University Transportation Research Center - Region 2

Final Report

The Socialization of Travel: The Effects of Social Networks on Resiliency

Performing Organization: Rochester Institute of Technology

September 2018

Sponsor:
University Transportation Research Center - Region 2

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The Region 2 University Transportation Research Center (UTRC) is one of ten original University Transportation Centers established in 1987 by the U.S. Congress. These Centers were established with the recognition that transportation plays a key role in the nation's economy and the quality of life of its citizens. University faculty members provide a critical link in resolving our national and regional transportation problems while training the professionals who address our transportation systems and their customers on a daily basis.

The UTRC was established in order to support research, education and the transfer of technology in the field of transportation. The theme of the Center is "Planning and Managing Regional Transportation Systems in a Changing World." Presently, under the direction of Dr. Camille Kamga, the UTRC represents USDOT Region II, including New York, New Jersey, Puerto Rico and the U.S. Virgin Islands. Functioning as a consortium of twelve major Universities throughout the region, UTRC is located at the CUNY Institute for Transportation Systems at The City College of New York, the lead institution of the consortium. The Center, through its consortium, an Agency-Industry Council and its Director and Staff, supports research, education, and technology transfer under its theme. UTRC's three main goals are:

Research

The research program objectives are (1) to develop a theme based transportation research program that is responsive to the needs of regional transportation organizations and stakeholders, and (2) to conduct that program in cooperation with the partners. The program includes both studies that are identified with research partners of projects targeted to the theme, and targeted, short-term projects. The program develops competitive proposals, which are evaluated to insure the mostresponsive UTRC team conducts the work. The research program is responsive to the UTRC theme: "Planning and Managing Regional Transportation Systems in a Changing World." The complex transportation system of transit and infrastructure, and the rapidly changing environment impacts the nation's largest city and metropolitan area. The New York/New Jersey Metropolitan has over 19 million people, 600,000 businesses and 9 million workers. The Region's intermodal and multimodal systems must serve all customers and stakeholders within the region and globally.Under the current grant, the new research projects and the ongoing research projects concentrate the program efforts on the categories of Transportation Systems Performance and Information Infrastructure to provide needed services to the New Jersey Department of Transportation, New York City Department of Transportation, New York Metropolitan Transportation Council , New York State Department of Transportation, and the New York State Energy and Research Development Authorityand others, all while enhancing the center's theme.

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The modern professional must combine the technical skills of engineering and planning with knowledge of economics, environmental science, management, finance, and law as well as negotiation skills, psychology and sociology. And, she/he must be computer literate, wired to the web, and knowledgeable about advances in information technology. UTRC's education and training efforts provide a multidisciplinary program of course work and experiential learning to train students and provide advanced training or retraining of practitioners to plan and manage regional transportation systems. UTRC must meet the need to educate the undergraduate and graduate student with a foundation of transportation fundamentals that allows for solving complex problems in a world much more dynamic than even a decade ago. Simultaneously, the demand for continuing education is growing – either because of professional license requirements or because the workplace demands it – and provides the opportunity to combine State of Practice education with tailored ways of delivering content.

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UTRC's Technology Transfer Program goes beyond what might be considered "traditional" technology transfer activities. Its main objectives are (1) to increase the awareness and level of information concerning transportation issues facing Region 2; (2) to improve the knowledge base and approach to problem solving of the region's transportation workforce, from those operating the systems to those at the most senior level of managing the system; and by doing so, to improve the overall professional capability of the transportation workforce; (3) to stimulate discussion and debate concerning the integration of new technologies into our culture, our work and our transportation systems; (4) to provide the more traditional but extremely important job of disseminating research and project reports, studies, analysis and use of tools to the education, research and practicing community both nationally and internationally; and (5) to provide unbiased information and testimony to decision-makers concerning regional transportation issues consistent with the UTRC theme.

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16. Abstract

With improvements in mobile information and communication technologies (ICT) and the increasing presence of innovative mobility services such as car-sharing, bike-sharing and ride-sourcing services, regional planning organizations (MPOs) critically consider these travel options in their strategic planning. The transportation modeling community increasingly view these scenarios as two-sided markets, where the service providers (suppliers) endogenously adjust their aspirations and behavior in relation to a dynamic traveler demand response. We adopt this two-sided market perspective in modeling the matching process for a ride-sharing service, where drivers match with riders through a bidding process. Through experiments from an agent-based simulation model, we investigate the convergence and stability of matches under varying initial assumptions about the willingness-to-pay (WTP) and willingness-to-accept (WTA) for riders seeking rides and drivers offering rides, respectively. These experiments also show that convergence towards a (relatively) stable state may be self-coordinating as social networks grow. Additionally, the results show that allowing for agents to accept a potential loss in order to match leads to a convergence for markets with infeasible match transaction values based on the riders' WTP and drivers' WTA. Overall, the results suggest that depending on initial conditions and behavioral preferences of the riders and drivers, rideshare services may have difficulty converging from the perspective of ensuring a stable match for all participants. Designing and implementing shared mobility systems must consider these conditions.

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ABSTRACT

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Keywords: Social Networks, Ridesharing, Agent-based Simulation

1.0 INTRODUCTION AND BACKGROUND

This paper examines the stability and convergence of ridesharing markets modeled as a two-sided matching market, similar to recent studies in this research area *(1)*. Metropolitan Planning Organizations (MPOs) face many challenges in making public transit feasible for low and medium density communities *(2,3,4)* and other communities, such as university campuses, that lie outside of high population, employment and housing density areas. With a wider adoption in mobile ICT, innovative mobility solutions such as car-sharing and ride-hailing services, such as Uber and Lyft, begin to enter the mainstream in terms of travel mode options. Planning organizations need to consider these alternatives. Services, such as Uber and Lyft, further improve the prospects of peer-to-peer (P2P) ridesharing for communities with high personal vehicle ownership, but few feasible alternative travel modes. If successfully implemented, these ridesharing services would greatly benefit. Low and medium density communities that face many challenges for implementing successful conventional public mobility systems, such as bus transit that provide many benefits *(5)*. The flexibility of ridesharing organically provides an alternative to the fixed nature of conventional public transit *(6,7)*. Rather than operating on relatively fixed routes and timetables, rideshare systems are untethered to any fixed infrastructure or schedules, and with enough participants, can respond to varying demand. These contexts underscore the motivation for this paper, which focuses on the stability and convergence of matching in rideshare markets.

We present the ridesharing market as a matching market, and describe the matching process from the viewpoint of an assignment game. The economics literature contains a large volume of research on the matching problem; many are related variants on the marriage problem *(8)*. In the marriage problem, players have ordinal preferences for matching with members of the other population. The "core" consists of matchings, such that no pair would prefer other participants to their current partners; matchings are typically stable *(9)*. Similar results exist for many-to-one and many-to-many matching perspectives, referred to as the roommate problem with non-transferable-utility in the literature *(10,11)*. Furthermore, we view the matching process as a self-coordinating system where drivers match with riders, each evaluating their own resulting payoffs relative to current matches and preferences. The ridesharing matching problem examined here differs from both the marriage and roommate problems. The latter problems are framed in terms of nontransferable (typically ordinal) utility. We frame potential matches in terms of a transferable value. The difficulty in using the known literature results from the marriage and roommate problems is that payoff improving deviations from a match result from players' current matches and preferences. In an assignment game, match payoffs result from splitting of the value of the matches, similar to an outcome from a negotiation process. Stability and convergence in matching in the assignment game arises is harder to reach, being more constrained relative to the marriage or roommate problems from the literature *(12)*.

Recently, within the transportation literature, researchers have contributed strongly the topic of ridesharing, from both a modeling *(1,13,14,15)* and empirical perspective *(16,17)*. Several day-to-day simulation studies on ridesharing capture its dynamics using an agent-based simulation to reach an assumed SUE and address the stochastic nature of these systems *(1)*. Agent-based simulations of day-to-day traffic equilibrium models have a long intellectual history the transportation literature (*18*,*19*,*20*,*21*,*22*,*23*,*24*,*25*) and typically assume an adjustment process for travelers. Extensions to systems with adjustments on both sides for travelers and service providers (*26*,*27*) fit naturally with the current scenario of shared mobility services with adjustments for both riders and non-traditional third party hailing taxi service drivers with variable fares (*1*).

Synergistic with develops in transportation, two-sided markets have a strong presence in the economics literature (*28*,*29*), defined as markets with platforms enabling interactions between end-users; the goal is to get both sides "on board" by appropriately charging each other. The literature indicates the social optimum in a two-sided market may differ from a conventional one-sided market (*28*). Modeling current mobility services, such as Uber and Lyft, should naturally follow a two-sided market perspective for representing network externalities between travelers and service providers. For services, such as Uber, the fleet size varies day-to-day based on the number of drivers available, which in turn depend on the availability of customers, operating costs and profit. Djavadian and Chow (*1*) specifically consider a broad set of flexible transport services matching service providers with riders in the context of a two-sided market. The authors model an endogenous adjustment between service operators (sellers) and user demand in a single modeling framework. Using an agent-based stochastic day-to-day adjustment process under ride-sourcing setting. This paper follows this body of work to consider a different adjustment process from a behavioral perspective, where agents, both driver and riders, adjust a time-dependent aspiration level for matching that endogenously varies with the history and experience of past encounters.

In this paper, we specifically examine the stability and convergence in the ridesharing matching market, where a single driver matches with a single rider and adjust a time-dependent aspiration level, given an initial willingness-to-pay (WTP) and willingness-to-accept (WTA), for riders and drivers respectively. A series of agent-based simulation experiments illustrate the different rates of convergence and robustness in stability from assuming: (i) different initial WTP and WTA distribution assumptions; (ii) varying the size of the system with respect to number of drivers and riders; and (iii) allowing for agents to accept a loss in order to match. This paper departs from previous studies by considering an adjustment process where agents on both sides of the market have an endogenous aspiration level adjusted over time as new experiences are gained. We present the modeling framework next, followed by a description and discussion of the simulation experiment results. We conclude with a summary of results and future directions.

2.0 MODELING FRAMEWORK

This section details the conceptual framework for matching markets, which provides a foundation for the ridesharing matching market investigated. Additionally, in this section we present the behavioral assumptions underlying the learning process developed to model market evolution towards a stable matching. We view ridesharing from the perspective of a two-sided matching problem, where drivers with access to personal vehicles match with potential riders in need of rides. From this perspective, ridesharing is a matching market where participants have limited knowledge about the market and each other. Participants have latent aspiration levels that participants adjust day-to-day based on their experienced payoffs. There is no presumption that the market participants or central authorities know anything about the distribution of preferences or that such they can learn this information from prior rounds of experimentation with respect to matching. Instead, participants follow a process of trial and error, adjusting their bids and offers in hope of increasing their payoffs. Such aspiration adjustment rules are rooted in the psychology and learning literature (*30*,*31*,*12*).

For this paper, we describe a one-to-one matching market. However, this framework can easily extend to a many-to-one market (*32*). For example, if a market consists of a driver with two seats to offer two potential riders, and two riders in need of a driver, we can consider the driver as two individuals in a one-to-one matching market. Past work has shown that many-to-one markets have similar properties with one-to-one markets (*33*).

2.1 The Rideshare Matching Market

To consistently describe this framework with previous work in the literature, we following the notation of Naxy and Pradelski (*12*), but reframed in the context of ridesharing. The population of rideshare participants $N = R \cup D$ consists of riders $R = \{r_1, \ldots, r_m\}$ and drivers $D = \{d_1, \ldots, d_n\}$. They interact by bidding and making offers to potential partners whom they randomly encounter, which occurs through an underlying random process. Matches form only if bids are mutually profitable. The system contains the following main components:

<u>Willingness-to-Pay (WTP)</u>: Each rider i has a willingness-to-pay $p_{ij}^{+} \geq 0$ for matching with driver j.

<u>Willingness-to-Accept (WTA)</u>: Each driver j has a willingness-to-accept $q_{ij}^{-} \geq 0$ for matching with rider i.

Both of these values are participant specific and are unknown to other participants or to a central management authority.

<u>Match Value</u>: The value of a match between a rider and drive $(i, j) \in R \times D$ is the potential (positive) surplus between the WTP and WTA:

$$\alpha_{ij} = \left(p_{ij}^{+} - q_{ij}^{-}\right)_{+} \qquad \text{(Eq. 1)}$$

<u>Time</u>: We introduce a time dimension to consistently develop the process of matching for ridesharing. Denote $t = 0, 1, 2, \ldots$ as time periods over which the matching process occurs. An assignment occurs between participants indicating a successful match (or unsuccessful match). We

riders are activated in random order, though we could also assume a Poisson clock for the timing of demand for ridesharing, in particular the arrival of a rideshare trips. In future work we may also consider other types of systematically varying arrivals for rideshare trips.

Assignment: For all pairs of participants $(i,j) \in R \times D$, let $a_{ij}^t \in \{0,1\}$ to indicate matching:

If (i,j) is $\begin{cases} matched & a_{ij}^t = 1 \\ unmatched & a_{ij}^t = 0 \end{cases}$

We consider a participant i *matched* if there exists a j such that $a_{ij}^t = 1$; otherwise i is *single*. For a one-to-one matching a rider i can only match with one other driver j. Therefore, in an assignment $\boldsymbol{A^t} = \left(a_{ij}^t\right)_{i \in R, j \in D}$ if $a_{ij}^t = 1$ for (i,j), then $a_{ik}^t = 0$ for all $k \neq j$ and $a_{lj}^t = 0$ for all $l \neq i$.

Matching Market: We characterize a matching market by $[R, D, \boldsymbol{\alpha}, \boldsymbol{A}]$ each defined as follows:

$R = \{r_1, \dots, r_m\}$ is the set of m riders

$D = \{d_1, \dots, d_n\}$ is the set of n drivers

$\boldsymbol{\alpha} = \begin{pmatrix} \alpha_{11} & \cdots & \alpha_{1n} \\ \vdots & \alpha_{ij} & \vdots \\ \alpha_{m1} & \cdots & \alpha_{mn} \end{pmatrix}$ is the matrix of match values

$\boldsymbol{A} = \begin{pmatrix} a_{11} & \cdots & a_{1n} \\ \vdots & a_{ij} & \vdots \\ a_{m1} & \cdots & a_{mn} \end{pmatrix}$ is the assignment matrix with 0/1 values

With respect to the game theory literature, the matching problem described is a cooperative assignment game with the following properties (*32*):

Cooperative Assignment Game: Given $[R, D, \boldsymbol{\alpha}]$, the cooperative assignment game $G(v, N)$ is defined as follows:

Let $N = R \cup D$ and define a function $v: S \subseteq N$ such that

$v(i) = v(\emptyset) = 0$ for all singles $i \in N$

$v(S) = \alpha_{ij}$ for all $S = (i,j)$

$v(S) = max\{v(i_1, j_1) + \cdots + v(i_k, j_k)\}$ for every $S \subseteq N$

The maximum above is taken over all sets $\{(i_1, j_1), \cdots, (i_k, j_k)\}$ consisting of disjoint pairs that can be formed by matching riders and drivers in S. Next, we present the dynamic process for reaching the solution to the cooperative assignment game described.

2.2 Dynamic Components of the Matching Process

In this section, we describe the dynamic components of the matching process. These components are dynamic and change with time period t as the participants experience new matches and break old matches, or transition status from single to matched.

Aspiration Level: At the end of the time period t a participant experiences an aspiration level s_i^t, which determines the minimal payoff at which the participant is willing to be matched in future time periods. Denote the set of aspirations for time period t as $\boldsymbol{s^t} = \{s_i^t\}_{i \in R \cup D}$.

Bids: In any time period t a pair of participants encounter each other and make bids for matching. We assume participants will make bids high enough such that the resulting payoff to both participants is at least equal to the aspiration level, with a positive probability the bid is exactly equal to the aspiration level.

Rider $i \in R$ encounters driver $j \in D$ and submits a bid $b_i^t = p_{ij}^t$, where p_{ij}^t is the maximum amount i is willing to pay to be matched with j. Similarly, driver $j \in D$ submits a bid $b_j^t = q_{ij}^t$, where q_{ij}^t is the minimum amount j is willing to accept to be matched with rider i.

A bid are separable into a deterministic and random component. The determinist component is the difference between the willingness-to-pay and willingness-to-accept, and the aspiration level. The random component, specifically P_{ij}^t and Q_{ij}^t represents exogenous "shocks" to aspiration levels. For all participants define the following:

$$p_{ij}^t = \left(p_{ij}^+ - s_i^{t-1}\right) - P_{ij}^t \quad \text{and} \quad q_{ij}^t = \left(q_{ij}^- - s_j^{t-1}\right) - Q_{ij}^t \qquad \text{(Eqs. 2 and 3)}$$

The final bid is between p_{ij}^t and q_{ij}^t and is drawn assuming a uniform distribution between these two values. We assume $P_{ij}^t \sim N(0,0.1)$ and $Q_{ij}^t \sim N(0,0.1)$.

Prices: When i is matched with j the transaction occurs at a unique price π_{ij}^t.

Payoff: Given $[\boldsymbol{A^t}, \boldsymbol{s^t}]$, the payoff to each participant is:

$$\phi_i^t = \begin{cases} p_{ij}^+ - \pi_{ij}^t & i \text{ matched to } j \\ 0 & i \text{ is single} \end{cases} \quad \text{and} \quad \begin{cases} \pi_{ij}^t - q_{ij}^- & j \text{ matched to } i \\ 0 & j \text{ is single} \end{cases}$$

Profitability: A pair of bids is profitable if both participants $\left(p_{ij}^t, q_{ij}^t\right)$ receive a higher payoff if the match forms. If both participants bid their aspiration levels and $p_{ij'}^t = q_{ij}^t$, they are profitable only if both participants are currently single.

Re-match: At each time period, a pair (i,j) that encounter each other randomly match only if their bids are profitable. The resulting price is finally set between q_{ij}^t and p_{ij}^t.

A new match forms only if it is profitable. Both participants receive a higher payoff due to the full support of the resulting price.

States: The state at the end of a time period t is given by $Z^t = [\boldsymbol{A^t}, \boldsymbol{d^t}]$ where $\boldsymbol{A^t} \in \mathrm{A}$ is an assignment and $\boldsymbol{d^t}$ is an aspiration vector.

2.3 Evaluation of Matching Solutions

We evaluate the matching process with respect to a final stable matching or solution. Define the following solution concepts:

Optimality: An assignment $\boldsymbol{A}$ is optimal if:

$$\sum_{(i,j)\in F\times W} a_{ij} \cdot \alpha_{ij} = \upsilon(N) \qquad \text{(Eq. 4)}$$

where $\upsilon(N)$ is the solution to the Cooperative Assignment Game described previously.

Pairwise Stability: An aspiration level vector $\boldsymbol{d^t}$is pairwise stable if for all i, j and $a_{ij}^t = 1$:

$$p_{ij}^+ - d_{ij}^t = q_{ij}^- + d_j^t \qquad \text{(Eq. 5)}$$

and $p_{i'j}^+ - d_{i'j}^t \le q_{i'j}^- + d_j^t$ for every alternative rider $i' \in R$ with $i' \neq i$ and $q_{ij'}^- + d_{j'}^t \ge p_{ij'}^+ - d_i^t$ for every alternative driver $j' \in W$ with $j' \neq j$.

We use both conditions to evaluate a stable matching to the ridesharing problem. In this paper, a stable match occurs if there is no alternative matching that will make at least one participant better off without making another participant worse off; there for matched (and unmatched) pairs do not change from day-to-day.

3.0 SIMUATION EXPERIMENTS AND DISCUSSION OF RESULTS

In this section, we describe the simulation model of matching developed for this paper, including key steps to the learning process. We finish this section with a presentation of the experimental set up and results.

3.1 Simulation Process

In the agent-based simulation process considered in this study, a fixed population of agents acting as participants in a rideshare program, $N = R \cup D$, plays the assignment game $G(v, N)$ described in the previous section. Repeatedly, at each iteration t, participants encounter other participants. Two participants enter a new match if their potential match is profitable. Profitability is determined from their current bids, offers and individual payoffs as described in the previous section. We depict the overall simulation framework in Figure 1 below.

The key steps of the learning and social encounter process investigated are as follows. At the start of period $t + 1$:

Step 1) Participant i randomly encounters participant j. In this paper, we simulate encounters by randomly ordering all riders R each simulation iteration and allowing each rider to match with one driver randomly. All drivers are available at start each iteration. Riders continue to try to match with drivers until no free unmatched drivers are left, or all riders have attempted to match and succeeded or failed.

Step 2) Determine the profitability of the match. The profitability is determined using expression presented in the next section.

a. If the encounter is profitable given their current bids and assignment, the pair matches; otherwise

b. If the encounter is not profitable, both participants return to their previous matches or remain single.

Step 3) Determine the transaction price and update individual aspiration levels. If a match occurs, the final transaction price is determined randomly by drawing a value between p_{ij}^t and q_{ij}^t. Updating of individual level aspiration levels occurs by setting them equal to the final realized payoffs.

a. If a new match (i, j) forms, the final transaction price is set somewhere between the bid and offer. This represents a negotiation of the price between the driver and rider. The aspiration levels are set relative to their realized payoffs, as described in the next section.

b. If no new match forms, the active participant, if previously matched, keeps the previous aspiration level and stays with the previous partner. If the participant was previously single, they remain single and lower their aspiration level with a positive probability, in hopes of finding a new match in a future iteration.

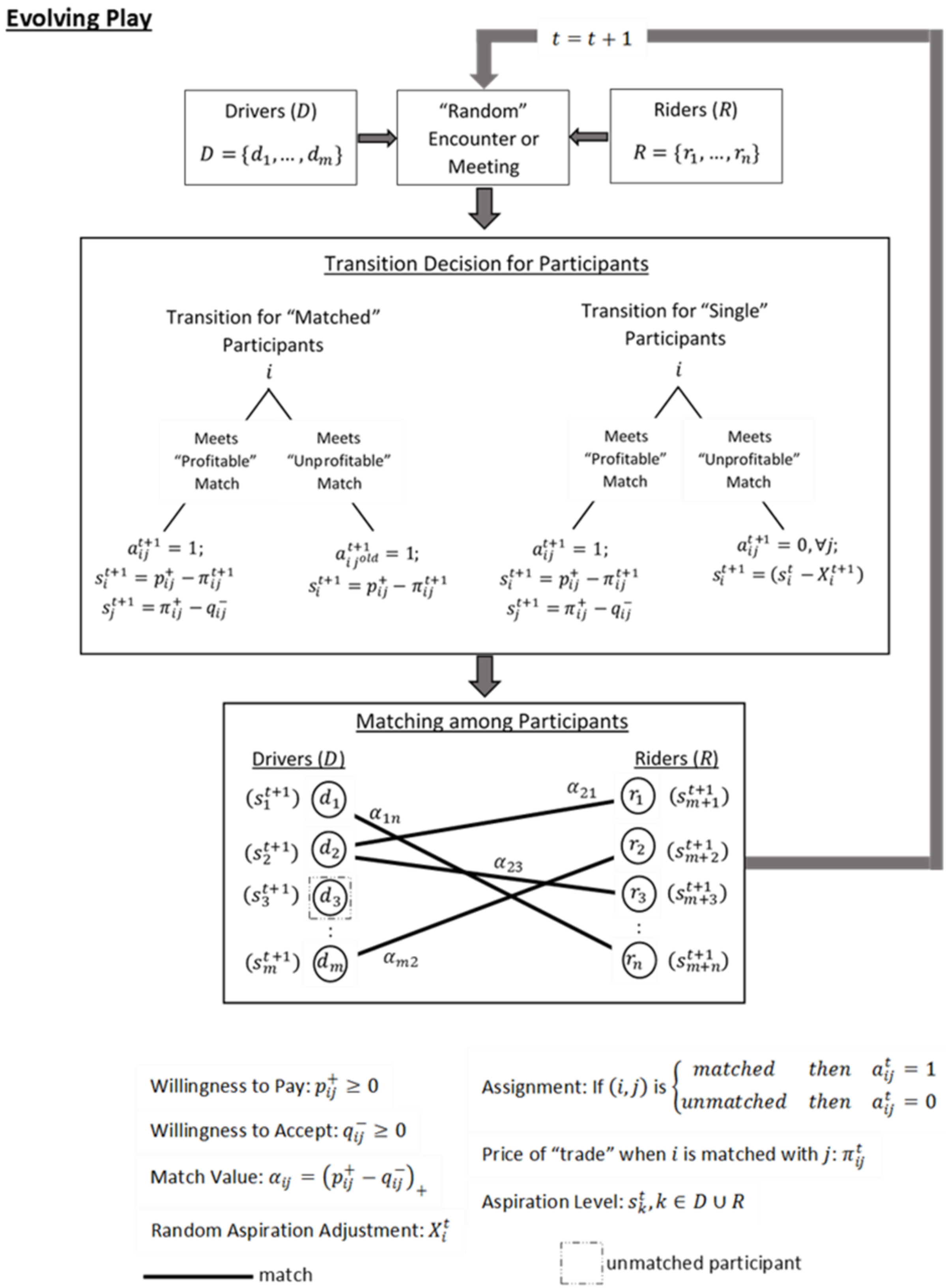

FIGURE 1 Simulation Framework: Evolving Play

The behavioral dynamics captured in the simulation process have a basis in psychology. However, the application towards matching markets in cooperative games, has received little attention until recently (*12*). The dynamics in this framework seem well suited for modeling traveler behavior in large decentralized assignment markets, such as rideshare matching markets where participants have little information about the overall game and the preferences of other participants. This process also has a relation with aspiration adjustment theory and related bargaining experiments on reinforced learning. We assume a simple directional learning model where matched drivers experiment with higher offers, while drivers without riders lower their offers, in hopes of attracting riders. This mechanism is similar to the one presented in Naxy and Pradelski (*12*). Next the transition for participants after an encounter is described for matched participants (Case 1) and then for single participants (Case 2).

<u>Case 1: Participant i is currently matched and meets participant j</u>

If encounter (i, j) is profitable, given current aspiration levels, it becomes a match. As a result, i's former partner is now single, as is j's former partner. The price governing the new match π_{ij}^{t+1} is randomly set between p_{ij}^{t} and q_{ij}^{t}, the bid and offer.

At the end of period $t+1$, we adjust and set the aspiration levels for the new matched pair (i, j) by adjusting them relative to their new realized payoffs as follows:

$d_i^{t+1} = p_{ij}^{+} - \pi_{ij}^{t+1}$ and $d_j^{t+1} = \pi_{ij}^{t+1} - q_{ij}^{-}$ (Eqs. 6 and 7)

All other aspiration levels and matched remain unchanged. If (i, j) is not profitable, i remains matched with the previous partner and that participant keeps the previous aspiration level.

<u>Case 2: Participant i is currently single and meets participant j</u>

Similar to Case 1, if encounter (i, j) is profitable, given current aspiration levels, it becomes a match. As a results, j's former partner is now single if previously matched. The price governing the new match π_{ij}^{t+1} is randomly set between p_{ij}^{t} and q_{ij}^{t}, the bid and offer.

At the end of period $t+1$, the aspiration levels are of the new matched pair (i, j) are adjusted relative to their new realized payoffs:

$d_i^{t+1} = p_{ij}^{+} - \pi_{ij}^{t+1}$ and $d_j^{t+1} = \pi_{ij}^{t+1} - q_{ij}^{-}$

All other aspiration levels and matches remain unchanged. If (i, j) is not profitable, i remains single and, with a positive probability, reduces the aspiration level in hopes of finding a match in a later iteration:

$$d_i^{t+1} = (d_i^t - X_i^{t+1})_+ \quad \text{(Eq. 8)}$$

where X_i^{t+1} is a random variable drawn from the normal distribution ~ N(0,0.5).

3.2 Simulation Experiment Setup

In this section, we describe the parameters and setup of simulation experiments conducted. We implement this agent-based simulation in Python. Outcomes from a total of seven experiments, each described below comprise the experimental results.

The parameters of interest for our experiments are:

i) Market Size ($N = R + D$): The total size of the market determined by the number of riders and drivers total. If the number of riders equals the number of drivers ($R = D$), potentially all riders could be matched with a driver.

ii) Riders' Willingness-to-Pay (p_{ij}^t): This is the maximum value riders will pay for a ride. For each rider *i*, this is drawn from a normal distribution $N(p_\mu^+, \$4)$. The variance was adjusted prior to the simulation experiments to ensure a reasonable convergence within 500 iterations.

iii) Drivers' Willingness-to-Accept (q_{ij}^t): This is the maximum value drivers will accept for giving a ride. For each driver *j*, this is drawn from a normal distribution $N(q_\mu^-, \$4)$. The variance was adjusted prior to the simulation experiments to ensure a reasonable convergence within 500 iterations.

A three sets of experiments were examined in this paper. Each set of simulation experiments are described as follows:

A) Varying Market Size ($N = R + D$): Three market sizes ($N = \{10, 100, 200\}$) were considered in this set of experiments. An equal number of riders and drivers ($R = D$) were assumed for each case.

B) Varying the Mean Willingness-to-Pay (WTP) and Willingness-to-Accept (WTA) Values (p_μ^+ and q_μ^-): Three sets of values were assumed: $\{p_\mu^+ = \$15;\ q_\mu^- = \$15\}$; $\{p_\mu^+ = \$20;\ q_\mu^- = \$10\}$; and $\{p_\mu^+ = \$10;\ q_\mu^- = \$20\}$.

   The assumed values for WTP and WTA have implications for the final transaction price between riders and drivers. The final price is drawn with equal probability between the two values WTP and WTA, specific to each rider *i* and driver *j* respectively, specifically p_{ij}^t

and q_{ij}^t. For $\{p_\mu^+ = \$20;\ q_\mu^- = \$10\}$, a range of feasible transaction prices exist; riders are *on average* willing to pay up to \$20 to match with a driver; similarly drivers are *on average* willing to accept down to \$10 to match with a rider. The actual final price depends on the individual WTP and WTA for riders and drivers respectively.

C) Allowing for any real-valued aspiration level ($d_i, d_j \in \mathbb{R}$): In this set of experiments negative aspiration values were allowed for the following two sets of mean WTP and WTA: $\{p_\mu^+ = \$20;\ q_\mu^- = \$10\}$; and $\{p_\mu^+ = \$10;\ q_\mu^- = \$20\}$. This relaxation of aspiration levels implies that agents are willing to accept a loss in order to match with a driver or rider. Otherwise, if we require aspiration levels to be non-negative, only positive payoffs are acceptable.

3.3 Simulation Results and Discussion

This section discusses the results for each of the three sets of experiments discussed previously (A-C). Each simulation experiment run was evaluated by the total match value $\upsilon(N)$ for each assignment matrix for each iteration (day-to-day), according to Equation 4. To visually determine if a convergence was reached, the total match value $\upsilon(N)$ was plotted across iterations. We define convergence in this paper as a state where agents stop switching matches.

The evolution of the total match value $\upsilon(N)$ across iterations are shown below for the three sets of experiments (A-C) in Figures 2 to 4. Only positive aspirations $d_i, d_j \geq 0$ were allowed for the first two sets of experiments (A and B); for the last set (C) any real-values aspiration was allowed: $d_i, d_j \in \mathbb{R}$.

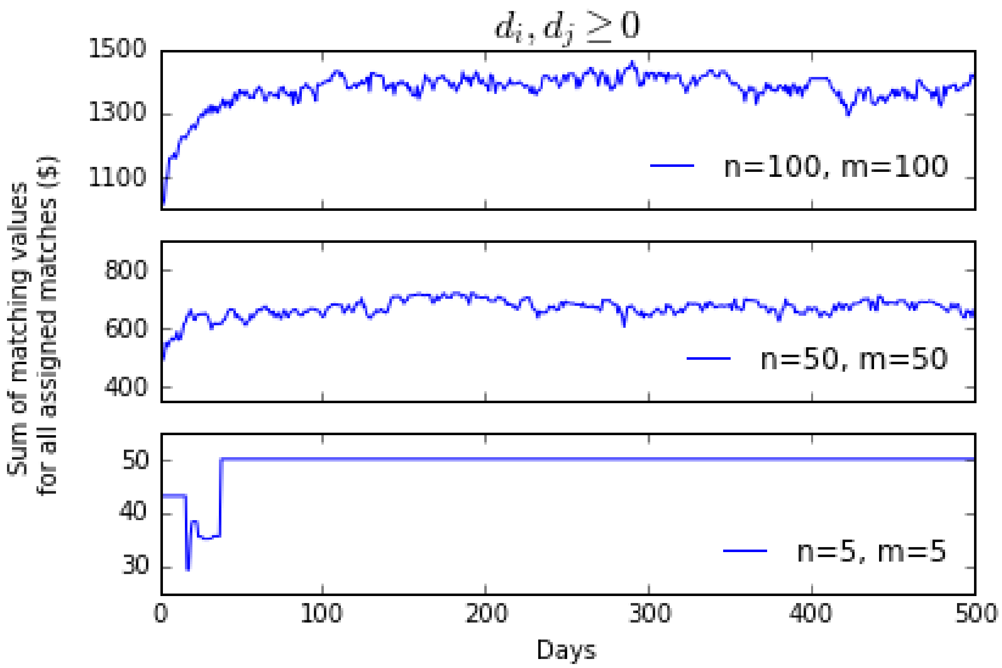

FIGURE 2: Evolution of Match Value $v(N)$ for varying Market Sizes: $N = \{10, 100, 200\}$; The number of riders (n) and drivers (m) was assumed equal in all simulation runs.

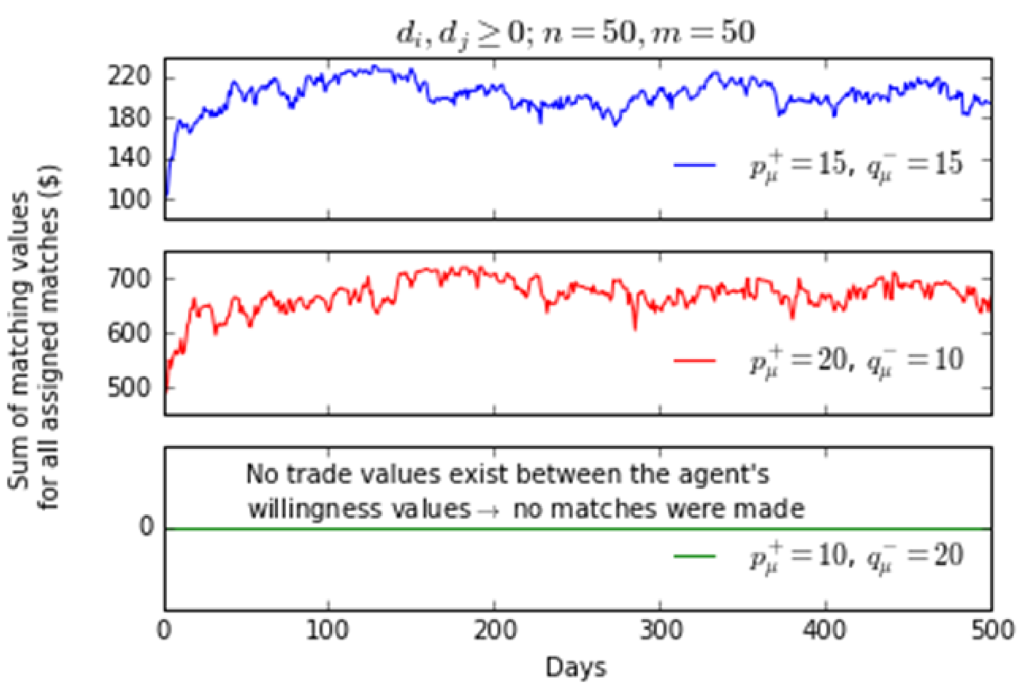

FIGURE 3: Evolution of Match Value $v(N)$ for varying mean WTP and WTA values: $\{p_\mu^+ = \$15;\ q_\mu^- = \$15\}$; $\{p_\mu^+ = \$20;\ q_\mu^- = \$10\}$; and $\{p_\mu^+ = \$10;\ q_\mu^- = \$20\}$; The number of riders (n) and drivers (m) was assumed equal in all simulation runs.

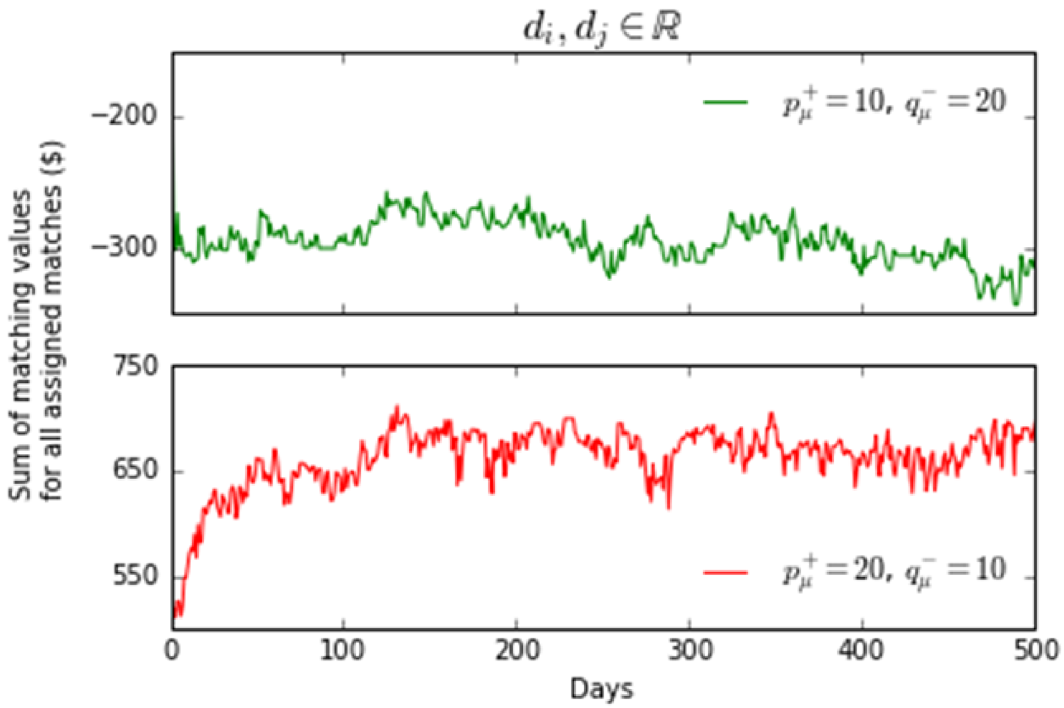

FIGURE 4: Evolution of Match Value $\upsilon(N)$ any real-values aspiration was allowed: $d_i, d_j \in \mathbb{R}$; $\{p_\mu^+ = \$20;\ q_\mu^- = \$10\}$; The number of riders (n) and drivers (m) was assumed equal in all simulation runs.

<u>*Varying Market Size*</u>: From Figure 2, the results show that for a smaller market size $N = \{10\}$, a strict convergence is reached relative to the other two cases $N = \{100{,}200\}$. For the final two cases, while a strict convergence was not reached, both experiments seem to converge towards a final total match value $\upsilon(N)$. For $N = \{10\}$, the final total match value was about \$50. For the final two $N = \{100{,}200\}$, the final total match values were about \$700 and \$1400 respectively. Some random switching occurs for $N = \{100{,}200\}$; this is due to random shocks to the aspiration which may results in a previous match dissolving (see Equations 2 and 3). The higher final total match value is the result of more participants in the larger market; if agent has a positive match value, the total will increase assuming almost all agents find a match. Finally, Figure 2 shows that as the market size increases, the volatility is more pronounced. This volatility difference is clear comparing $N = \{10\}$ and $N = \{200\}$. These results are consistent with past results looking at convergence in evolving traffic network flows, which indicate that strict convergence is more difficult for a higher number of users (*23*). These experiment runs also suggest that as the number of participants in the ride-share system increases, it may be more difficult to achieve a strict convergence where participants stop switching partners after a match. This result is counterintuitive from the standpoint that a larger number of participants indicates a higher probability of finding a match (“always other fish in the pond…”).

Varying the Mean Willingness-to-Pay and Willingness-to-Accept Values (p_μ^+ and q_μ^-): Figure 3 shows the impact of varying the mean WTP and WTA values for the normal distribution used to draw the individual WTP and WTA values. Before discussing the results, recall the individual WTP and WTA values dictate the range for the final transaction price. Give this association, the results in Figure 3 are unsurprising. For the case $\{p_\mu^+ = \$10;\ q_\mu^- = \$20\}$, drivers are only willing to pay up to \$10, but drivers are only willing to accept a minimum of \$20, which suggest that no feasible transaction values exist in this system on average. Given that aspirations must remain positive, which indicates that agents are unwilling to accept a loss of any magnitude for matching, the market participants cannot find a matching partner. Notice that no matches occur over time in this case. Compare this with the opposite case $\{p_\mu^+ = \$20;\ q_\mu^- = \$10\}$. In this case a range of feasible transaction prices exist. Figure 3 shows that for this case the system converges around a total $\upsilon(N)$ of about \$650. Contrast this with $\{p_\mu^+ = \$15;\ q_\mu^- = \$15\}$ which provides a tighter band $(p_\mu^+ - q_\mu^-)$ or feasible transactions prices. This tighter brand is reflected in the lower total $\upsilon(N)$ of about \$200 relative to the case $\{p_\mu^+ = \$20;\ q_\mu^- = \$10\}$. The results suggest that initial conditions may affect the eventual convergence of matching. If the WTP and WTA of do not allow for any feasible transaction prices, clearly no matching will occur on average. Additionally, if a tight band for feasible transaction prices exists due to individual WTP and WTA, the system will converge onto a lower total $\upsilon(N)$ relative to the case where the band is looser.

Allowing for any real-valued aspiration level ($d_i, d_j \in \mathbb{R}$): By allowing any real-valued aspiration level, essentially we allow agents to accept a loss in order to find a match. This is reflected in Figure 4. Notice that for the case $\{p_\mu^+ = \$10;\ q_\mu^- = \$20\}$, previously no matcher were made due to infeasible transactions prices from the WTP an WTA values. However, now that losses are possible, the system evolves over time with some matches forming, although some of these are negative in value, indicating a loss. This is also reflected in the case $\{p_\mu^+ = \$20;\ q_\mu^- = \$10\}$, where there is a range of feasible transaction prices. However, in this case there seems to be more volatility compared to the case where only positive aspirations were allowed $d_i, d_j \geq 0$.

4.0 CONCLUSION

In this paper, we examine the stability and convergence of a ride-sharing two-sided ridesharing market where a set of drivers with personal vehicles match with a set of riders seeking rides. Using a series of simulation experiments, we show that this matching market converges to a relatively stable matching state under a self-coordinating system. We learned the following lessons through these experiments:

1) As the size of the market increases, a strict convergence is more difficult to obtain. Interestingly, this is counterintuitive from the standpoint that a larger number of

participants indicates a higher probability of finding a match ("always other fish in the pond…").

2) Depending on the values for the WTP and WTA for riders and drivers respectively, the range of feasible transaction prices will vary. The tighter the band of transaction prices $(p_{\mu}^{+} - q_{\mu}^{-})$ the lower the total match value for the system. If the WTP of riders is less than the WTA of drivers, then on average few feasible transaction prices are possible. Only if agents are willing to accept a loss, represented a negative aspiration do matches occur. However, some of these matches occur with loss (negative transaction prices).

3) Finally, if negative aspiration values are allowed, indicating agents are willing to accept a loss to have a match, clearly more matches occur, though some at a loss. This may result in a total negative match for the market.

Future extensions envisioned include allowing for many-to-one matching to represent multiple riders assigned to one driver. Additionally, future studies would consider different behavioral mechanism to update aspirations over time. Finally, while these studies are simulation in nature, empirical data to verify some of these results could be obtained through laboratory economic experiments.

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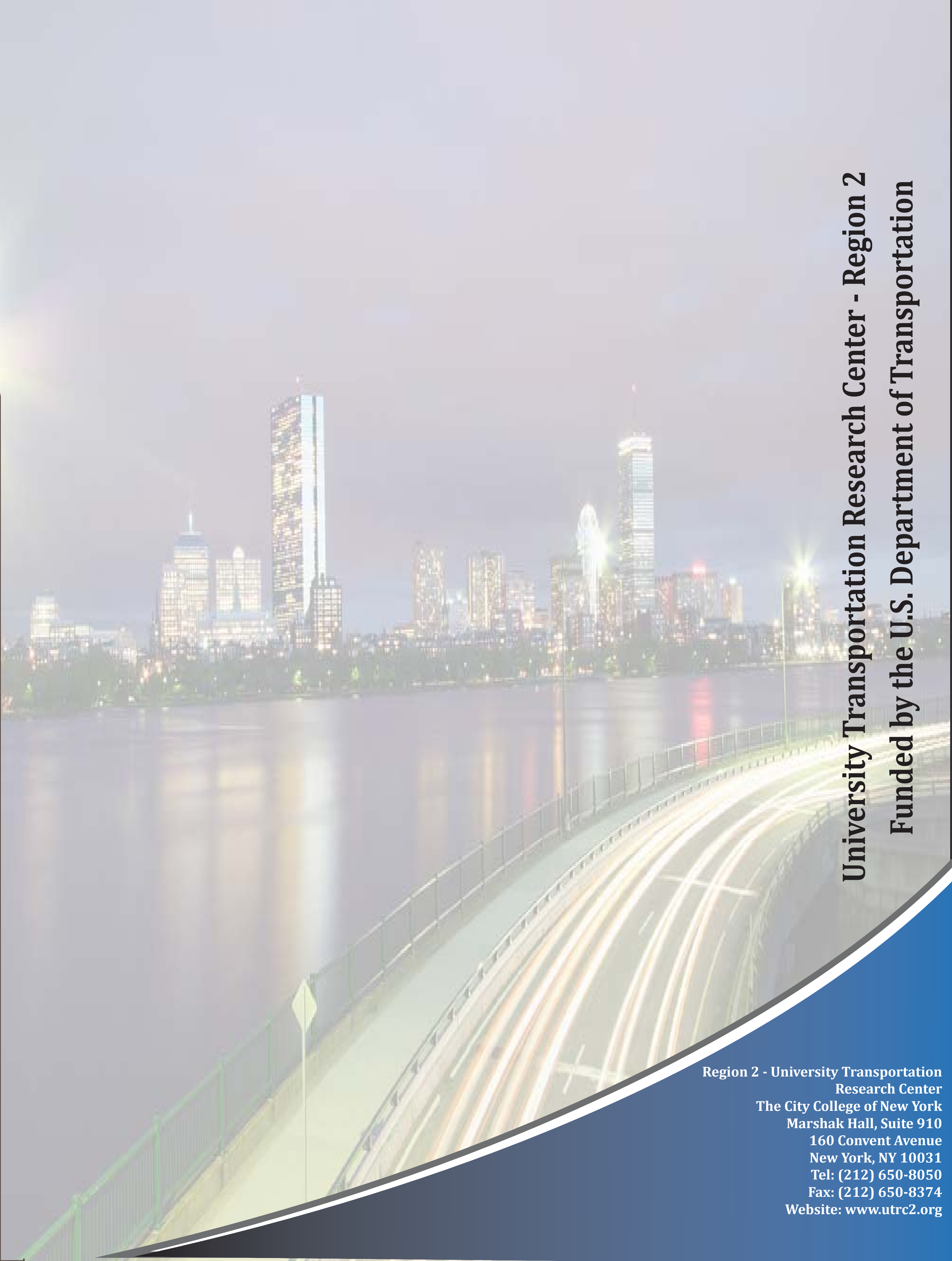

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