Understanding Behavior of Self-Organizing Vehicle Sharing Systems

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ABSTRACT

Mobility on Demand (MoD) is a self-organizing one-way vehicle sharing system that allows users to pick-up from and drop-off to at station. MoD uses sensors to understand fleet distribution asymmetry and price incentives to motivate users to drive vehicles to stations that need the them most thereby increasing service performance. This paper presents current work done at the Smart Cities group of the MIT Media Lab for understanding decision-making in dynamically priced vehicle sharing systems, and exploring the circumstances under which such systems can become stable, sustainable, and profitable.

KEYWORDS. vehicle-sharing, mobility on demand, dynamic pricing, system dynamics, self-organization.

How many times have you found yourself waiting endlessly for a taxi while next to you dozens of empty cars remain parked and unused? Have you ever envisioned a future in which you could borrow any of these parked cars, drive it as much as you need, and drop it off anywhere else? Cities could have fewer cars to park while citizens would have more cars to use. How feasible is this scenario?

Urban mobility describes the state of moving freely between different locations, while controlling where, when, and how you move. Quality of mobility typically follows decreasing marginal gains as demand increases due to limits in infrastructure capacity: increasing cars in the streets increases carrying capacity but decreases travelling speed due to congestion. Likewise, increasing cars decreases available parking spaces, which consequently increases trip time due to the search for a parking space. Affordable customized mobility is hard to get. On one hand, in public transit others decide for you when, where, with whom, and how you move. Schedules are inflexible, and service coverage is often driven by political motivations rather than social needs. As a consequence, many areas are privileged while other areas are underserved. On the other hand, the high cost of private vehicle ownership compared to their low utilization rates, and the increasing parking requirements compared to the high cost of available urban land, make private automobiles an unsustainable solution for the future of dense urban environments. Given the limited capacity of roads, vehicles, and urban land, the question of providing better sustainable mobility seems not to be of endlessly increasing existing infrastructure capacity but rather of inventing organizational policies that may increase utilization of existing infrastructure by making it more intelligently responsive to the needs of its users.

Vehicle Sharing: Merging Public with Private Mobility

Sharing or *fractional ownership* is a well-tested method for sharing the cost of a large resource allocation network that also increases utilization. Typically, a sharing system involves a policy that allows fractional ownership rights over the allocated common resources and a network of depositories where shareholders can deposit or withdraw these resources. Banking systems with bank accounts, freight rental services with their trucks, and airports with their luggage carts, are only a few of the many examples that have successfully adopted similar methods to deal with the increasing complexity of their networks and the accompanying unpredictable demand patterns. Recently, sharing entered public transit systems as a complementary way to provide customized personal mobility in the form of one-way bike sharing programs, while one-way car sharing is just about to start. One-way vehicle sharing systems utilize a decentralized network of parking stations and a fleet of shared vehicles. Users can pick up a vehicle from any station and drop it off at any other station without having to return the vehicle back to the place of origin.

However, sharing has drawbacks too. Lack of cooperation and selfish individual behavior undermine sustainable welfare in sharing systems. For example, in vehicle sharing since departures and arrivals vary randomly in stations, eventually all vehicles end at the stations with no demand. Vehicles need to constantly return to the stations where demand accumulates to maintain service levels. While it is possible to centrally monitor bikes and periodically redistribute them with trucks, this is clearly not a viable solution for larger vehicles such as cars. Not only it is difficult to move cars by trucks but furthermore it is highly complex to plan and expensive to operate: either the fleet needs to be too large or the redistributions need to be too frequent. As a consequence, current vehicle sharing systems end up wasting more resources in order to sustain their performance than the value of the service they provide.

Mobility on Demand: A Self-regulating Vehicle Sharing System

Incentive-based strategies such as dynamic pricing have been successfully employed in decentralized resource allocation networks with limited capacity as a means to create feedback mechanisms to regulate demand patterns: congestion pricing zones, smart grids of renewable energy resources, e-bay or Amazon style online auctions, and carbon trading programs are just few of the many successful examples.

The Smart Cities group of the MIT Media Lab has been developing Mobility on Demand (MoD), a self-organizing sharing system of electric vehicles that uses sensors to understand fleet distribution asymmetry and dynamic pricing as a feedback policy to smooth demand imbalances (Mitchell, 2010, 131). Such a policy incentivates users to drive vehicles to stations that most need them while discouraging users to drive vehicles to stations that do not need them. Each station determines a pick-up and a drop-off price component based on its inventory change rate, which are then added to the standard trip price as a negative or positive discount (Papanikolaou, 2010). Therefore, some drop-off stations can charge higher prices while other drop-off stations may even pay back money to the users (Fig. 1). Continuous redistribution ensures minimum fleet size and maximum level of service. There are no trucks, or employees involved in the fleet redistribution, just users.

While most of existing work has been focused on exploring dynamic pricing as a means to regulate demand and supply in vehicle sharing systems, understanding the efficiency limits of such policies in which they can indeed become instruments for creating smart, sustainable, vehicle sharing systems remains an open question. In this work we focus on understanding how users make decisions in dynamically priced mobility systems, under which circumstances their actions may make up a self-regulating economy, and how this economy dynamically behaves based on a given demand pattern. Is there a pricing policy that can make a one-way vehicle sharing system self-sustaining?

A Market Economy of Trips

Dynamically priced MoD systems are in essence market economies of trips: mobility implies a form of temporal ownership rights to both a vehicle and a parking space and as such, each right can be exchanged for value in a market. Markets constitute remarkable mechanisms for efficiently allocating scarce resources between buyers and sellers through price competition. In equilibrium, the price of exchanged resources matches demand with supply in a way that each side gets what it is willing to pay for. In a dynamically priced MoD system users would make decisions in order to minimize their total trip cost compared to the average cost of transportation in their city. Total trip cost in MoD consists of the standard fare per mile, the parking discount rate, and the forgone time value. To understand how the first two prices are determined we must describe MoD as a conjunction of two distinct markets: a *mobility options market*, and a *parking rights market*.

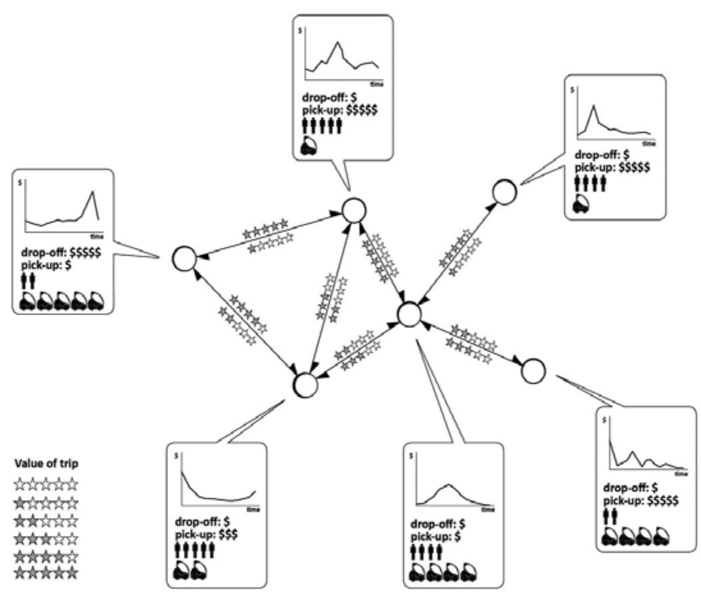

Figure 1. Trip value depends on pick-up and drop-off stations

The task of the mobility options market is to determine how various urban mobility options (e.g. cars, taxis, buses, trains, trams, walking, etc.) are priced based on their traveling speeds and the relative value of time. In a competitive mobility options market, price per mile would compensate for time value forgone and therefore fast options would cost more than slow options, relative to their speed ratios. All options together make up the average cost of transportation. Different users would evaluate differently each mobility option based on their own perceived value of time.

The task of the parking rights market is to determine the parking discount rate. On one side are users, and on the other side are stations; users buy parking rights from the stations to pick-up and drop-off a vehicle. The value of a parking right depends on how fast the parking inventory of a particular station changes relative to its current level; this value is then applied as a positive or negative discount to the standard trip fare that someone would pay to arrive to that station (pick-up and drop-off discounts). Parking discounts are calculated as a percentages of the trip fare to ensure that the weight of dynamic pricing is independent from trip length. For example, a user could have a 20% premium to the standard fare if he were driving to a station with low pick-up demand, or a -110% discount to the standard fare if he would be driving to a station with high pick-up demand in which case he would actually receive money back.

How would users make decisions given this pricing context? Each urban trip is inevitably a combination of at least two options (one of which is always walking) and rational users will select the combination which minimizes total trip costs. According to their level of income, different people evaluate differently time. As an example, a user traveling with a MoD system that starts from an origin O, and ends to a final destination D, will select another in-between drop-off station Q if the total trip price from O to Q with m (including parking discount) plus the trip price from Q to D with the average transportation option (ATO) (e.g. bus, taxi, walking, etc.), plus the total associated time delay costs (from O to Q with m, and from Q to D with ATO) are in sum less or equal than the original price from A to B with m plus time cost with m (Fig. 2).

A sustainable, dynamically priced, MoD system would be one that first, is able to deliver the requested level of service and second, receives sufficient funds provided by its overpaying users to reward its underpaying users. To understand the circumstances under which such conditions are possible, we need to see whether there is an equilibrium point in such a market. In game theory, such an equilibrium point is called *Nash equilibrium* and is achieved when there is nothing else to do to improve the payoffs of each party (Dixit, Reiley, & Skeath, 2009, 82). Since at each moment some users will be overpaying and some other users will be underpaying, such that the excess of money from the overpayers matches exactly the demanded reward of the underpayers this is equivalent to saying that the overpayers are buying underpayers' time value. Spatially, this equilibrium solution is defined by a market boundary line that separates the stations in two groups of high payers and low payers; the stations along the market boundary are the ones where dynamic pricing is zero. The solution is determined on how time value (or wealth) is distributed among the users.

Price information is essential for efficient market economies. Users could be informed by the pricing condition and inform other users about their strategic decisions either at the stations or during driving. Smart Cities has been developing a geographically related price information system that effectively communicates price information through an intuitive user interface that employs isometric heat-map displays (Papanikolaou, 2010). Isometric price curves describe areas with the same parking discount rates. It is like an analogy of navigating in a price landscape, climbing from valleys to hills would be expensive, descending from hills to valleys would be rewarding, while traveling through flat areas would be neutral (Fig. 3). In this interface, the market boundary is the isometric curve that splits the landscape into regions with the same but opposite dynamic pricing cash flows.

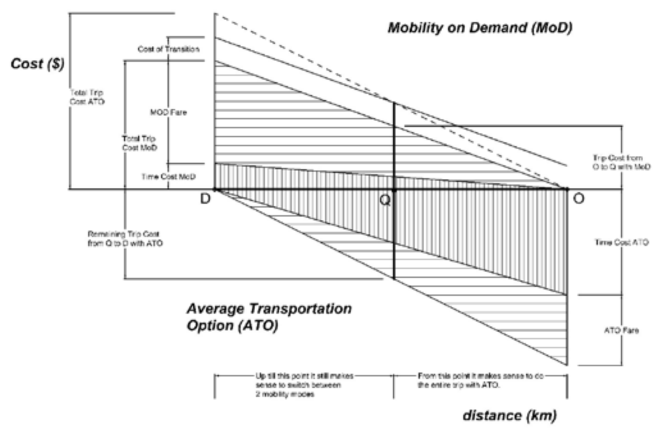

Figure 2. Cost-Distance diagram showing price equilibrium between MoD and ATO

Figure 3. Interactive heat-map user interface with areas of high/low demand

Understanding System Stability Using Dynamic Stock-Flow Modeling

Nash equilibrium describes a long-run steady state solution of a system but it tells nothing about how much time it may take the system to reach this solution. If demand fluctuates faster than it takes for the system to reach the Nash equilibrium there will never be a steady state. This inherent delay time depends on the average trip time, which is how much time it takes the users to drive from origins to destinations, and the total available stock of vehicles. For example small network deployments covering a university campus with few vehicles will have small delays while large networks covering entire cities with many vehicles will have large delays. To understand the dynamic behavior of the system, Smart Cities has been developing a feedback stock-flow computational model using system dynamics that is based on urban economics and game theory (Papanikolaou, 2010). The model evaluates service performance as a parameter of demand pattern, price sensitivity, and network size and it will be used to determine pricing policy and fleet size necessary to establish a stable and sustainable system (Fig. 4).

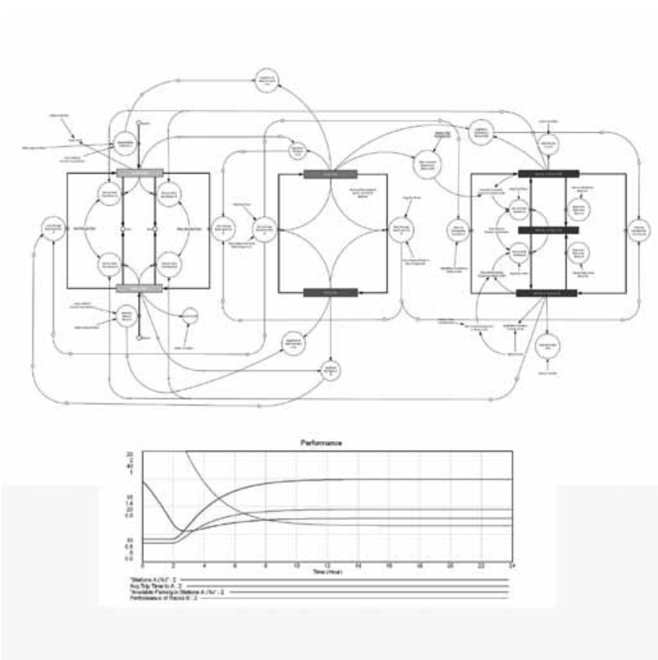

Figure 4. System dynamics model and simulation results of MoD

Conclusions

In summary, three basic components make up intelligent infrastructure systems: nervous networks of sensors and microcontrollers that collect and compute information from users; an adaptive policy to convert this information into payoffs; and a communication platform to convey payoff information back to users. Future urban infrastructure systems should not be regarded as complex centralized service delivery mechanisms but rather as human-driven decentralized infrastructure economies.

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