DESIGN METHODS FOR ADAPTIVE MOBILITY

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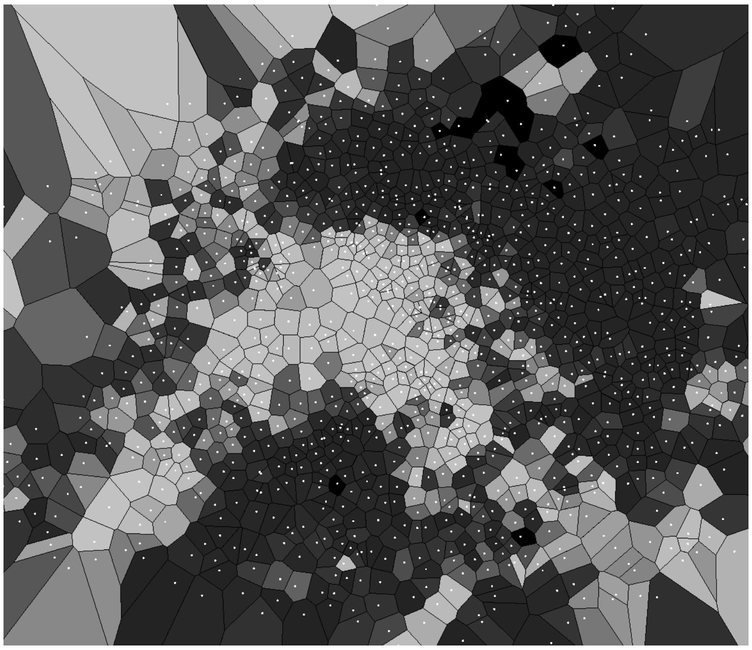


1 Above

Map of Velib in Paris showing spatial imbalance of inventory levels. Polygons in light grey represent areas of stations with full inventories, while areas in dark grey represent stations with empty inventories. Visualization generated with data collected on November 4th, 2012, at 1pm.

2 Facing Page

Trucks with trailers, redistributing bikes in Paris.

In their book *Reinventing the Automobile*, William Mitchell, Chris Borroni-Bird and Larry Burns describe their vision for the future of intelligent Mobility on Demand (MoD) systems: cities covered with networks of docking stations and shared fleets of electric compact vehicles—bikes, scooters, automobiles—allowing users to make point-to-point (P2P) trips on demand.[3] Dense layers of sensors, communication networks, and mobile devices, enable users to quickly locate vehicle and parking availability in real time. Today, more than 250,000 bikes in 300 cities across the world mobilize 2 billion trips per day, while at least 200 new systems are being planned. MoD systems follow cyclic "flood and ebb tide" commuting patterns. During the morning peak, vehicles deplete from residential areas and pile up at commercial areas. During the evening peak, the reverse pattern occurs until the system returns more or less to its starting state.[1] Despite their convenience, MoD systems have significant operational complexities. In bike sharing, about 10 to 40 per cent of the daily trip volume remains imbalanced, causing some stations to temporarily run out of vehicles while others run out of parking spaces. This displaced fleet must be hauled back by the end of each day—otherwise the condition of the system would increasingly worsen. To rebalance the system, operators often spend their entire revenues paying gas, trucks and employees to manually move bikes from full to empty stations.[2] Yet, many MoD systems suffer from a low level of service. In Paris 48 per cent of users find no bikes at points of departure while 58 per cent find no empty docks at destination.[4] In Barcelona almost 50 per cent of the stations are either empty or full during 30 per cent of the time.[5] In car sharing, these problems are worse because workers must either tow or drive cars using other service vehicles to move between relocations. What is somehow unclear in the description of intelligent

3 Mitchell, William J., Chris E. Borroni-Bird, and Lawrence D. Burns. 2010. *Reinventing the Automobile: Personal Urban Mobility for the 21st Century*. New ed. Cambridge: The MIT Press.

4 Coles, Peter A., Elena Corsi, and Vincent Dessain. 2011. "On Two Wheels in Paris: The Vélib Bicycle-Sharing Program," *Harvard Business School Case Study* N9-911-067.

5 See http://www.codeline-telemetry.com/maps/bcn-depletion_summary.htm.

mobility provided by Mitchell, Borroni-Bird and Burns, is how information from the physical world turns into action. Who senses the world, who distributes information, who makes decisions, who takes action, and who evaluates the results? How is intelligence constructed?

MoD systems are a relatively new area in the literature of intelligent systems. Some works focus on analyzing human mobility patterns;[6] others focus on modeling or improving inventory rebalancing using stochastic[7] or deterministic[8] methods. Finding provably optimal routing methods is however intractable. In practice, repositioning is done empirically using real time information from the stations, directions from a central dispatcher, and the truck drivers' experience[9] Many experts argue that future intelligent MoD systems will rely on incentivizing user behavior to mitigate, or even eliminate, operation burden.[10] Several MoD systems have already used incentives: Paris offers additional riding time while Washington offered redeemable coupons to users that rode bikes from full to empty stations; other systems have experimented with rewards and penalties. However, an obscurity in these approaches is that there is no clear mechanism for evaluating payoffs. How much should a reward be and where will the funds to pay it come from? A growing field of research in collective intelligence, studies how market mechanisms, game theory, and information technology

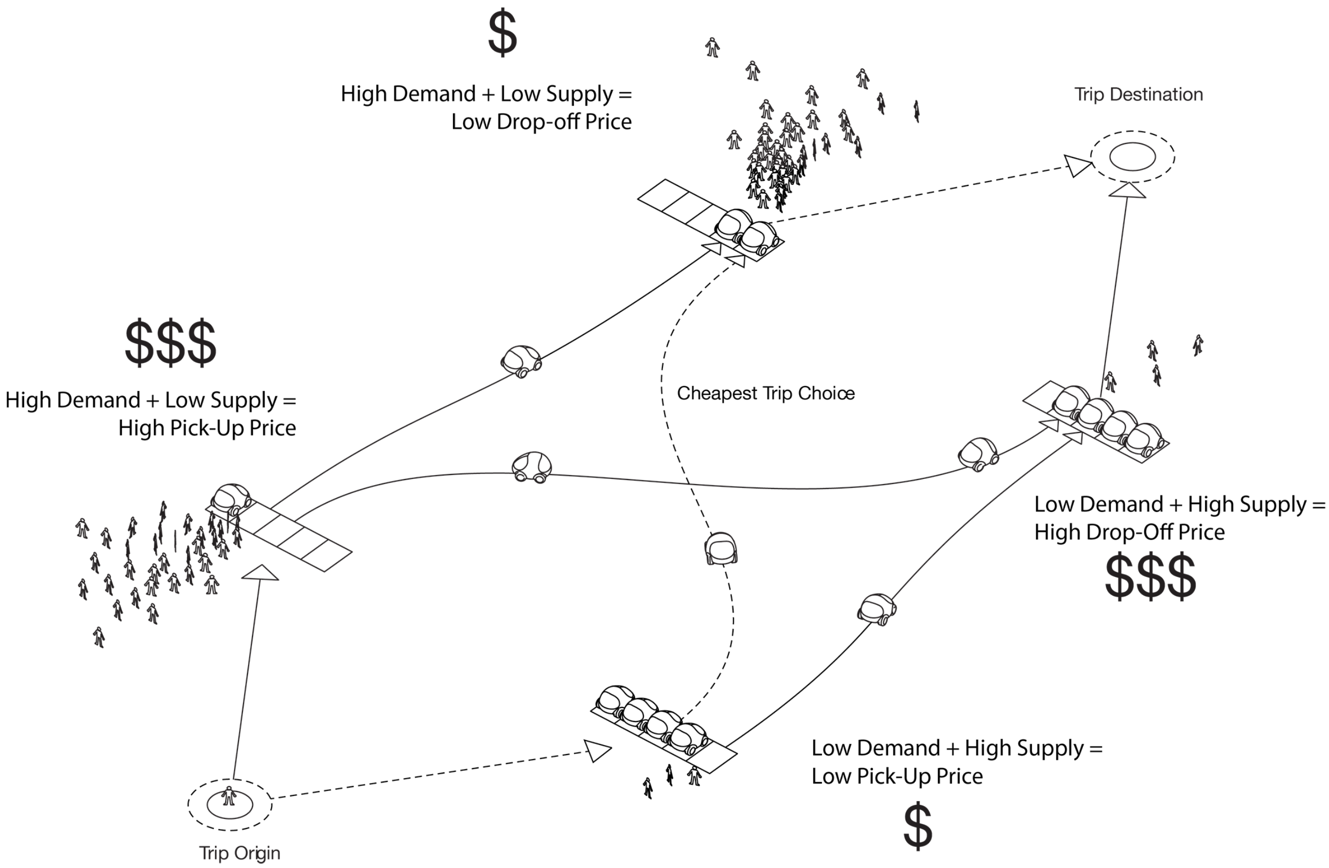
6 Kaltenbrunner, Andreas, Rodrigo Meza, Jens Grivolla, Joan Codina, and Rafael Banchs. 2010. "Urban cycles and mobility patterns: Exploring and predicting trends in a bicycle-based public transport system." *Pervasive and Mobile Computing* vol. 6(4):455–466.

7 Nair, Rahul, and Elise Miller-Hooks. 2011. "Fleet Management for Vehicle Sharing Operations." *Transportation Science* vol. 45: 524-540.

8 Vogel, Patrick, and Dirk Christian Mattfeld. 2010. "Modeling of Repositioning Activities in Bike-Sharing Systems," in Proceeding of the 12th World Conference on Transport Research, Lisbon, Portugal, July 11-15.

9 Ralph Buehler et al. 2012. "Virginia Tech Capital BikeShare Study: A Closer Look at Casual Users and Operations." Virginia Tech, Alexandria, Virginia.

10 DeMaio, Paul. 20009. "Bicycle-Sharing: History, Impacts, Models of Provision, and Future." *Journal of Public Transportation* 12(4):41-56.



11 Above

The Market Economy of Trips. The origin-destination path in dashed line has the highest payoffs for a user.

12 Easley, David, and Jon Kleinberg. 2010. *Networks, Crowds, and Markets: Reasoning about a Highly Connected World*. New York: Cambridge University Press.

13 Papanikolaou, Dimitris. 2011. "The Market Economy of Trips." MSc. Thesis, Massachusetts Institute of Technology.

can be used to resolve resource allocation in networks with bandwidth and capacity constraints in a self-governed manner.[12] Applications include P2P file sharing systems, distributed sensor networks, smart power grids, carbon trading programs, water banking systems, and more.

At the Smart Cities and Changing Places groups of the MIT Media Lab we developed a pricing model, titled *the Market Economy of Trips* (MET)[13] in which trip prices depend on inventory needs of origins and destinations, causing some trips to be more expensive while others pay back users.[11] The system resembles a two-sided market; on one side stations buy vehicles from arriving users and on the other side they sell them to departing users. The two-sided market can be seen the other way around, too: on one side users buy vehicles from origin stations and on the other they sell them to destination stations. Thus both users and stations buy from, and resell to each other. Stations act as traders, "bidding" and "asking" prices based on demand, supply and the competition with their peer neighbor stations. Trip values are determined by the transactional difference between "buying" a vehicle from an origin and "reselling" it to a destination. If the pick-up price that an origin "asks" is lower than the drop-off price that a destination "bids," then the user wins the transactional difference from the system as a reward; in the opposite case the user pays the system the difference. Finally, if pick-up and drop-off prices are the same then the ride is free for the user. By redirecting funds from overpaying to underpaying users the system gradually adapts to new self-sustaining equilibria. Users are not aware of this mechanism, as they only perceive the difference between the underlying transactions. The MET is essentially a self-organizing system operated by and for its users.

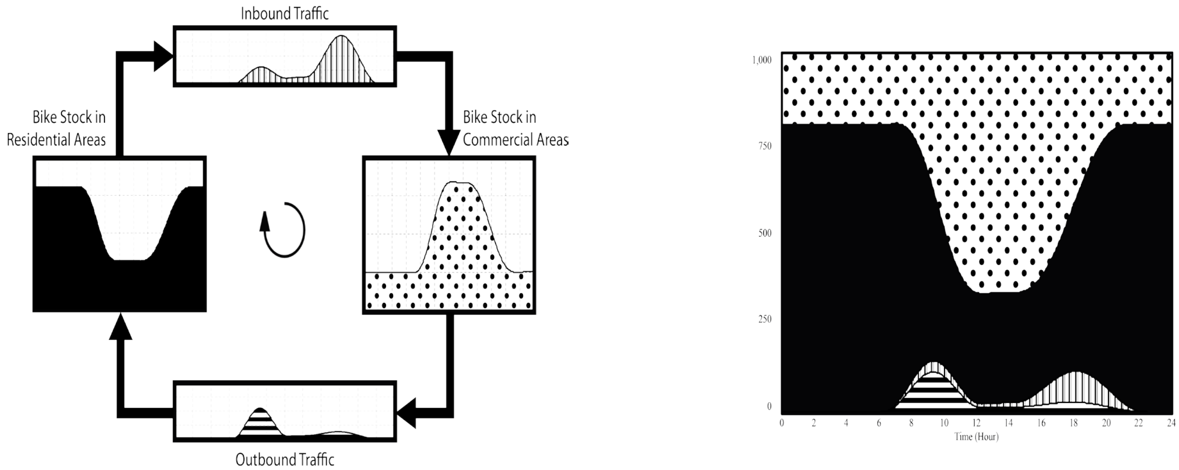
Estimating the limits of self-governance requires understanding how equilibrium emerges both in theory and in practice. Urban trips are combinations of multiple mobility modes: you walk from home to the bus station; take the bus to the city center; ride a bike inside the center; walk to your final destination. The commuting cost of each compound trip is the sum of the prices that have been paid for each mode, plus the total cost of time that was spent traveling. People choose those bundles of modes that minimize their costs based on the price of each mode (for example MoD vehicle, bus, taxi, walking, et cetera), its average commuting time (speed), and their individual evaluation of time. In MoD, users who place a higher value on time are willing to pay higher prices to minimize their commute, while users who place a lower value on time are willing to ride longer for better prices. For the stations, the transactions should balance revenues from pick-ups with costs from drop-offs. The Market Economy of Trips is thus a form of a strategic game. Territorial decisions of users change the pricing of stations, which changes the payoff landscape affecting the decision making of other users and vice versa. Urban economic theory shows that users with sufficient information would make pickup and drop-off decisions that minimize their time-adjusted commuting costs, eventually bringing the system into a competitive equilibrium where no further action can be taken to increase anyone's payoffs.

Can decentralized self-governance outperform centralized control? On one hand, we have no reasons to believe that truck repositioning is done efficiently—neither we know how much better it can get. On the other hand, we have no evidence to believe that people can perceive price information efficiently or indeed make rational decisions. Besides the complexity of vehicle routing, the efficiency of truck repositioning is bounded by physical and economic constraints. On average a truck with 22 slots can visit 2-3 stations per hour, repositioning a maximum of 33 to 44 bikes. Considering the lease of a truck, the wage of a work shift, gas costs, communication costs, and the amount of bikes that a truck repositions in one day, the average cost per bike repositioned is between 2 to 15 times higher than the average revenue per trip. In the short run, the question for an operator—given a number of bikes and docks—is how many trucks to use, for how long, and within what time window, so that ridership is maximized while usage revenues still pay trucking costs. In the long run however, the decision problem is slightly different: Given a budget constraint, what portion of the budget should be allocated to sizing the system (by adding more bikes and docks) and what portion of it should be allocated to rebalancing (by adding more trucks and workers)? Holding all else equal, what mix of those two inputs maximizes service rate? To analytically explore the limits of efficiency of truck repositioning, we are currently developing at Harvard GSD a computational framework using System Dynamics (SD) that simulates ridership, costs and revenues as a function of the trip pattern, number of trucks, work shifts, and operation time windows. SD is a computer-aided method for studying complex feedback systems by modeling their causal structure and simulating their behavior through nonlinear differential/integral equations in the form of stock-flow models.[14] SD finds applications in modeling the spread of epidemics, economic systems, and supply chains. The computational framework is calibrated using data from Boston's and Washington's bike sharing systems.[15] System planners and operators can use the model to find the combination of parameters that maximizes ridership given a demand pattern.

14 Forrester, Jay Wright. 1968. *Principles of Systems.* Cambridge: Productivity.

15 Below

The System Dynamics computational framework simulates inbound and outbound flows of vehicles between two stocks in residential and commercial areas.



16 Facing Page (Top)

A controlled experiment using an interactive board game to assess perception of payoffs and decision-making. The game represents a basic network of three stations. Players can move between stations using either a MoD vehicle (red links) or public transit (blue arcs).

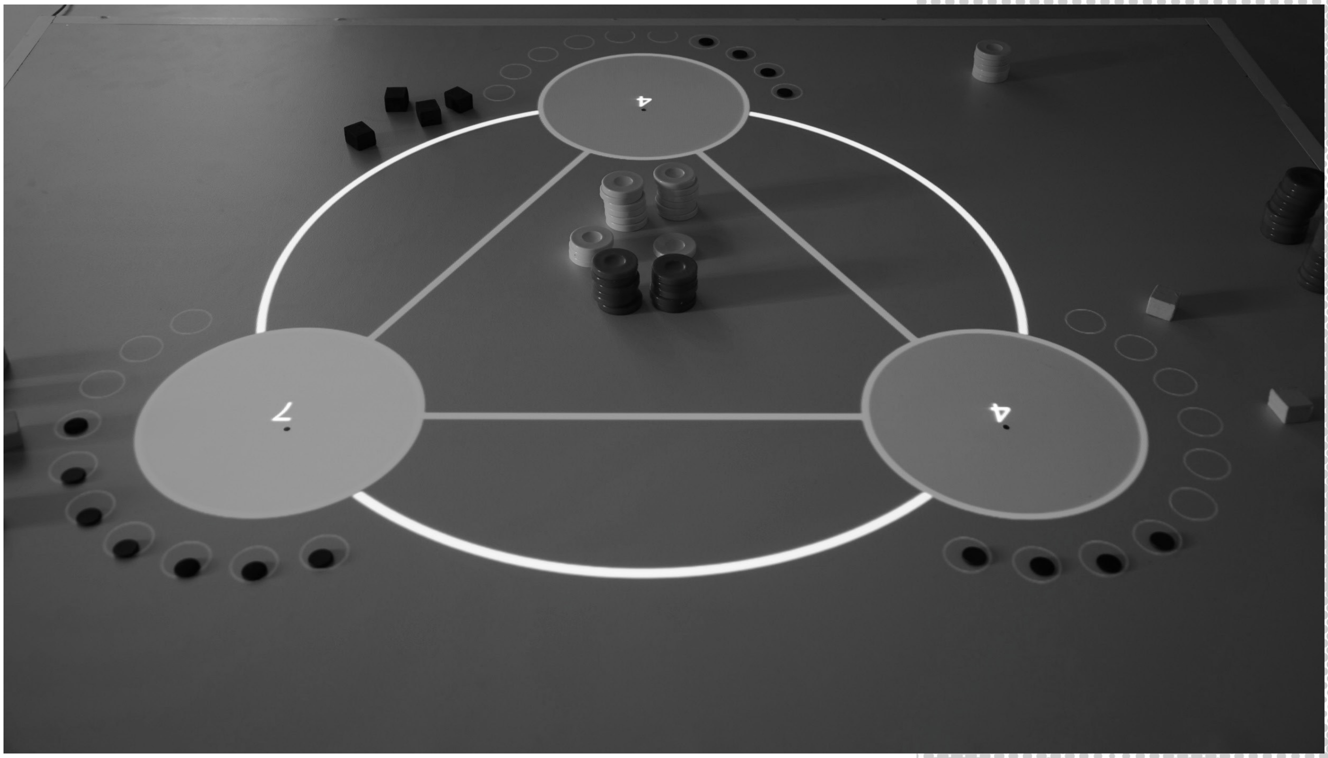
17 Facing Page (Bottom)

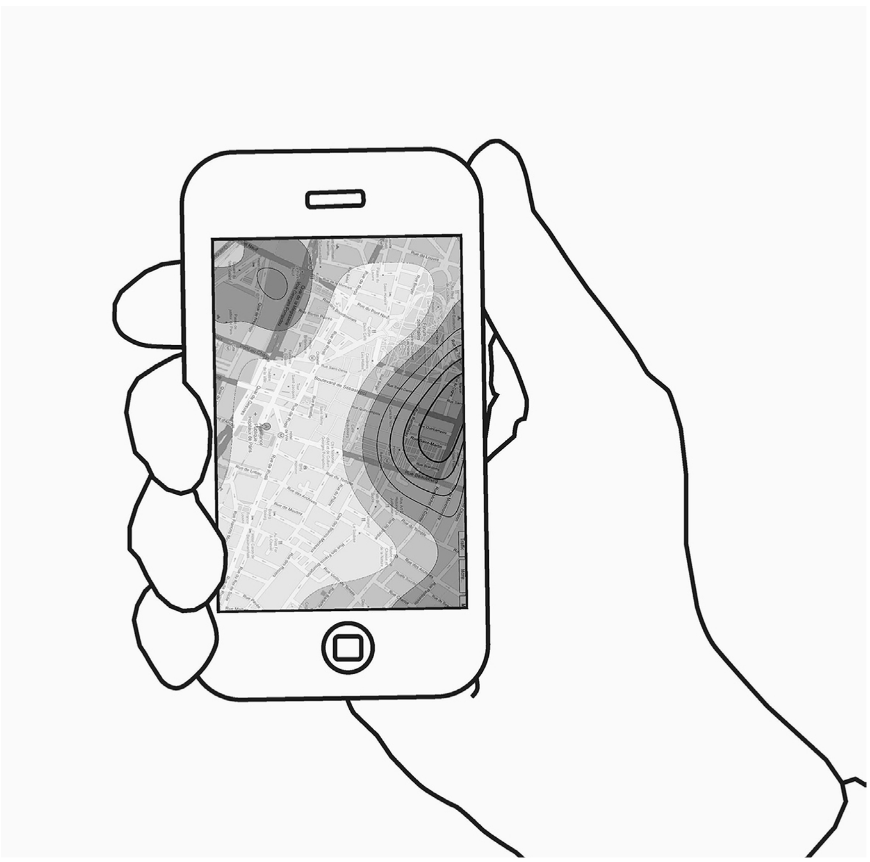
The Pricescapes Graphic User Interface uses a heat map to associate trip prices to slope gradients.

18 Papanikolaou, Dimitris. 2013. "Cloudcommuting: Games, Interaction, and Learning," in the Proceedings of ACM IDC13 Interaction Design and Children. New York, NY, USA.

In practice, the performance of MET during equilibrium depends on the communicational and perceptional inefficiencies associated with the implemented technology and design. In addition to the economic analysis of the equilibrium in MET we are currently planning a series of experiments to empirically test these assumptions. One stream of experiments aims to assess how efficiently users perceive price information through Pricescapes, a novel color-coded graphic user interface (GUI) that uses a heat contour map to relate prices to slope gradients: isometric price curves describe areas with same prices. Like navigating through a price landscape, climbing from valleys up to hills is expensive, descending from hills down to valleys is rewarding, while traveling through flat areas is neutral.[17] A second stream of experiments aims to assess how multiple users can make rational decisions when they collectively compete for prices using the Pricescapes platform. We are currently designing and conducting a series of controlled, interactive, participatory game experiments.[16, 18] The final stream of experiments deals with how the MET performs in a real-life context, using Boston's bike sharing system as a living laboratory.

That of architectural systems that intelligently adapt to changing external conditions is a new, fascinating, and increasingly important topic in design education. However as designers, researchers, and educators we must rethink what tools and disciplinary knowledge we must integrate in our professions to study these systems, both in theory and practice. The study, design, and engineering of collective adaptation and self-organization requires on one hand integration of the fields of technology, policy, and design and on the other hand deployment of both analytical and experimental methodologies.





DIMITRIS PAPANIKOLAOU is an architect, engineer, and creative technologist. He is currently a doctoral candidate at Harvard GSD, and a recent graduate of the MIT Media Lab where he worked as a researcher at the Smart Cities and Changing Places groups. His interests explore the intersection of media technology, economics, and complex systems theory with applications on cities, buildings, products, and services. Dimitris holds a M.Sc. in Media Arts and Sciences from the MIT Media Lab, a M.Sc. in Architecture Studies from the Design Computation group of MIT as a Fulbright Scholar, and a Diploma in Architectural Engineering from the National Technical University of Athens in Greece.