to conflicts with humans:

a) the route choice game, where user-equilibrium of travellers selecting optimal paths to reach their destination is disrupted by collaborative machines (fig. 2a),
b) the day-to-day adaptation game, where the behavioural process of adjusting to the new situation (e.g. closed bridge) is violated by machines anticipating human behaviour (fig. 2b),
c) the dynamic pricing game, where detailed behavioural profiles of individuals are abused by mobility platform correctly predicting human behaviour,
d) the repositioning game, where individual drivers collectively supplying the two-sided mobility platform are outperformed by the centralised management of the automated fleet (fig. 3).

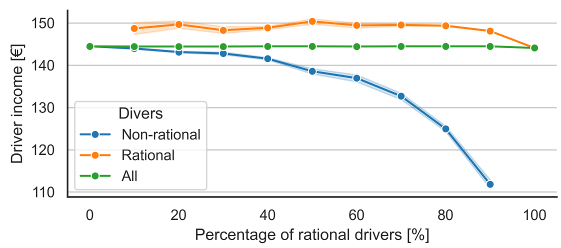


Figure 3: Preliminary results of **conflict by automation:** average incomes when using AI-driven guidance (orange) are greater than those of human drivers (acting behaviourally - blue). Experimental results of my student (F. Ghasemi) on my agent-based two-sided mobility platform simulator MaaSSim - one of the workhorses of this project.

Opening four conflict frontiers covering a variety of technologies, methodologies and social interactions. The first two are illustrated with **case studies** in fig. 2, while fig. 3 shows **preliminary findings** from the last one.

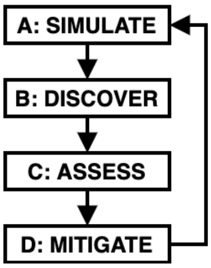
The objective is to experimentally verify the two main hypotheses:

- **H1** intelligent machines in urban mobility games will learn to win **at the cost of humans**.
- **H2** yet, intelligent machines can learn to simultaneously reach their own goals and **mitigate conflicts**.

To this end, I will integrate and extend existing simulation frameworks, behavioural models and machine learning algorithms to reproduce the complexity of future urban mobility. Reproducing games in the mixed human-machine environment is *challenging* and requires an interdisciplinary research programme spanned between deep reinforcement learning (RL), urban mobility, agent-based models, human behaviour and adaptive complex systems. All simultaneously integrated within the already complex social system of urban mobility with non-deterministic behaviour and feedback loops. I will create virtual environments for human-machine interactions and conduct experiments aimed to discover new phenomena. Conflicts, observable via quantifiable measures will be assessed from various perspectives: humans, machines and their operators, system and policymakers. Finally, the negative impact of machines will be internalised within agents learning loops.

Discovering human-machine conflicts and demonstrating them on reproducible realistic scenarios will be ground-breaking and shift the paradigm of evaluating human-machine *COeXISTENCE* in future urban mobility system. Consequently, the new reinforcement learning paradigm where the machines care not only about their own goals, but also about their external impact can be a breakthrough - paving a path to the synergy of humans and machines in urban mobility and beyond.

Methodology: To reach the project's objectives I set up the following <u>research programme</u> in which:



First, I create virtual environments where humans and agents play urban mobility games,

where I experimentally discover conflicts between machines and humans,

which are assessed with the proposed measures so that

they can be integrated within agents learning process to mitigate conflicts.

A **SIMULATE**

where machines interact with humans within mixed the urban mobility simulation environment.

Objective: Create simulation environments capable to reproduce human-machine urban mobility games.
Method: I will build on the state-of-the-art urban mobility models and simulation frameworks[27], underpinned with realistic behavioural models[28] and disaggregated agent-based representations[29]. I selected three open-source state-of-the-art urban mobility simulators capable to reproduce four games in which conflicts may arise a) `FLOW`[27] (to simulate traffic flow with RL agents), b) `MATSim`[30] (to simulate day-to-day adaptations) and c) `MaaSSim`[31] (our own two-sided mobility platform simulator to simulate dynamic pricing and repositioning). I will integrate them with reinforcement-learning frameworks - like in `FLOW`[27], where traffic model of `SUMO` is already integrated with `RLlib`.
Challenges: Integrate human behaviour and reinforcement learning within a single framework. Ensure effective and stable learning of agents and enable flexibility (of inputs and parameters), efficiency (to conduct thousands of replications) and realism.
Outcome: Set of sandbox environments (deployed in the virtual computing environment, using both CPUs and GPUs for deep learning on distributed experiments) ready to reproduce scenarios of interest.

B **DISCOVER**:

where I conduct broad and deep expedition searching for a variety of conflicts.

Outcome: Reproducible benchmark case-study for each game:

B.1 **The route choice game**

where CAVs use reinforcement learning to collaboratively outperform humans.

State-of-the-art: Recent studies demonstrated how intelligent machines improve system-wide performance both in macroscopic[25] and microscopic[32] route-choice problems.
Method: I start with an agent-based dynamic user equilibrium on a road network, where travellers iteratively adjust their route choices until they stabilise at their individually optimal routes. I gradually replace humans with autonomous vehicles and introduce RL in which they collectively learn how to maximise rewards - reduce travel times (like[14,24,33]). To induce conflicts I will experiment with the individual vs. centralised vs. collaborative behaviour, rewarding, discount factors, evolutionary adaptations or exploitation-exploration trade-offs.
Challenge: Making sure that agents successfully learn - improve their actions and reach stable optimum - which is non-trivial and highly sensitive to hyper-parameters, inputs and local minima. Identifying case-studies where agents strategies are negative for humans (like in fig. 2a).

B.2 **The day-to-day adaptation game**

where machines learn to anticipate the human behaviour and benefit from it.

State-of-the-art: Solid theoretical understanding of both optimal[26] and behavioural[34] day-to-day adaptive process, allows to reproduce how travellers adjust to new situations[35]. ML algorithms successfully anticipate human actions in a game-theoretical setting[15].
Method: I simulate the case where humans adapt to the new traffic situation (e.g. closed bridge[35]) along with machines, that learn how to anticipate our behaviour.
Challenge: Simulate the learning process in which machines not only anticipate the human adaptation process but also collectively induce non-damping oscillations and benefit from this (like in fig. 2b).

B.3 **The dynamic pricing game**

where mobility providers abuse traveller behavioural profiles to maximise their profits.

State-of-the-art: Accurate picture of heterogeneous travel behaviour is available via discrete-choice models[28,36,37] and predictive machine-learning algorithms[38] including RL models for discriminatory pricing[39]. Human behaviour is not only better understood from data[40], but also predicted[41] and controlled[42]. Notable for this case, evidence suggests that e.g., Uber employs long-term aggressive market entry strategies, heavily subsidised in the early stage for the sake of future profits[43].

Method: Using my own MaaSSim[31] I will simulate the multi-modal scenario, where travellers select between mobility platform (like Uber) and public transport. I will assume that each individual is different and the platform operator needs to learn this heterogeneity. I will simulate a day-to-day pricing game with real-world demand patterns (e.g. for Amsterdam[44]) on the synthetic, yet realistic population. Platform will learn the behaviour of individuals by testing if they accept price offers[45]. Eventually, AI-driven operator will learn a balance between trip fares and market share (which drops when fares are high) for which the profits are maximised[46].

Challenges: See if such policy can induce the so-called Mohring effect[47] and harm public transport (publicly subsidised) - being negative not only for the travellers but also for sustainability goals.

B.4 The repositioning game

where drivers' labour becomes less efficient than centrally controlled robots.

State-of-the-art: Centralised[48] and decentralised[49] algorithms were demonstrated to increase profits of service providers with deep RL algorithms[50,51]. Our preliminary studies on two-sided platforms demonstrate how human drivers are outperformed with a data-driven method (fig. 3).

Method: I will use our two-sided mobility simulator[31] to reproduce the game of repositioning - where drivers predict the demand and move closer to incoming requests. I will simulate a variety of real-world demand patterns (e.g. from NYC[52]), imperfectly predicted by machines due to their non-deterministic nature. I presume human drivers to hold some advantages that I want to reveal. For instance, the efficiency-oriented dispatcher may restrict services to high-income zones of greater demand, leaving out outskirts and low-income zones - as we observed in our analysis of 4 million Uber trips[53].

Challenge: While human drivers seem to be in a hopeless situation (easily outperformed by data-driven centralised fleet management) challenge is to anyhow identify the added value of human operations on the decentralised platforms (e.g. diversity, non-determinism) and justify human presence in the future systems (e.g. in system resilience, coverage or equity).

C ASSESS

where conflicts are quantified from perspectives of humans, machines and policymakers.

Method: Here I will take various angles to observe the system. Starting from individual humans and machines (their travel times and costs), machine operators (their profits), up to the system perspective (total delays) and externalities (emissions). Such comprehensive set of KPIs will allow to understand subtle trade-offs between the benefits and costs of introducing machines to urban mobility.

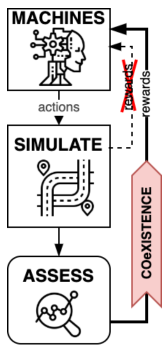
Challenge: Assess simulation results (interpreted as statistical distributions of stochastic process replications[54]) and propose a set of new KPIs covering the multiple angles to reveal both positive and negative impacts needed to identify Pareto-optimal trade-offs. Challenging to quantify: *equity* and *societal impact* - i.e. how human mobility is constrained with machine actions (possibly by extending the notion of *price-of-anarchy*[55]).

Outcome: Complete picture of positive and negative impacts of introducing machines into urban mobility - quantified with measurable, interpretable KPIs.

D MITIGATE

model-free reinforcement learning framework to mitigate conflicts and reach *COeXISTENCE*.

State-of-the-art: Multi-task RL with multiple agents' goals is successfully deployed, which allows to control behaviour in several dimensions[56] e.g. in social dilemmas of sustainability[57].



Method: I propose the generic learning framework where conflicts are an internal part of the reinforcement (see fig to the right). Now, along with the individual rewards, the environment outputs also the negative impact on humans (quantified via proposed measures). By reformulating agent's rewards I may internalise conflicts, either as a hard constrain or a new dimension in multi-objective reinforcement learning. The latter is more promising since it allows exploration of strategies that initially yield conflicts but eventually evolve towards their mitigation and paves the way towards synergy, when initially negative conflicts become positive. Surprisingly, it simplifies the learning convergence[58] (a central issue in multi-agent learning) and can be seen like a central level bias orchestrating non-coordinated, selfish agents. Moreover, we do not need to peek under the hood of IP-protected black-box AI, as only the reward is modified. Finally, it is model-free, even when the true roots of conflicts are not interpretable, the deep RL framework shall learn it and - along with maximising own rewards - mitigate it. I argue for feasibility of such approach relying on recent advances in multi-criteria[56], hierarchical[58] and cooperative[59] RL.

High risk - high gain Reaching project objectives, highly significant for the future of our cities is equally challenging. It requires a broad interdisciplinary expedition into the unknown, where one can easily get lost or come back with nothing. I anticipate a series of technical hurdles in this complex research plan. To make it feasible, my solid background on urban mobility[60], agent-based modelling[31], game-theory[55], complemented with industry experience in Machine Learning is backed-up with an ecosystem of gmum lab where I tenure-track, building unique expertise on the intersection between urban mobility and ML.

Thus (and thanks to complementary skills of the interdisciplinary team to be hired) the simulation of urban mobility, stochasticity of human behaviour, demanding computations of non-smooth complex adaptive systems are more challenges than risks. Including the most demanding technical challenge: the convergence of multi-agent, cooperative reinforcement learning in human-machine urban mobility games. The true risks lay in verifying the two hypotheses of the project: **H1** discovering unknown phenomena and **H2** mitigating it - here the stake and challenges are the biggest.

Discovering and reproducing conflicts is far from granted. It requires a carefully tailored simulation framework, precisely reproduced urban mobility games and effectively learning, collaborative machines. Despite relying on solid theoretical and practical background in the tailored experiments, I may fail to discover conflicts - even on the minimal examples of the famous paradoxes, with extensive directed grid-searches. In such, unlikely, case I will resort to the positive side of the project: the synergy of COeXISTENCE. I will use the loop designed to internalise negative impact and now focus on learning how intelligent machines may help us reach sustainability goals and improve performance for humans. Such research will be equally significant to the original plan.

plan in case of failing to:	
DISCOVER	**MITIGATE**
focus on synergy, rather than mitigation	report and understand discovered conflicts

Similarly, *mitigating conflicts is far from granted.* I may fail to effectively internalise conflicts, with a risk that in the already complex, multi-agent collaborative stochastic environment it may be impossible for agents to learn multiple objectives. In such a case, I will resort to new discoveries and their assessment - which will anyhow shift the paradigm and set the new ground for designing the future urban mobility in mixed human-machine environment.

The team: To tackle this interdisciplinary project, the PI (with unique expertise in urban mobility modelling, software development and ML) will form a team of 3 PhD students (each for 48 months) and a PostDoc (36mo). PhDs will cover backgrounds in deep learning, urban mobility and complex systems. To tackle interdisciplinarity I will expertise of prof. Oded Cats - Urban Mobility expert from TU Delft; and prof. Jacek Tabor - founder and head of the leading Machine Learning Group in Central Europe - gmum - with strong alumni, e.g. Wojciech Czarnecki - the main contributor behind the famous StarCraft[17] and Quake III[61] RL breakthroughs - cover stories in the Nature and Science.

Impact and Conclusion: We are on the brink of another major, disruptive (r)evolution in urban mobility, which may dramatically change not only urban mobility but the entire urban landscapes of future cities. Technology shall be ready anytime and will enter the market straightaway. Mobility providers will start implementing technology that remains largely a black-box. State-of-the-art broadly reports benefits but crucially overlooks the potential threats. New phenomena, discovered in quantifiable simulation experiments within *COeXISTENCE*, shall bring a scientific *breakthrough* in our assessment of new technologies. Giving us a methodologically solid framework not only to anticipate conflicts and mitigate them but also to explore limits and unleash a full synergic potential responsibly.

With a set of reproducible benchmarks, *COeXISTENCE* will set a new standard, shifting the paradigm by introducing a new dimension to the picture. Proposed AI solutions will be assessed not only based on how they perform but also how they affect others, in particular us - humans. Such a novel approach will be a foundation for scientifically solid assessments - substantial for the societies of the future to solve dilemmas: how much freedom shall be traded for sake of improving urban mobility and reducing carbon trail. The model-free mitigation framework with a novel multi-objective learning loop may be applied beyond this project to help us to solve urgent dilemmas in sustainability, urban planning or equity. Findings may be significant not only for the broad scientific community but also inspirational for the general public, for which topics of AI and sustainable mobility are vital. Exposing overlooked threats with sharp and eye-opening experiments will resonate within the wider public, whose social participation is crucial before democratic societies will decide on the future of their cities.

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Me and my collaborators appear in bold.

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Section b: Curriculum vitae (max. 2 pages)

PERSONAL INFORMATION

Family name, First name: KUCHARSKI, Rafał

Researcher unique identifier(s):

https://www.researchgate.net/profile/Rafal-Kucharski-2
https://orcid.org/0000-0002-9767-8883
https://www.linkedin.com/in/rafalkucharski/
https://scholar.google.pl/citations?user=z3bOMUAAAAAJ
https://github.com/rafalkucharskiPK

Date of birth: **17th Oct 1986**

Nationality: **Polish**

URL for web site: https://rafal-kucharski.u.matinf.uj.edu.pl/

- **EDUCATION**

2015 PhD, *Simulation of rerouting phenomena in dynamic traffic assignment with the information comply model*
Faculty of Civil Engineering, Cracow University of Technology, Poland
prof. Andrzej Szarata (co-supervised by prof. Guido Gentile, La Sapienza, Rome)

2010 MSc in Transport Engineering (*cum laude)*, Cracow University of Technology, Poland
(written at KIT Karlsruhe under Erasmus Programme)

- **CURRENT POSITION(S)**

2021 Assistant Professor, **Group of Machine Learning**, Faculty of Mathematics and Computer Science, Jagiellonian University, Poland

- **PREVIOUS POSITIONS**

2019-2021 – **ERC StG postdoctoral researcher,** Dept. of Transport & Planning, TU Delft, Netherlands.
2017-2019 – **senior data scientist,** NorthGravity, Kraków/Chicago
2015-2019 – **assistant professor,** Dept. of Transport Systems, Cracow University of Technology, Kraków
2013-2016 – **R&D software developer,** PTV SISTeMA, Rome
2011-2013 – **CEO & Founder** – i2 intelligent infrastructure, scientific software for transport modelling
2010-2015 – **PhD student,** Cracow University of Technology, Kraków/ La Sapienza, Rome

- **SELECTED GRANTS**

2021 – Recipient of competitive selection process of Tenure Track (assistant professor) position within Group of Machine Learning of Faculty of Mathematics and Computer Science, Jagiellonian University, Poland

2021 – 2024 NCN OPUS 19 - Post-corona shared mobility: Modelling and controlling virus spread processes in shared mobility networks. - PI (ranked 1st in the panel of 197 submissions in this nationwide research program with success rate around 12%)

2011 – 2015 EU funded DOCTUS full PhD Scholarship – (ranked 9th out of over 100)

- **SUPERVISION OF GRADUATE STUDENTS AND POSTDOCTORAL FELLOWS**

2021 – two PhD students, one PostDoc
Faculty of Mathematics and Computer Science, Jagiellonian University, Poland

2019 – 2021 four PhD students (daily supervision), four Master Students
Transport & Planning Department, TU Delft, Netherlands

2016 – 2019 14 Master Students
Department of Transportation Systems, Cracow University of Technology, Poland

- **ORGANISATION OF SCIENTIFIC MEETINGS**

2019 **Chairman and organizer** - 6th IEEE International Conference on Models and Technologies for ITS – MT-ITS, Kraków, Poland – www.mt-its2019.pk.edu.pl, editor of 91 Scopus indexed conference proceedings in IEEE Xplore, 120 participants from over 20 countries.

- **TEACHING ACTIVITIES**

2020 The University Teaching Qualification (UTQ) programme - TU Delft
2017 - Public teaching materials: https://github.com/RafalKucharskiPK/LecturesAndCourses
2015 - Lecturer at: **PhD studies** (IT systems in transportation, Demand modelling in passenger and freight transportation) and **Graduate and undergraduate studies** (Introduction to Transportation Planning; Transport Networks Planning; Traffic Microsimulation; Demand Forecasting ; Assessment for Transport System Development)

- **REVIEWING ACTIVITIES**

Journals: reviewer in over 10 IF journals (selected) including most respected in my field: Journal of Intelligent Transportation Systems: Technology, Planning, and Operations, Journal of Advanced Transportation, IET Intelligent Transport Systems, Transportation Research Record, IEEE ITS Transactions, European Journal of Transport and Infrastructure Research, Transportation Research Part C: Emerging Technologies, IEEE Access, Frontiers In Future Transportation, Promet, Archives of Transport and more.
Conferences (selected): Models and Technologies for ITS 2015, 2017, 2019, 2021, hEART 2017, 2018, 2019, 2020. Transportation Research Board 98th, 99th, 100th, Transportation Research Arena 2019, International Symposium on Transport Network Reliability 2020, 2021, The 12th International Conference on Ambient Systems, Networks and Technologies, 2021

- **INVITED TALKS (selected)**

2021 University of Warsaw, “What constituted transportation engineering as a Science”
2021 Hungarian Academy of Sciences, “Virus spreading in ride-pooling networks”
2021 Vrije Universiteit Amsterdam, “Exact matching of attractive shared rides”
2018 EPFL Lausanne, “Rerouting phenomena in Dynamic Traffic Assignment”
2017 PTV Karlsruhe, “Modelling rerouting phenomena in Dynamic Traffic Assignment”

- **PUBLIC SCIENTIFIC REPOSITORIES (selected)**

ExMAS Exact Matching of Attractive Shared rides
https://github.com/RafalKucharskiPK/ExMAS
MaaSSim Agent-based simulator for two-sided urban mobility markets
https://github.com/RafalKucharskiPK/MaaSSim

- **RESEARCH APPLICATION BEYOND ACADEMIA**

Warsaw Agglomeration Transport Model – multimodal model for purposes of strategic development of the 3 million agglomeration, used to assess multi-billion EU-funded investment schemas. I led the development of mathematical supply and demand models of multimodal transport networks. With Cracow University of Technology for Warsaw Municipality
https://transport.um.warszawa.pl/-/model-ruchu-aktualizacja-2016-2017
North Gravity AI & data cloud platform - producing AI insights for the Global Market. With the 75+ pre-built tasks to collect data and build production AI/ML pipelines. Integrated with python and notebooks tasks to customize the pipelines. I led the data-science and ML/AI development:
https://www.northgravity.com/product

- **MAJOR COLLABORATIONS**

Oded Cats (TU Delft), Costas Antoniou (TU Munich), Javier Alonso-Mora (TU Delft, MIT), Guido Cantelmo (DTU Copenhagen), Guido Gentile (La Sapienza), Andrzej Szarata (Cracow University of Technology), Lorenzo Meschini (PTV SISTeMA), Michal Niedzielski (Polish Academy of Science), Malte Schroeder (TU Dresden), Julian Sienkiewicz (Warsaw University of Technology), Achille Fonzone (Napier University), Andres Fielbaum (Universidad de Chile), Hans van Lint (TU Delft).

Appendix: All current grants and on-going and submitted grant applications of the PI (Funding ID)

Mandatory information (does not count towards page limits)

Current grants (Please indicate "No funding" when applicable):

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*[1]
Post-corona shared mobility	National Science Centre Poland – OPUS 19	1 090 800 PLN (250 000 EUR)	08.2021-08.2024	PI, group leader with two PhD students and a PostDoc	none
DigiCity	Excellence Initiative: Research University – Ministry of Science	455 000 PLN (100 000 EUR)	08.2021-08.2024	Competitive procedure for a tenure-track position to build own group in the Machine Learing lab at Jagiellonian University	none

On-going and submitted grant applications (Please indicate "None" when applicable):

Project Title	*Funding source*	*Amount (Euros)*	*Period*	*Role of the PI*	*Relation to current ERC proposal*[2]
COeXIST	HORIZON-TMA-MSCA-PF-EF ID: 101065305 (HORIZON TMA MSCA Postdoctoral Fellowships - European Fellowships)	155 000 EUR	2022-2024	PI. 24-month training and research in the Group of Machine Learning, with a 3 month secondment at Berkeley, CA	Overlapping – **in case of successful evaluation of this ERC StG proposal I will resign from Marie Curie**. MSCA proposal can be seen as a first part of this ERC proposal. In MSCA proposal I introduce the very same idea of human-machine conflicts. I propose to explore and identify selected conflicts without focusing on assessment and mitigation – which ERC proposal does. MSCA proposes to enter and explore the novel problem of COeXISTENCE – this ERC proposal plans to systematically address it and methodologically solve. Resigning from MSCA will not impact this ERC proposal, which remains complete and self-containing research programme.

[1] Describe clearly any scientific overlap between your ERC application and the current research grant or on-going grant application.

Section c:Early achievements track-record

I research complex social systems: urban mobility. Congested, urban multimodal networks used by millions of agents to reach their destinations and leaving huge sets of mobility traces ready to be applied for modelling, optimization, design and control across multiple disciplines.

I did PhD with prof. Guido Gentile (*La Sapienza*) in non-equilibrium dynamic traffic assignment. During my PhD I worked as R&D developer in spin-off company, implementing state-of-the-art real-time traffic models (e.g. for Beijing, Dusseldorf, Abu-Dhabi and Torino). I created official transport models used for strategic development of Warsaw and Krakow transport systems. I spent two years (2017-2019) outside of academia, working as *Senior Data Scientist* in a technological start-up, where I developed machine-learning skills inevitable to this project. I decided to come-back full time to academia in 2019 to join as a PostDoc to a prestigious **ERC Starting Grant** Critical MaaS of the young and enigmatic prof. Oded Cats at a world-leading T&P Institute at TU Delft, which (hopefully) set me on fast-track to become mature and independent researcher. Lately, I won the **tenure track** position in the **leading machine learning group** in Central Europe at the top-ranked university in Poland (Jagiellonian University in Krakow, est. 1364) to explore exciting and to the system performance (resilience, coverage, etc.), where I set up my **own team** (currently two PhDs and one PostDoc).

Only in the past 3 years I published 13 papers in the IF-indexed journals, with 4 further in the review. I was both a leading author, second author and supervisor in **Q1 journals of four different fields**: Transportation (*Transportation Research Part:B*), Operations Research (*European Journal of Operational Research*), Tourism *Current Issues in Tourism*) and Multidisciplinary (*Scientific Reports, PLOS One*). I co-supervise 3 PhD students and collaborated with 10 different groups from 4 countries, including top labs in Europe (*TU Munich, DTU, La Sapienza, TU Delft*). I gave 9 invited talks in five different countries. I authored or co-authored 56 peer-reviewed scientific publications in international journals and conference proceedings. In total I published: 14 IF journal papers, 10 other Scopus indexed papers, 14 peer-reviewed articles, 18 conference proceedings and 13 conference presentations and posters. I created two impactful scientific code repositories (Python simulation packages) broadly utilised by graduate and PhD students inside and outside my community.

I was continuously securing funding for my research at **five Universities in four countries**. Since my Master Studies (Erasmus at KIT Karlsruhe), through PhD (EU funded DOCTUS Scholarship – ranked 9th out of 100), international collaboration (COST action short-term scientific missions to La Sapienza University of Rome), I was selected as a PostDoc in the ERC Starting Grant and secured a national individual grant NCN OPUS (ranked 1st out of 197 proposals in the panel with a success rate of 12%). I contributed towards developing transportation research community in Poland, via: first papers in the most-reputable journals, cooperation with world-leading labs, organising top conferences in the field (6th MT-ITS - 120+ IEEE Xplore papers from 20+ countries), supervising PhD students who made a solid and recognised contributions to the field

I have a broad teaching experience (several courses at undergraduate and graduate level including creating new study programmes and online materials) and supervision (over 15 master students graduated, 3 on-going PhD students). I regularly contribute to the most popular venues of transportation community presenting work of my students and mine at the major transportation conferences. I serve to the community as the reviewer, committee member and a chairman. I gave invited talks at: EPFL Lausanne, VU Amsterdam, Hungarian Academy of Sciences, University of Warsaw, TU Delft and PTV Karlsruhe. I collaborate with machine-learning experts towards contributions to the Core A* conferences (NeurIPS, AAAI, ICML, etc.).

Research Highlights

In reverse chronology I list five papers selected to demonstrate capability to conduct independent, ground-breaking research and experience needed to complete challenging goals of this project:

- **Kucharski, R., Cats, O., & Sienkiewicz, J.** (2021). *Modelling virus spreading in ride-pooling networks*. Scientific Reports, 11 (7201). `https://doi.org/10.1038/s41598-021-86704-2`.
  In less than six months of the pandemic I described a novel phenomena with this urgent contribution. I mixed network science, epidemic modelling and our transportation expertise to understand the role of ride-pooling (emerging transport mode) in the virus spreading phenomena. We applied our own algorithm `ExMAS` to see how sharing rides in Amsterdam contribute to the virus spreading and proposed a novel effective mitigation strategy. Instead of submitting to the well-known journals of our field we managed to reach a multidisciplinary journal (which is rare in transportation). Moreover, as a preliminary study this work secured a personal grant for me (ranked 1st in the panel of 197, with success rate of 12%) - cornerstone of my own group (now 2 PhDs and PD), which, in turn, granted me a tenure track position within top-notch Machine Learning group.

- **Kucharski, R., & Cats, O.** (2020). *Exact matching of attractive shared rides (ExMAS) for system-wide strategic evaluations*. Transportation Research Part B: Methodological, 139, 285-310. https://doi.org/10.1016/j.trb.2020.06.006.
This is a methodological contribution - breakthrough ride-pooling algorithm - on which the previous virus spreading study relied. I proposed a smart formulation where otherwise exploding search-space imploded, allowing for the first exact formulation of the ride-pooling problem. Crucial for strategic assessment of the future urban mobility. This study was published in the most respected methodological journal of the field. Notably, I published it in less than a year after starting my PostDoc position in the leading transportation lab in the world, which was a pleasant surprise after a two-year break from academia in the industry.
- **Cats, O., Kucharski, R., Danda, S. R., & Yap, M.** (2022). *Beyond the Dichotomy: How Ride-hailing Competes with and Complements Public Transport*, PLOS One, *in press*, https://doi.org/10.1371/journal.pone.0262496.
This rare cooperation between a tech giant (Uber) and academia gained high visibility reaching also a non-academic audience. I processed, analysed, quantified and visualised 4 million trips from 6 cities in US and Europe to understand what is the relation between Uber and PT. I proposed new measures and visualisations to understand where Uber provides added value to public transport - revealing meaningful spatial patterns in New York, Stockholm, Houston and Amsterdam. Again, going outside of our comfort zone we reached to the multidisciplinary journal. Our clear and strong findings were synthesised in the official TU Delft press release which then spread across professional magazines and social media.
- **Drabicki, A., Kucharski, R., Cats, O., & Szarata, A.** (2021). *Modelling the effects of real-time crowding information in urban public transport systems*. Transportmetrica A: Transport Science, 17(4), 675-713. https://doi.org/10.1080/23249935.2020.1809547.
In this study I successfully played a role of the supervisor. We examined a novel technology of real-time crowding information using complex agent-based transit simulations and provided the first system-wide assessment allowing to understand the true impact of the new technology before it is deployed. With the detailed case-study results from Krakow this work is becoming an assessment benchmark. Besides, this is my personal success, since Arkadiusz is my first PhD student, whom I convinced to leave the comfort zone and pursue scientific excellence, which payed back with a stream of high quality, methodological papers that allowed him to join international scientific community - as my first alumni.
- **Kucharski, R., & Gentile, G.** (2019). *Simulation of rerouting phenomena in dynamic traffic assignment with the information comply model*. Transportation Research Part B: Methodological, 126, 414-441. https://doi.org/10.1016/j.trb.2018.12.001.
Novel model extending the state-of-the-art with a new phenomena. I proposed a real-time method to simulate how drivers adapt to unexpected events (traffic events) with a closed-form formulas to estimate the new equilibrium on the urban traffic networks. Published in the most respected methodological journal of the field, previously beyond reach for researchers from Poland. To make it happen I first secured personal PhD grant, then initiated collaboration with renowned prof. Guido Gentile in Rome, collaborated with La Sapienza (rejecting several low hanging fruits), became R&D developer in technological start-up, presented at most significant conferences of the field and finally made this solid contribution allowing me to become the core member of the transportation research community. This work is the only one listed with my PhD supervisor.

Above research outputs make a solid and diverse experience to address challenges of this proposal. In particular to reproduce first two games, I leverage on my PhD experiences in dynamic user equilibrium, for the second two games I will exploit my PostDoc experiences with agent-based models of two-sided mobility platforms, for game-theory I can build on my theoretical study of ride-pooling and for deep learning my experiences are supported with the excellent ecosystem of the lab where I tenure (GMUM). I have strong software development skills (R&D software developer at PTV), algorithmic skills (two public python scientific packages), data-science skills (Senior Data Scientist at NorthGravity) gained with exclusive datasets (UBER), under competitive grants (ERC StG), within world-leading labs (T&P at TU Delft, ranked 1st in EU, 4th in the World).

I have experience in coaching students, managing projects and leading research teams. I was leading research teams in the R&D, business and scientific projects. In particular I led development of: Strategic Models for Krakow and Warsaw research areas (at Cracow University of Technology), Data-Science pipelines (e.g. at NorthGravity), agent-based two-sided mobility platform simulator (e.g. MaaSSim at TU Delft).

Altogether laying complete set of skills needed to conduct interdisciplinary and challenging programme of **COeXISTENCE**.