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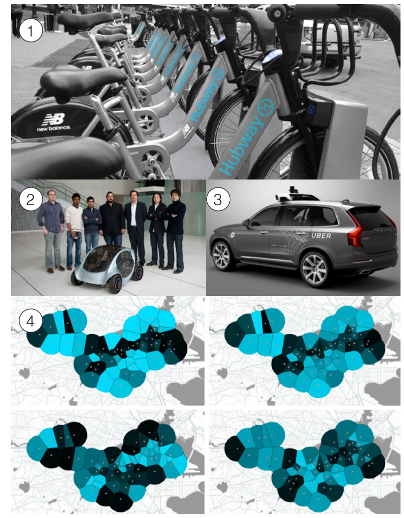
RESEARCH STATEMENT / URBAN SYNERGETICS

I leverage data, complex systems modeling, and information technology to study, design, and assess, synergies for smarter cities, architecture, and mobility systems. My position to urban cybernetics is not from a command-and-control perspective but rather from a cooperative one, in which, control emerges as a collective interaction of individual responses to goals of common interest. I contribute to the fields of planning, architecture, engineering, information/computer/social science, and design, in three ways:

1. **Data-driven urban dynamics modeling:** I develop data-driven system dynamics models to understand how human, physical, and information resources move in cities, and how their movements and concentrations affect performance of urban cyber-physical systems.
2. **Institutional mechanisms for self-regulation:** I design and study institutional mechanisms for collective control, and I assess their equilibrium dynamics both analytically and experimentally.
3. **Connective technologies and novel human-computer interfaces:** I design and prototype novel human-computer interfaces, sensing technologies, smart building systems, and embedded/distributed systems that close the loop between information and action in more intuitive ways.

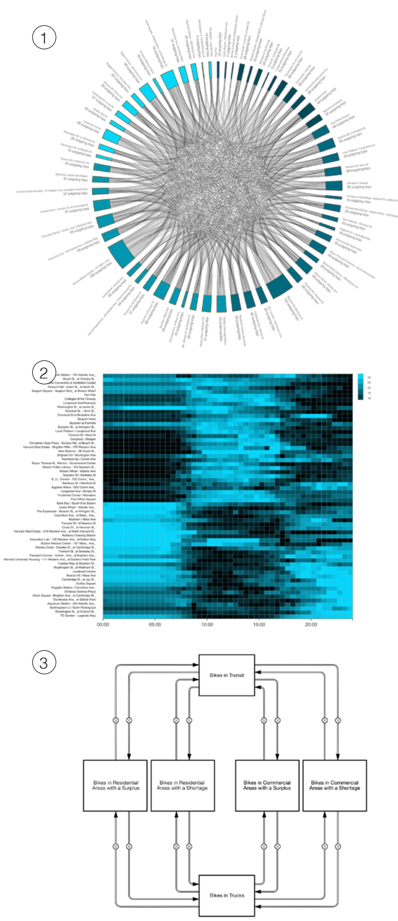


[1] The average shared bike costs more to rebalance than to ride while remains unutilized as much time as a private vehicle. 2] Mobility on Demand team, MIT Media Lab. [3] Self-driving Uber; utilization in car sharing is similar to bike sharing. [4] Flood-ebb tidal patterns in Boston's bike sharing system. Lighter tones indicate higher inventory levels; darker tones indicates lower inventory levels.

Data-driven Urban Dynamics Modeling

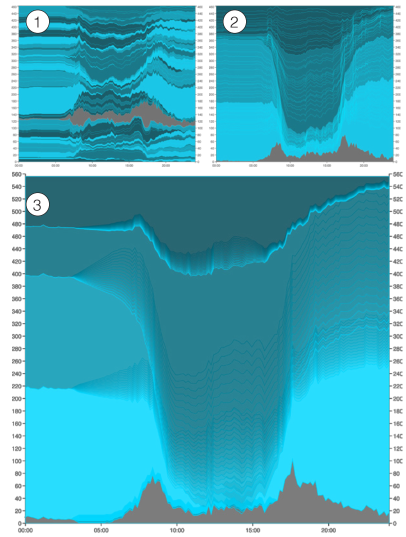
My first research area seeks to understand systemic laws of urban mobility by combining complex systems modeling with big data. The 21st century has witnessed a boom in on-demand mobility (MoD). Bike share, the quintessential MoD model today, mobilizes more than 7M daily trips in 1150 cities with an industry doubling biannually while the first autonomous vehicles have already hit the roads of Pittsburgh, Singapore, and Silicon Valley. Yet, contrary to common belief, the average shared bike costs more to rebalance than to ride, emits a third CO_2 of a modern automobile, and remains idle nearly as much time as a private vehicle. In car sharing, utilization is not much better. Efficiency in MoD systems cuts down to the value of the least-cost combination of empty trips, vehicles, parking land, and road capacity required per demanded trip. No theory today can explain what parameters and how, drive these four variables in equilibrium, why utilization remains low, why cities persistently rebalance so much, and why some cities have over a tenfold magnitude performance than others even though the technology and operations they use are commensurate. To what extent can technology improve personal mobility? In my dissertation, The Potential of On-demand Urban Mobility: Lessons from System Analysis and Data Visualization I showed that urban form, land use patterns, and key sizing and rebalancing decisions, define performance limits for MoD systems that outweigh the ability of technology to overcome. I built my argument in three parts.

In the first part, I revealed similarities across MoD systems that allow their comparative analysis by simple stock-flow models. By analyzing trip data, both synthetic and from cities, I found that even though trip patterns are random, vehicular mass always moves palindromically between four areas. Particularly, I showed that any MoD system subject to a trip pattern, can consolidate to a four-node network without changing its sizing and rebalancing requirements. The consolidated network has analogous behavior to a hydraulic compartment system in which inflows in each compartment are delays of outflows from other compartments. This reduction allows modelling of MoD systems with methods from system dynamics to address questions such as: How and to what extent does trip pattern affect system size and rebalancing requirements across cities?



[1] Randomness of trip patterns; [2] Consistency of mass allocation patterns. [3] Stock-flow model simulates palindromic vehicle flows between residential and commercial areas.

In the second part, I developed a novel data-driven system dynamics model, that shows how sizing, rebalancing, and technology decisions determine ridership and cost in cities. The model uses a trips dataset as input, numerically integrates the trajectory of the system, and allows a user to interactively control size and rebalancing parameters and explore what-if scenarios such as: how would ridership, cost, carbon emissions, or traffic congestion change for a marginal change in the fleet size or rebalancing policy? Working with interviews and a dataset covering over a year of operations (62K trips and 32M station updates) from Boston's bike sharing system, I performed a sensitivity analysis assessing a range of sizing and rebalancing options.



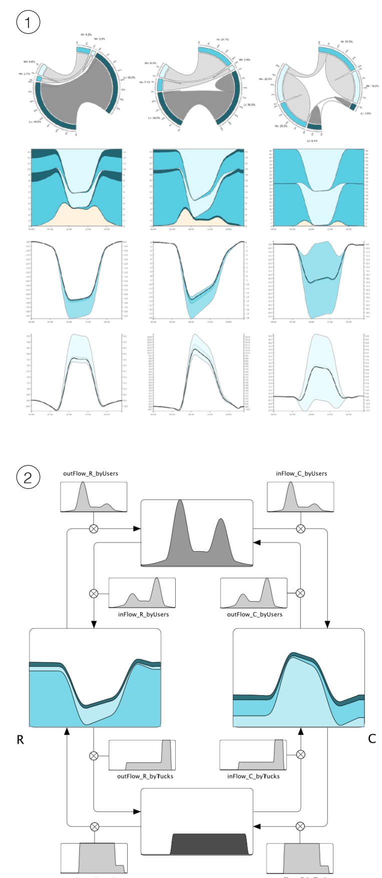
[1,2,3] Numerical integration of the trajectory of Boston's bike sharing system using trip data. [1] Shuffled stations. [2] Ordered & Clustered stations. [3] Exploration of alternative scenarios for sizing and rebalancing.

In the third part, building up on literature from urban economics and operations research, I developed a novel mathematical Land Use Transport Interaction (LUTI) dynamic macromodel, that shows how urban form determines performance limits for MoD systems. The LUTI model generates a land use pattern from eight input structural parameters, calculates daily trip patterns from the land use pattern, and mathematically integrates the trajectory of the system from the daily trip patterns. The model can be used to interactively address questions such as: how does urban form and land use patterns affect ridership and cost of mobility? I performed a sensitivity analysis illustrating the impact of each index on ridership, cost, or carbon emissions.

My analysis concluded with three findings: First, ridership varies significantly with land uses but exceeds 4 trips/bike only when more than half demand is leisure-related. Second, improving rebalancing decreases stationary (parked) stock but increases stock in transit with empty trips. This suggests that, based on the technology/land cost ratio, there are cities in which, no MoD system can ever constitute a viable way of commuting. Third, unless capacity exceeds demand, MoD systems will always rebalance more vehicles than those imbalanced by users.

Institutional Mechanisms for Self-regulation

My second research area investigates institutional mechanisms for self-regulation, problems of agency in participatory systems, and new pedagogies for designing self-regulating systems. In my MSc thesis The Market Economy of Trips (MET), I asked the question: Can self-interested users collectively govern MoD systems? I designed and analyzed a pricing mechanism to incentivize users to rebalance the fleet, causing some trips to cost more while others to pay back. The problem of pricing concentrates on maximizing ridership in a socially equitable manner while guaranteeing that revenues from penalties pay costs for rewards. Pricing trips is hard since: (a) state space (the set of all possible prices for all possible trips) grows exponentially with number of stations; (b) trips are intangible assets, neither in shortage nor in abundance; and (c) determining socially fair prices through a central agency (monopoly) is unfeasible. To address this problem, I designed a two-sided market in which users "buy" vehicles from origin stations and "sell" them back to destination stations, essentially translating the intractable problem pricing trips to the tractable problem of pricing inventories. Trip values derive as transactional differences between buying and selling and can be positive, negative, or zero. Price competition between "station dealers" brings the system in equilibrium by relocating wealth from users willing to pay to save time to users willing to profit from spare time. By analyzing the equilibrium, I showed that the surplus wealth from high to low payers equals the cost of the substitute plus the time value difference in users. In theory, this guarantees a Pareto optimal equilibrium. To test this hypothesis in practice, I prototyped a web-based electronic marketplace platform that allows online riders and traders to transact over physical MoD networks in real time, that will soon be tested in an urban context. I also conduct cyber physical participatory game experiments with my students, exploring how players respond in tradeoffs involving currency and physical relocation, and game design workshops to explore how designers design self-regulating systems.



[1] Land Use Transport Interaction model: generates daily trip volumes from household, work, and leisure land use patterns. Results from from the effect of different land use patterns on ridership performance and system size. [2] Dynamic macromodel links daily trip flows to dynamics of stocks and flows.

Connective Technologies and Novel Human-Computer Interfaces

My third research area contributes to novel ways of sensing, processing, and communicating information between humans and their built environment. This includes (1) tangible or (2) visual human-computer interfaces, and (3) embedded distributed systems. As an example of (1), in BodyPods, I inquired the potential of architecture

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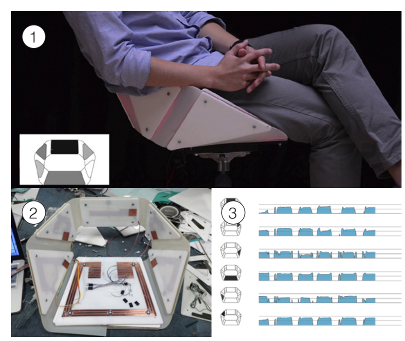
to mediate human presence through digital information. I developed a series of multi-sensory seats that allow users to remotely perceive each other's presence by sharing their bodyprint traces through the internet. Analogous to a fingerprint, a bodyprint manifests a person's sitting posture as a distribution of their body pressure on the seat. Results from a 10-person study show that BodyPods detect 8 unique postures with only 6 pressure sensors. As an example of (2), in PriceScapes, I investigated the ability of visual information to communicate complex price information to users of incentive-driven MoD systems. I developed a visual interface for handheld devices that associates trading prices of stations to color-gradients in an interactive map. Relocating vehicles from lighter to darker colors is rewarding while the opposite is penalizing. Relocating vehicles between same colors is free. I tested this hypothesis in preliminary user studies with interactive strategic games. As an example of (3), in BlockNet, I investigated the potential of physical structures to compute, using their parts and their assembly interconnectivity as a local internet. To test this hypothesis, I designed and prototyped a set of addressable building blocks (NetBlocks) that communicate through physical contact, and explored how they may guide a user to assemble them in preprogrammed configurations.

[1,2] The Market Economy of Trips: an electronic two-sided marketplace for dynamic pricing of MoD systems. [3] PriceScapes: a price visualization interface that associates trip values with color relationships. [4] Experiments with cyber-physical games for MoD systems.

Conclusion and Future Directions

In conclusion, my research aims to build on a comprehensive theory about the design and study of intelligent mobility and cyber-physical urban systems, based on systems analysis, data science, and hands-on experimental studies. In the next 5 years I want to expand my research to a number of open questions: Will autonomous sharing increase cruising vehicles more than decreasing parked vehicles in cities and if so, will the new equilibrium improve urban mobility and the environment? Can self-governed MoD systems outperform autonomous centrally-controlled MoD systems? Is it possible to have low-tech intelligent MoD systems in which information propagates physically with the vehicles? Can the built environment manifest and communicate information physically in large participatory systems? How do we educate designers and planners of self-regulating urban systems? I want to conduct a series of large-scale experiments to empirically explore the aforementioned questions. Such experiments can take place in urban districts or a university campus using the physical infrastructure as a living laboratory. I hope that, learning outcomes from such research may change profoundly how people live, move, and share, in 21st century cities.



[1,2] BodyPods: Multi-sensory seats allow remotely located users to perceive each other's presence through the internet. [3] Sensor readings from different postures.

Related Publications

Papanikolaou, D., "Choreographies of Information: Communication through Architectural Form in the Early Napoleonic Internet of Optical Telegraphy" in New Geographies 07: Geographies of Information, ed. Ali Fard and Taraneh Meshkani (Harvard Graduate School of Design Press, 2015).

Papanikolaou, D. Data Driven Dynamic Modeling: Towards a Visual Analytic Framework for Mass Allocation Dynamics in MoD Systems, under peer review in IEEE Pervasive Computing: Special Issue on Smart Buildings and Cities, April, June 2017

Papanikolaou, D. and Larson K. Designing a Self-operated Point-to-Point Mobility System. In Proceedings of the 9h International Conference of Intelligent Environments (Athens, Greece, 18-19 July 2013)

Papanikolaou, D.. A.J. Bernheim Brush, and Asta Roseway. BodyPods: Designing Posture Sensing Chairs for Capturing and Sharing Implicit Interactions. In Proceedings of the 9th International Conference on Tangible, Embedded and Embodied Interaction – TEI'15 (Stanford University, Stanford, CA, 15-19 January 2015). Video: https://vimeo.com/112138052

Papanikolaou, D. Cloudcommuting: Games, Interaction, and Learning. In Proceedings of the 12th International Conference on Interaction Design and Children - IDC13 (New York, NY, 24-27 June 2013). Video: https://vimeo.com/68466794

BlockNet: Addressable building modules transmit information through physical contact formulating a local internet.