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Fighting for Fares: Uber and the Declining Market Price of Licensed Taxicabs

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Fighting for Fares: Uber and the Declining Market Price of Licensed Taxicabs*

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Abstract

In this paper, we study how the emergence of Uber in a large North American city affects the financial value of taxicab licenses. A taxicab license provides a claim to a stream of dividends in the form of rents generated by operating the taxicab or leasing the license. The introduction of Uber undoubtedly affects the anticipated stream of dividends because Uber drivers capture part of the farebox revenue that might otherwise go to the owners/drivers of licensed taxicabs. At the same time, the launch of Uber's innovative technology-driven approach to the provision of ride-hailing services can be viewed as a partial obsolescence of the traditional taxicab approach. The economic incentives facing market participants may therefore change as Uber gains momentum in the ride-hailing market, which could further affect the market value of licensed taxicabs. Using transaction-level data, we apply a theory of asset pricing to the secondary market for Toronto taxicab licenses to explore these potential price effects. We learn that both the farebox and innovation effects contribute to the overall decline in market value, with the farebox effect accounting for just over half of the $170K price decline from 2011 to 2017. We explore the welfare implications for taxicab license owners with counterfactual simulations. We find that, consistent with the anti-Uber protests organized by Toronto taxi drivers, there was a high willingness to pay among license holders to prevent or postpone the launch of Uber's ridesharing services.

JEL classification: G12

Keywords: Uber, Taxicabs, Asset Pricing, Search and Bargaining

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1 Introduction

The sharing economy (comprised of companies such as Uber and Airbnb) has given rise to breakthrough sustaining innovations that disrupt traditional markets. A specific example is Uber's innovative technology-driven approach to ridesharing and ride-hailing which has led to the partial obsolescence of the traditional taxicab approach. Not surprisingly, declines in the average prices of taxi medallions in major cities with a strong Uber presence have been documented in the media.[1] In Toronto, we document that the average price of a taxicab license fell from about $250K to $80K between 2011 and 2017, during which time Uber began its operations and gained momentum in the ride-hailing market. In this paper, we study how the emergence of Uber in this large North American city affected the market price of taxicab licenses and the financial well-being of license owners. More specifically, we apply a theory of asset pricing to the secondary market for Toronto taxicab licenses using transaction-level data. Using proxy variables for Uber's impact on the traditional taxicab industry, we simulate a transition path from a stationary equilibrium without Uber to one in which Uber is well-established. We then isolate and quantify the different channels through which Uber adversely impacted the financial positions of taxicab license holders.

Uber is a company that partners with freelance drivers to offer technology-based ride-hailing services. Traditional taxicabs, in contrast, require taxicab licenses issued by the municipality in order to operate a taxicab vehicle. The municipal licensing requirement effects a barrier to entry that has historically benefited both owners and operators of traditional taxicabs. Today, the private car transportation services through Uber and those offered by licensed taxicab operators are undoubtedly considered close substitutes by most tech-savvy consumers. It follows that the introduction of Uber's private-vehicle-for-hire services may have undermined the regulatory supply constraint, resulting in licensed taxicab operators completing fewer rides and collecting fewer fares. In other words, we hypothesize that the economic rent associated with a traditional taxicab license declines as Uber builds

[1] See Barro (2014), for example, for a discussion of the plummeting prices of taxi medallions in New York, Chicago, Boston, and Philadelphia.

momentum in the ride-hailing market.[2] This phenomenon and potential source of price decline, referenced in the title of this paper, is hereinafter labelled the *farebox effect* of Uber on traditional taxicabs.

The rise of Uber was arguably more sophisticated than a mere flood of unregulated unlicensed so-called "bandit cabs." Uber is an example of a *sustaining innovation* that added tremendous value to the provision of ride-hailing services. Relative to the traditional provision of taxicab services, the Uber approach to ride-hailing uses technology and smartphone applications, leverages otherwise idle capital and labor, and has the advantage of flexible pricing to strategically respond to dynamically changing local supply and demand.[3] These innovations in ride-hailing service provision may have triggered a reallocation of resources from traditional taxicabs to less-regulated smartphone application-based ride-hailing service providers. Our second hypothesis can thus be summarized as follows: participation in the traditional taxicab market becomes relatively less appealing for both current and prospective taxicab license holders following the introduction of Uber's innovative approach to ride-hailing. In addition to the farebox effect summarized above, Uber's *innovation effect* on the traditional taxicab industry may further depress the market value of licensed taxicabs.

We explore these price effects by developing and calibrating a model of the secondary market for taxicab licenses in Toronto. *Taxicab license* (TL) refers specifically to a license plate that can not only be used by an owner-driver to operate a taxicab vehicle in Toronto, but can also be leased, rented to a shift driver or transferred to a new owner by means of a transaction in a secondary market. A TL can therefore be viewed as a durable *asset*, where the monthly *dividend* is the rent generated from operating the taxicab or leasing/renting the license. Accordingly, we model the secondary market for TLs as a decentralized asset market with search frictions and bilateral price negotiations. The framework draws from the recent literature that applies search theory to decentralized financial markets (e.g., Duffie et al., 2005 and 2007; Vayanos and Wang, 2007; and Lagos and Rocheteau, 2009). We

[2] Several media articles have advanced this argument for Toronto (Cain, 2015; Cheney, 2015) and other North American cities (Barro, 2014).

[3] Uber's *surge pricing* is a feature that adjusts fares in response to the geographic distribution of drivers and prospective riders.

model the emergence of Uber with two features: (i) a potential change to the distribution of dividends (to reflect the farebox effect), and (ii) an exogenous alternative for potential market participants to the traditional taxicab market with a present discounted value that can vary with Uber's share of the market (to capture the innovation effect).

Our calibration exercise uses TL transaction data and monthly lease payments recorded by the city. We calibrate parameters according to the properties of the no-Uber and post-Uber stationary equilibria. We also exploit the timing of the launch of Uber and UberX in Toronto, and a measure of Uber's presence in the Toronto ride-hailing market derived from a Google Trends search intensity index in order to simulate prices along the transition path between the two stationary equilibria. The simulated transition path closely follows the observed price decline for licensed taxicabs. By means of counterfactual simulations we learn that both the farebox and innovation effects are important contributors to the overall decline in market value. The farebox effect accounts for approximately 53 percent of the $170K price decline from 2011 to 2017; the innovation effect along with endogenous market participation can account for the rest. In other words, the dilution of fares caused by the flood of Uber drivers is only a partial explanation. Our interpretation is that Uber's technology-driven approach to the provision of ride-hailing services further depressed TL prices by drawing participants away from the now partially obsolete traditional taxicab market.

While these price effects are of interest in their own right, we also consider the welfare consequences for taxicab market participants. These are less straightforward, especially when it comes to the innovation effect, because the emerging opportunity to transition to a more innovative regime could offset the financial loss from the price depreciation of their license. We explore the welfare implications for TL owners by calculating the present discounted expected value of TL ownership. We consider the effect of an anticipated delay in the launch of Uber's ridesharing services which would postpone the farebox and innovation effects. We find that an 18 month delay could be worth about $4,455 to each of the 5,000 Toronto TL owners from the perspective of the second quarter of 2012. These non-negligible financial repercussions of Uber for owner/drivers of traditional taxicabs rationalize the extensive anti-

Uber protests that occurred in Toronto (Ferreira, 2015; Mangione and Balca, 2015) and elsewhere (Lindeman, 2015) as Uber initiated ridesharing operations in cities around the world.

A brief review of the recent Uber-related literature is in order. Whereas our paper focuses on the financial consequences for owners of TLs, the existing literature has explored Uber's impact on other stakeholders in the ride-hailing market. The implications for consumer welfare have been studied by Bian (2018); Cohen et al. (2016) and Shapiro (2018). The consequences for drivers have been examined by Berger et al. (2018); Hall and Krueger (2018) and Chen and Sheldon (2015). Finally, Hall et al. (2018) considers public transit-related outcomes following the introduction and rise of Uber. Uber's effects on riders and drivers are indeed interesting in their own right. To our knowledge, however, we are the first to consider the financial consequences of Uber for the owners of the traditional ride-hailing "technology."

The rest of the paper is organized as follows. Section 2 provides background on the Toronto market for TLs and the entrance of Uber. The model environment and equilibrium are described in Section 3, and comparative statics are derived in Section 4. Section 5 explains the data, and Section 6 presents our calibration of the model. Section 7 discusses the results and the counterfactual simulations. Section 8 concludes.

2 Background

A Toronto TL gives you the right to operate a taxicab vehicle within the city of Toronto. The license can be used by an owner-driver to operate the vehicle, leased to a driver long-term, or rented to a shift driver. Licensed taxicabs can queue up at airports, train stations, and other designated taxicab stands. Licensed operators tend to drive their taxicab vehicles throughout the city, ready and willing to pick up passengers, while waiting to be dispatched to customers that submit requests for ride-hailing services. Taxicab operators accept cash fares as well as debit and most major credit card payments. In order to control the supply of taxicabs, the City of Toronto issued only a limited number of TLs. Their are currently 5,000 licenses in Toronto. New licenses get issued periodically after a review of the industry is performed. The last review occurred in 2014 and no new licenses were issued.

TLs that have been issued can be bought and sold in a secondary market. Exchange in this market is decentralized in nature; it takes time to find a trading partner by word-of-mouth or via an online platform for classified advertisements such as `Kijiji.ca`, and prices are negotiated bilaterally. Because ownership transfers must be approved and comply with the guidelines of the Municipal Code, TL transfers are reported to and recorded by the City of Toronto's Municipal Licensing and Standards division. A record of lease agreements, each formed and negotiated bilaterally between a license holder and their lessee (i.e., the operator of the taxicab), was also maintained by the City until June, 2016.

Uber developed and operates smartphone applications to connect customers with local freelance drivers. Uber entered the Toronto ride-hailing market on March 16, 2012, dispatching limousines to customers seeking a ride-for-hire via their smartphone application. In 2013 they started dispatching licensed taxicabs in the same technology-based manner. On September 14, 2014, they began dispatching unlicensed unregulated freelance drivers with the launch of UberX. While these operations were in violation of the current bylaws, taxicab companies claimed at the time that there was little to no municipal bylaw enforcement (Shum and Miller, 2015). It was not until Toronto City Council passed a bylaw on March 3, 2016, that Uber and other ridesharing companies were explicitly permitted to operate private vehicles-for-hire in the regulated market. The ridesharing regulations established thereafter require Uber drivers to have a Private Transportation Company license to pick up passengers in Toronto. Unlike traditional taxicabs, Uber drivers are not permitted to pick up passengers unless solicited via the smartphone application. Nor can they use designated taxicab stands.

3 Theory

As argued above, a TL can be viewed as a long-lived *asset*, where the *dividend* is the profit generated from operating the taxicab or leasing the license. The secondary market for TLs is thin and opaque. It features trading frictions and a high degree of price dispersion. For these reasons, we view search theory as an appropriate modeling framework for studying the secondary market for TLs. We therefore advance a model of an asset market with search frictions, price negotiations, and endogenous market participation given an exogenous outside opportunity.

The emergence of Uber represents an innovation in the *ride-hailing market* that affects *asset market* fundamentals, including dividends. Since ridesharing is an appealing alternative approach to the provision of ride-hailing services, its introduction may also be viewed as an increase in the value of the outside option that can further affect prices and welfare.

Generic asset market language is used to describe the market in the model environment presented below, which we subject to an exogenous imperfectly anticipated innovation. This is for convenience and generality even though the secondary market for TLs amid the launch and rise of Uber is the application of interest.

3.1 Environment

Assets. Time is discrete and denoted by $t = 0, 1, \ldots$. There is a fixed measure of indivisible assets (TLs), normalized to 1. Each asset pays a stochastic dividend (operating rents or lease payments), $d_t \in \{d_1, \ldots, d_J\}$, in each period $t = 0, 1, \ldots$ to its owner. The dividend is idiosyncratic and follows a Markov process with a $J \times J$ transition matrix $\mathbf{\Pi}$. In Appendix A, we provide explicit microfoundations for the idiosyncratic stochastic dividend process following the interpretation of the asset as a TL that can be used to operate a licensed taxicab and/or leased to a driver. The transition matrix associated with these microfoundations,

$$\mathbf{\Pi} = \begin{bmatrix} (1-\rho)+\rho\pi_1 & \rho\pi_2 & \cdots & \rho\pi_J \\ \rho\pi_1 & (1-\rho)+\rho\pi_2 & \cdots & \rho\pi_J \\ \vdots & \vdots & \ddots & \vdots \\ \rho\pi_1 & \rho\pi_2 & \cdots & (1-\rho)+\rho\pi_J \end{bmatrix}, \tag{1}$$

takes into account idiosyncratic periodic changes in dividends with probability ρ, in which case a new dividend amount is drawn from a discrete distribution with probability mass function $\pi(d_j) = \pi_j$, $j = 1, \ldots, J$. The distribution of asset types (i.e., current dividends) at time t is described by $\{a_t^1, \ldots, a_t^J\}$, where $\sum_{j=1}^J a_t^j = 1$ and $a_t^j \in [0, 1]$ is the fraction of assets yielding dividend d_j in period t. To distinguish the distribution of *new* dividends (i.e., the π_js) from the distribution of *current* dividends (i.e., the a^js), we hereinafter refer to the former as the distribution of dividends, and the latter as the distribution of assets. Dividend heterogeneity is not essential for illustrating the dividend and innovation effects (see Section 4), but helps align the theory and the data for the calibration exercise in Section 6.

Agents. Agents are risk neutral with common discount factor $\beta \in (0, 1)$, and have opportunity to participate in the asset market. Each agent, regardless of their asset holdings, is subject to a random preference shock that reduces their valuation of the dividends from $d \in \{d_1, \ldots, d_J\}$ to $(1-\sigma)d$, with $0 < \sigma < 1$. The preference shock arrives with probability δ each period. Once an agent experiences a shock, the low valuation applies to all present and future dividends from any asset. This generates incentives to exit the model for an exogenous outside opportunity, and those with an asset will be motivated to sell it in the secondary market. At any point in time, each market participant can thus be one of three trader types: a *buyer* that searches but does not yet own the asset; an *owner* that fully values their asset's dividends, or a *seller* that still owns the asset but has experienced the preference shock and no longer fully values dividends. Let $\{n_t^b, n_t^m, n_t^s\}$ denote the measures of traders across trading status at the beginning of time t, where b, m and s denote buyer, owner, and seller types. New prospective buyers that fully value dividends can enter from a limited pool of potential market participants that otherwise pursue the same exogenous opportunity as traders that exit. To maintain a fixed measure $\mathcal{N} > 1$ of agents in every period, we assume that every trader that exits at time t is replaced at time $t+1$ with a new potential market participant.

Trading process. The meeting process between buyers and sellers is subject to search frictions which we model using a bilateral matching function. Let $\mathcal{M}((1-\delta)n_t^b, n_t^s)$ denote the number of matched buyer-seller pairs at time t.[4] The matching function exhibits constant returns to scale, is increasing in both arguments, and satisfies the property that the number of matches is less than or equal to the number of traders on the short side of the market, $\mathcal{M}((1-\delta)n^b, n^s) \leq \min\{(1-\delta)n^b, n^s\}$. We denote the ratio of buyers to sellers by $\theta_t \equiv (1-\delta)n_t^b/n_t^s$, often termed *market tightness*, so that meeting probabilities for buyers and sellers can be written

$$q(\theta_t) = \frac{\mathcal{M}((1-\delta)n_t^b, n_t^s)}{(1-\delta)n_t^b} = \mathcal{M}(1, 1/\theta_t) \tag{2}$$

and

$$p(\theta_t) = \frac{\mathcal{M}((1-\delta)n_t^b, n_t^s)}{n_t^s} = \mathcal{M}(\theta_t, 1) = \theta_t q(\theta_t). \tag{3}$$

Values and quasi-free entry. The expected present discounted value associated with buying an asset at time t is denoted V_t^b. Similarly, the values associated with owning and selling an asset at time t are denoted $\{V_t^m(d_j)\}_{j=1}^J$ and $\{V_t^s(d_j)\}_{j=1}^J$. The time t value of non-participation, which is also the value of exit, is denoted V_t^x. It is worthwhile for an agent to enter the market as a buyer at time t if the expected present discounted value associated with searching to buy an asset exceeds the value of non-participation. Entry, however, is limited by the fixed measure $\mathcal{N}$ of potential market participants. In other words, there is free entry up to $\mathcal{N}$ traders: $n_t^b + n_t^m + n_t^s \leq \mathcal{N}$ and $V_t^b \geq V_t^x$ for all t with complementary slackness.[5]

[4] While the measure of potential buyers at the beginning of time t is n_t^b, a fraction δ of them are hit by the preference shock and hence opt out of the secondary market.

[5] With a fixed measure of traders and $V_t^b > V_t^x$, a marginal change in market fundamentals affects values and prices, but not market tightness. Putting a cap on the measure of potential market participants makes it easier to account quantitatively for a dramatic price change like the one observed in the secondary market

Price determination. When a buyer and seller meet, the transaction price is determined by the generalized Nash bargaining solution, where parameter $\phi \in (0,1)$ is the buyer's share of the match surplus and is interpreted as the relative bargaining strength of the buyer. Transaction prices are denoted $\{P_t(d_j)\}_{j=1}^{J}$.

The Innovation. The emergence of Uber is modeled as a one-time imperfectly anticipated innovation that has the potential to affect market fundamentals. First, the dividend process may change when Uber begins operations in Toronto's ride-hailing market, which represents the farebox effect.[6] Second, the ridesharing innovation provides an alternative to the traditional taxicab approach, which can affect the value of the outside option. This is the innovation effect.

We refer to the *post-innovation* market as one in which the innovation has already occurred. The innovation is irreversible; once Uber begins operations in Toronto's ride-hailing market, we assume for simplicity that the ridesharing company remains active indefinitely. In a *pre-innovation* market, the innovation has yet to occur, but market participants anticipate its possibility. Uber enters the market in period t with probability μ_t. We denote using "hat" notation the objects that are specific to the pre-innovation regime. For example, the transition matrix for the stochastic dividend process switches from $\hat{\mathbf{\Pi}}$ to $\mathbf{\Pi}$ with the launch of UberX, and the value of the outside option is $\hat{V}_t^x$ instead of V_t^x in any pre-innovation period t.

Timing. In terms of the ordering of events within a time period, we assume that a time period can be subdivided into the following five stages:

for TLs without also generating an implausible endogeneous response to market liquidity (e.g., a dramatic increase in expected time-to-sell). To characterize a dynamic equilibrium with discrete changes to market fundamentals, however, we nevertheless allow for an endogenous response in the measure of buyers so as not to violate buyers' participation constraint, $V_t^b \geq V_t^x$. If a situation arises in which the free-entry condition binds (i.e., $V_t^b = V_t^x$) in equilibrium, the endogenous response in the measure of buyers represents an additional channel through which Uber can influence the financial value of a TL. Our notion of quasi-free entry allows us to start with fixed market participation while still allowing for the possibility of endogenous entry/exit effects in response to an exogenous innovation.

[6] The ridesharing innovation could in principle increase overall demand for ride-hailing services, in addition to reallocating fares away from licensed taxicabs. The total net effect on the economic rents associated with TL ownership is captured here by a change in the dividend process.

(i) *Innovation.* If the innovation has yet to occur, market participants learn whether the innovation occurs in the current period.

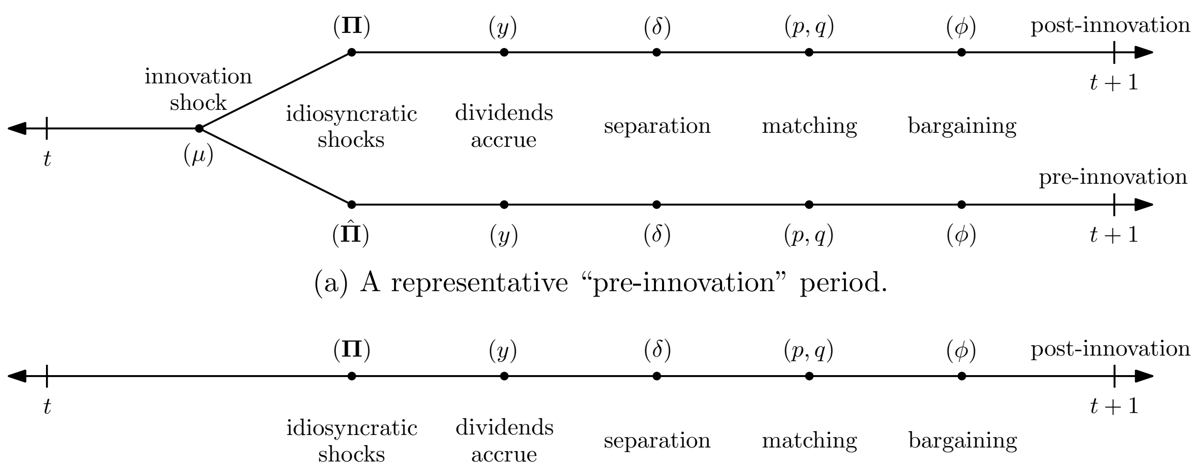
(ii) *Dividends.* Dividends evolve according to the idiosycratic stochastic process, and assets pay dividends to their owners.

(iii) *Separation.* A fraction δ of market participants experience a preference shock. Those without assets exit the market; those with assets enter the subsequent period as sellers.

(iv) *Matching.* Buyers and sellers match with a trading partner with probabilities $q(\theta_t)$ and $p(\theta_t)$.

(v) *Price negotiations and asset transfers.* Matched buyer-seller pairs negotiate the price and transfer ownership of the asset.

The timing of a representative pre-innovation period is illustrated in Figure 1a. Figure 1b illustrates the timing of a representative period in a post-innovation market.



(a) A representative "pre-innovation" period.

(b) A representative "post-innovation" period.

Figure 1: Timing

3.2 Equilibrium

Distribution of traders. In any period t, the total measure of asset holders (i.e., owners and sellers) must equal the total measure of assets in the economy (normalized to 1):

$$n_t^m + n_t^s = 1. \tag{4}$$

The law of motion for the measure of asset owners is given by

$$n_{t+1}^m = (1-\delta)n_t^m + \mathcal{M}((1-\delta)n_t^b, n_t^s), \tag{5}$$

which states that the measure of asset owners at time $t+1$ is equal to the measure of traders that maintain their status as owners from period t to $t+1$, plus the inflow of traders into ownership given by the number of matched buyer-seller pairs at time t. The distribution of assets evolves according to

$$\boldsymbol{a}_{t+1} = \boldsymbol{a}_t\hat{\mathbf{\Pi}} \quad \text{or} \quad \boldsymbol{a}_{t+1} = \boldsymbol{a}_t\mathbf{\Pi}, \tag{6}$$

where $\boldsymbol{a}_t$ is a $1 \times J$ vector of the a_t^js defined previously, representing the distribution of assets as of the beginning of time t. Finally, the measure of buyers is determined by quasi-free entry. If the free-entry condition is slack at time t, the measure of buyers is fixed at

$$n_t^b = \mathcal{N} - n_t^m - n_t^s = \mathcal{N} - 1.$$

Otherwise, θ_t is pinned down by a binding free-entry condition, and the measure of buyers must satisfy the definition of market tightness:

$$n_t^b = \frac{\theta_t n_t^s}{1-\delta}. \tag{7}$$

The quasi-free-entry conditions can therefore be written

$$n_t^b \leq \mathcal{N} - 1 \quad \text{and} \quad V_t^b \geq V_t^x \quad \text{(with complementary slackness)}, \tag{8}$$

with "hat" notation in a pre-innovation period. Traders enter the market as buyers until either the set of potential market participants, $\mathcal{N}$, is exhausted, or congestion in the market drives the expected present discounted value of buying an asset down to the value of non-participation.

Values and prices. Value functions for owners and sellers, V_t^m and V_t^s, and prices, P_t, are functions of the asset's most recent dividend payment. For notational convenience, we organize these values/prices into $J \times 1$ vectors and denote these by $\boldsymbol{V}_t^m$, $\boldsymbol{V}_t^s$ and $\boldsymbol{P}_t$. Values are calculated as of the beginning of the period (i.e., before the current realizations of the idiosyncratic dividend shocks), whereas current prices were bargained at the end of the previous period as per the timing depicted in Figure 1. Furthermore, values and prices depend on whether traders perceive themselves to be in the pre- or post-innovation market.

Post-innovation. The post-innovation values associated with owning an asset at the beginning of time t satisfy

$$\boldsymbol{V}_t^m = \boldsymbol{\Pi}\big\{\boldsymbol{d} + \beta\big[(1-\delta)\boldsymbol{V}_{t+1}^m + \delta\boldsymbol{V}_{t+1}^s\big]\big\}. \tag{9}$$

The value of owning equals the expected current dividend, where $\boldsymbol{d} = [d_1 \ \cdots \ d_J]'$ is the $J \times 1$ vector of possible dividend payments, plus the discounted expected value going into period $t+1$. Expectations reflect both the evolution of dividends as per the post-innovation transition matrix $\boldsymbol{\Pi}$, as well as the possibility of a preference shock, which occurs with probability δ. If an owner is hit by a preference shock in period t, they transition to seller status in period $t+1$. Otherwise, they maintain the trading status of an owner.

The post-innovation values of selling an asset at the beginning of time t satisfy

$$\boldsymbol{V}_t^s = \boldsymbol{\Pi}\big\{(1-\sigma)\boldsymbol{d} + \beta\big[\,(1-p(\theta_t))\,\boldsymbol{V}_{t+1}^s + p(\theta_t)\big(V_{t+1}^x\boldsymbol{1} + \boldsymbol{P}_{t+1}\big)\big]\big\}. \tag{10}$$

The values in equation (10) reflect the low valuation of expected dividends following a preference shock, as well as the discounted expected continuation value. A seller in period t maintains the same trading status going forward unless they match and bargain with a buyer, in which case they receive the negotiated payment and exit the model at the beginning of period $t+1$.

The post-innovation value of trying to buy an asset in period t satisfies

$$V_t^b = \beta\big[\delta V_{t+1}^x + (1-\delta)(1-q(\theta_t))V_{t+1}^b + (1-\delta)q(\theta_t)\boldsymbol{a}_t\boldsymbol{\Pi}\big(\boldsymbol{V}_{t+1}^m - \boldsymbol{P}_{t+1}\big)\big]. \tag{11}$$

The last term takes into account the composition of sellers at the matching stage of post-innovation period t, given by $\boldsymbol{a}_t\boldsymbol{\Pi} = \boldsymbol{a}_{t+1}$. Transition to asset ownership occurs only if the buyer matches with a seller after avoiding the preference shock. Otherwise, they maintain the trading status of a buyer or, if hit by the preference shock, exit the market at the beginning of period $t+1$.

Finally, post-innovation prices are determined by generalized Nash bargaining:[7]

$$\boldsymbol{P}_{t+1} = \boldsymbol{V}_{t+1}^m - V_{t+1}^b\mathbf{1} - \phi\big[\boldsymbol{V}_{t+1}^m - V_{t+1}^b\mathbf{1} + V_{t+1}^x\mathbf{1} - \boldsymbol{V}_{t+1}^s\big]. \tag{12}$$

If the value of the outside option converges to a constant ($V_t^x \to V^x$), the market converges to a stationary equilibrium in which values and prices are constant (e.g., $\boldsymbol{P}_t = \boldsymbol{P}_{t+1} = \boldsymbol{P}$), the distribution of traders does not change over time, and the distribution of assets is the stationary distribution associated with the Markov transition matrix $\boldsymbol{\Pi}$. The stationary distribution of assets satisfies $\boldsymbol{a} = \boldsymbol{a}\boldsymbol{\Pi}$ which, given the construction of $\boldsymbol{\Pi}$ in equation (1),

[7] For an asset that paid a time t dividend of d_j, the generalized Nash bargaining problem is

$$P_{t+1}(d_j) = \arg\max_P \big(V_{t+1}^m(d_j) - V_{t+1}^b - P\big)^{\phi}\big(V_{t+1}^x - V_{t+1}^s(d_j) + P\big)^{1-\phi}.$$

Taking the first-order condition and rearranging yields

$$P_{t+1}(d_j) = V_{t+1}^m(d_j) - V_{t+1}^b - \phi\big[V_{t+1}^m(d_j) - V_{t+1}^b + V_{t+1}^x - V_{t+1}^s(d_j)\big].$$

implies

$$\boldsymbol{a} = \left[\begin{array}{cccc} \pi_1 & \pi_2 & \cdots & \pi_J \end{array}\right].$$

A formal definition of the *post-innovation stationary equilibrium* is provided in Appendix B.

Pre-innovation. The pre-innovation values take into account the possibility that the innovation occurs in the current period. With probability μ_t, the innovation happens at the start of the current period and traders capture the post-innovation value of owning/selling/buying. Otherwise, with probability $1 - \mu_t$, current payoffs, transition probabilities and continuation values continue to reflect the pre-innovation regime. Recall that all pre-innovation values and prices are denoted with "hat" notation to distinguish them from their post-innovation analogues. The pre-innovation values satisfy the following Bellman equations:

$$\hat{\boldsymbol{V}}_t^m = \mu_t \boldsymbol{V}_t^m + (1-\mu_t)\hat{\boldsymbol{\Pi}}\left\{\boldsymbol{d} + \beta\left[(1-\delta)\hat{\boldsymbol{V}}_{t+1}^m + \delta\hat{\boldsymbol{V}}_{t+1}^s\right]\right\} \tag{13}$$

$$\begin{aligned} \hat{\boldsymbol{V}}_t^s = \mu_t \boldsymbol{V}_t^s + (1-\mu_t)\hat{\boldsymbol{\Pi}}\Big\{&(1-\sigma)\boldsymbol{d} \\ &+ \beta\left[(1-p(\theta_t))\,\hat{\boldsymbol{V}}_{t+1}^s + p(\theta_t)\left(\hat{V}_{t+1}^x\mathbf{1} + \hat{\boldsymbol{P}}_{t+1}\right)\right]\Big\} \end{aligned} \tag{14}$$

$$\begin{aligned} \hat{V}_t^b = \mu_t V_t^b + (1-\mu_t)\beta\Big\{&\delta\hat{V}_{t+1}^x \\ &+ (1-\delta)\left(1-q(\theta_t)\right)\hat{V}_{t+1}^b + (1-\delta)q(\theta_t)\boldsymbol{a}_t\hat{\boldsymbol{\Pi}}\left(\hat{\boldsymbol{V}}_{t+1}^m - \hat{\boldsymbol{P}}_{t+1}\right)\Big\}. \end{aligned} \tag{15}$$

Pre-innovation prices are given by the generalized Nash bargaining solution:

$$\hat{\boldsymbol{P}}_{t+1} = \hat{\boldsymbol{V}}_{t+1}^m - \hat{V}_{t+1}^b\mathbf{1} - \phi\left[\hat{\boldsymbol{V}}_{t+1}^m - \hat{V}_{t+1}^b\mathbf{1} + \hat{V}_{t+1}^x\mathbf{1} - \hat{\boldsymbol{V}}_{t+1}^s\right]. \tag{16}$$

These pre- and post-innovation dynamic systems of equations determine the equilibrium transitional dynamics as the market anticipates and responds to the innovation. Recall that market fundamentals differ between the pre- and post-innovation markets in two ways: (i) the Markov transition matrix governing the evolution of dividends switches from $\hat{\boldsymbol{\Pi}}$ to $\boldsymbol{\Pi}$, and (ii) the value of the exit changes from $\{\hat{V}_t^x\}$ to $\{V_t^x\}$.

In the ride-hailing context, we use the framework to analyze the impact of Uber on the secondary market for taxicab licenses. We use the pre- and post-innovation equilibria to illustrate the effects of the changes in market fundamentals brought on by the mobile app-based ridesharing innovation. Before turning to our quantitative analysis, we first present comparative statics to formalize the economic interpretation of the farebox and innovation effects.

4 Comparative Statics

For the purposes of transparent comparative static analysis, in this section we simplify the model by collapsing dividend heterogeneity by setting $J = 1$ and denoting the constant dividend by d. In this case, the post-innovation stationary equilibrium values satisfy the following versions of (9), (10), and (11):

$$(1-\beta)V^m = d - \beta\delta\left[V^m - V^s\right] \tag{17}$$

$$(1-\beta)V^s = (1-\sigma)d + \beta p(\theta)\left[V^x + P - V^s\right] \tag{18}$$

$$(1-\beta)V^b = \beta\delta\left[V^x - V^b\right] + \beta(1-\delta)q(\theta)\left[V^m - P - V^b\right]. \tag{19}$$

Similarly, the post-innovation stationary equilibrium asset price satisfies a version of (12):

$$P = \left[V^m - V^b\right] - \phi\left[V^m - V^b + V^x - V^s\right]. \tag{20}$$

We are interested in the implications of the farebox and innovation effects. To that end, we solve for the stationary equilibrium price, P, as well as the value of asset ownership, V^m, and derive comparative statics with respect to d and V^x. These results capture the long-term price effects and welfare consequences for asset owners of a change in dividends (i.e., the farebox effect) or the value of the outside option (i.e., the innovation effect). The economic intuition derived from these analytical results will prove helpful for understanding the equilibrium transition path to the post-innovation stationary equilibrium in Section 6.3.

Solving the above system of equations yields the following asset pricing equation:

$$\begin{aligned} P = \frac{d}{1-\beta}\left\{1 - \frac{(1-\beta)\phi + \beta\delta + \beta(1-\delta)q(\theta)\phi}{1-\beta\left(1-\delta-p(\theta)(1-\phi)-(1-\delta)q(\theta)\phi\right)}\sigma\right\} \\ - \frac{(1-\beta)\phi + \beta\delta + \beta(1-\delta)q(\theta)\phi}{1-\beta\left(1-\delta-p(\theta)(1-\phi)-(1-\delta)q(\theta)\phi\right)}V^x. \end{aligned} \tag{21}$$

The first part of (21) is the present discounted value of the stream of dividends, adjusted by an *illiquidity discount* that reflects preference shocks, search frictions and bargaining. The last term reflects the present discounted value of exit following participation in the secondary market.

The present discounted expected value of asset ownership in a stationary equilibrium is

$$\begin{aligned} V^m = \frac{d}{1-\beta}\left\{1 - \left(\frac{\beta\delta}{1-\beta(1-\delta)}\right)\frac{1-\beta(1-\delta)(1-q(\theta)\phi)}{1-\beta\left(1-\delta-p(\theta)(1-\phi)-(1-\delta)q(\theta)\phi\right)}\sigma\right\} \\ - \left(\frac{\beta\delta}{1-\beta(1-\delta)}\right)\frac{\beta p(\theta)(1-\phi)}{1-\beta\left(1-\delta-p(\theta)(1-\phi)-(1-\delta)q(\theta)\phi\right)}V^x. \end{aligned} \tag{22}$$

The interpretation of the three components of V^m is very similar to that of the price equation. The value of asset ownership reflects the present discounted value of dividends, subject to what happens following a preference shock: namely, reduced dividend valuation, time-to-sell, price negotiations and, finally, exit.

The comparative statics depend on whether the free-entry condition, $V^b \geq V^x$, holds with equality. Proposition 1 summarizes the results when the value of the outside option is sufficiently low (given $\mathcal{N}$) that the free-entry condition is slack.

Proposition 1. *If $V^b > V^x$, then (i) $dP/dd > 0$, (ii) $dP/dV^x < 0$, (iii) $dV^m/dd > 0$ and (iv) $dV^m/dV^x > 0$.*

When the free-entry condition is slack (i.e., $V^b > V^x$), it is straightforward to derive these comparative statics results from (22) and (21). Differentiating with respect to d yields

$$\begin{aligned}\frac{dV^m}{dd} &= \frac{1}{1-\beta}\left\{1-\left(\frac{\beta\delta}{1-\beta(1-\delta)}\right)\frac{1-\beta(1-\delta)(1-q(\theta)\phi)}{1-\beta\left[1-\delta-p(\theta)(1-\phi)-(1-\delta)q(\theta)\phi\right]}\sigma\right\} \\ &= \frac{\left[1-\beta(1-\delta)\right]\left[1-\beta(1-p(\theta)(1-\phi))\right]+\beta\delta(1-\sigma)\left[1-\beta(1-\delta)(1-q(\theta)\phi)\right]}{(1-\beta)\left[1-\beta(1-\delta)\right]\left[1-\beta\left(1-\delta-p(\theta)(1-\phi)-(1-\delta)q(\theta)\phi\right)\right]} > 0.\end{aligned} \tag{23}$$

When there is an increase in the dividend, the corresponding increase in the value of asset ownership reflects the change in the present value of the stream of dividends, taking into account expectations about preferences and liquidity. For the same reason, an increase in the dividend raises the price:

$$\begin{aligned}\frac{dP}{dd} &= \frac{1}{1-\beta}\left\{1-\frac{(1-\beta)\phi+\beta\delta+\beta(1-\delta)q(\theta)\phi}{1-\beta\left[1-\delta-p(\theta)(1-\phi)-(1-\delta)q(\theta)\phi\right]}\sigma\right\} \\ &= \frac{(1-\beta)(1-\sigma\phi)+\beta p(\theta)(1-\phi)+(1-\sigma)\left[\beta\delta+\beta(1-\delta)q(\theta)\phi\right]}{(1-\beta)\left[1-\beta\left(1-\delta-p(\theta)(1-\phi)-(1-\delta)q(\theta)\phi\right)\right]} > 0.\end{aligned} \tag{24}$$

In the hide-hailing market, farebox revenues could decline if the introduction of Uber adversely affects taxicab ridership. This would lower the value associated with holding a TL (part (iii) of Proposition 1), which in turn would lower the price (part (i) of Proposition 1). This is what we call the *farebox effect*. From the expressions in (23) and (24), we can write

$$\frac{dV^m}{dd}-\frac{dP}{dd} = \frac{\phi\left[1-\beta(1-\delta)(1-q(\theta)\phi)\right]}{1-\beta\left[1-\delta-p(\theta)(1-\phi)-(1-\delta)q(\theta)\phi\right]} > 0, \tag{25}$$

which means a change in farebox revenue affects prices less than it affects the present discounted expected financial value of TL ownership.

Differentiating (21) and (22) with respect to V^x yields parts (ii) and (iv) of Proposition 1:

$$\frac{dV^m}{dV^x} = \frac{\beta\delta}{1-\beta(1-\delta)}\frac{\beta p(\theta)(1-\phi)}{1-\beta\left[1-\delta-p(\theta)(1-\phi)-(1-\delta)q(\theta)\phi\right]} > 0, \tag{26}$$

and

$$\frac{dP}{dV^x} = -\frac{(1-\beta)\phi+\beta\delta+\beta(1-\delta)q(\theta)\phi}{1-\beta\left[1-\delta-p(\theta)(1-\phi)-(1-\delta)q(\theta)\phi\right]} < 0. \tag{27}$$

Asset owners expect to eventually sell their asset and exit the market. An increase in the value of exit therefore improves the financial well-being of an asset holder, although some of the expected benefit gets eroded by an endogenous reduction in the negotiated price.

There are two reasons for the decline in price. First, the seller's net surplus from exiting the market, $V^x - V^s$, is increasing in V^x. An increase in the value of the outside option makes sellers more motivated to sell, and consequently they accept less during price negotiations. Second, the surplus associated with the transition from buyer to owner, $V^m - V^b$, is decreasing in V^x because the trader anticipates eventually being hit with a preference shock. When experiencing the shock as a buyer, they leave the market immediately for the outside opportunity. When an owner is hit with the preference shock, they wait to sell in a frictional market before capturing the value of exit. Trading frictions therefore delay the value of exit for owners but not buyers, which reduces how much the trader is willing to pay to acquire the asset. In response to an increase in V^x, the two negative price effects maintain the Nash surplus splitting rule:

$$(1-\phi)\big[\underbrace{V^m - V^b}_{\downarrow \text{ as } V^x \uparrow} - P\big] = \phi\big[\underbrace{V^x - V^s}_{\uparrow \text{ as } V^x \uparrow} + P\big]. \tag{28}$$

In the context of TLs, the opportunity to drive for Uber improves the value of exiting the traditional taxicab market. This could improve the present values among market participants, but reduce negotiated prices. This is the *innovation effect*.

As summarized below in Proposition 2, three out of four of these comparative statics results are unaffected qualitatively when the value of exit is sufficiently high (given $\mathcal{N}$) that the free-entry condition binds. The effect of V^x on V^m (part (iv) of Proposition 2) is the only exception.

Proposition 2. *If $V^b = V^x$, then (i) $dP/dd > 0$, (ii) $dP/dV^x < 0$, (iii) $dV^m/dd > 0$ and (iv) $dV^m/dV^x < 0$.*

If the free-entry condition binds, market tightness is pinned down by equating the value of the outside option, V^x, with the value of participating in the secondary market, V^b. The free-entry condition can thus be written:

$$V^x = \frac{\beta(1-\delta)q(\theta)\phi}{1-\beta\left[1-\delta-p(\theta)(1-\phi)\right]}\frac{\sigma d}{1-\beta}. \tag{29}$$

The value of asset ownership under a binding free-entry condition further simplifies to

$$V^m = \frac{d}{1-\beta}\left\{1-\left(\frac{\beta\delta}{1-\beta(1-\delta)}\right)\frac{1-\beta(1-\delta)(1-q(\theta)\phi)}{1-\beta\left[1-\delta-p(\theta)(1-\phi)\right]}\sigma\right\}-\left(\frac{\beta\delta}{1-\beta(1-\delta)}\right)V^x, \tag{30}$$

and the price equation under free entry can be written

$$P = \frac{d}{1-\beta}\left\{1-\frac{\beta\delta+(1-\beta)\phi}{1-\beta\left[1-\delta-p(\theta)(1-\phi)\right]}\sigma\right\}-V^x. \tag{31}$$

The last term in (31) now reflects both the buyer's and seller's negotiated share of the value of the outside opportunity.

When the free-entry condition binds (i.e., $V^b = V^x$), the comparative statics results can be derived from (31) and (30), given the free-entry implications of (29). First, differentiating (31) with respect to d yields

$$\begin{aligned}\frac{dP}{dd} = \frac{\partial P}{\partial d}+\frac{\partial P}{\partial \theta}\frac{d\theta}{dd} = {} & \frac{1}{1-\beta}\left\{1-\frac{\sigma\left[\beta\delta+(1-\delta)\phi\right]}{1-\beta(1-\delta-p(\theta)(1-\phi))}\right\} \\ & +\frac{\sigma d}{1-\beta}\frac{\beta p'(\theta)(1-\phi)\left[\beta\delta+(1-\delta)\phi\right]}{\left[1-\beta(1-\delta-p(\theta)(1-\phi))\right]^2}\frac{d\theta}{dd}.\end{aligned} \tag{32}$$

The first part reflects the direct effect of d on the present value of the stream of dividends, taking into account the illiquidity discount. The direct effect is offset by an endogenous response in market tightness. This indirect effect depends on $d\theta/dd$, which can be obtained by implicitly differentiating the free-entry condition. Doing so yields

$$\frac{d\theta}{dd} = \frac{\sigma\beta(1-\delta)q(\theta)\phi}{\beta(1-\beta)(1-\phi)p'(\theta)V^x-\sigma\beta(1-\delta)q'(\theta)\phi d} \tag{33}$$

Combining (32) and (33) and simplifying yields

$$\frac{dP}{dd} = \frac{1}{1-\beta}\left\{\frac{\beta(1-\phi)p(\theta) + [(1-\beta)(1-\sigma\phi) + \beta\delta(1-\sigma)]\,(1-\eta_p(\theta))}{\beta(1-\phi)p(\theta) + [1-\beta(1-\delta)](1-\eta_p(\theta))}\right\} > 0, \tag{34}$$

where $\eta_p(\theta) \in [0,1]$ is the elasticity of the seller's matching probability with respect to market tightness:

$$\eta_p(\theta) \equiv \frac{\theta p'(\theta)}{p(\theta)} = 1 + \frac{\theta q'(\theta)}{q(\theta)}. \tag{35}$$

As is the case when the free-entry condition is slack, lower dividends translate into lower prices. When the free-entry condition binds, lower dividends also imply fewer market participants (i.e., lower market tightness) which renders more severe the illiquidity discount. Thus, the *farebox effect* is qualitatively unaffected by the free entry of market participants, although the economic interpretation of the effect is more complicated when the free-entry condition binds.

A similar approach using (30) and (29) yields dV^m/dd under a binding free-entry condition:

$$\frac{dV^m}{dd} = \frac{1}{1-\beta}\left\{\frac{\beta(1-\phi)p(\theta) + (1-\beta)(1-\eta_p(\theta)) + (1-\sigma)\beta\delta(1-\eta_p(\theta))}{\beta(1-\phi)p(\theta) + [1-\beta(1-\delta)](1-\eta_p(\theta))}\right\} > \frac{dP}{dd} > 0. \tag{36}$$

Once again, higher dividends enhance the value of asset ownership. The fact that lower dividends (fewer fares) depress the value of asset (TL) ownership is the welfare consequence of the *farebox effect* for TL owners. The first inequality in (36) reveals that this effect is even more severe than the farebox effect on the equilibrium price.

To determine dP/dV^x under a binding free-entry condition, we start by differentiating (31) with respect to V^x:

$$\frac{dP}{dV^x} = \frac{\partial P}{\partial V^x} + \frac{\partial P}{\partial \theta}\frac{d\theta}{dV^x} = -1 - \frac{\sigma d}{1-\beta}\frac{\beta p'(\theta)(1-\phi)\,[\beta\delta + (1-\delta)\phi]}{[1-\beta(1-\delta-p(\theta)(1-\phi))]^2}\frac{d\theta}{dV^x}. \tag{37}$$

The first term reflects the direct effect of V^x on the generalized Nash bargaining solution.[8]

[8]Note that (20) simplifies to $P = V^m - V^x - \phi[V^m - V^s]$ under free entry when $V^b = V^x$.

The direct effect is different from the corresponding effect in (27) when the free-entry condition is slack because here it affects both the seller's value of exit and the continuation value of a buyer. The price is then further reduced by an endogenous response in market tightness, obtained by implicitly differentiating the free-entry condition:

$$\frac{d\theta}{dV^x} = \frac{(1-\beta)\left[1-\beta\left(1-\delta-p(\theta)(1-\phi)\right)\right]}{\beta(1-\delta)\phi q'(\theta)\sigma d - \beta(1-\beta)(1-\phi)p'(\theta)V^x} < 0. \tag{38}$$

When the free-entry condition binds, a more appealing outside option draws away potential market participants. In the context of the secondary market for TLs, the ridesharing alternative attracts drivers that would have otherwise searched to buy a TL. Combining (38) with (39) and simplifying yields

$$\frac{dP}{dV^x} = -1 - \frac{\beta\delta + (1-\beta)\phi}{(1-\delta)\phi}\left(\frac{(1-\phi)\theta\eta_p(\theta)}{\beta(1-\phi)p(\theta) + \left[1-\beta\left(1-\delta\right)\right]\left(1-\eta_p(\theta)\right)}\right) < 0. \tag{39}$$

The first term is the direct effect of V^x on the negotiated price. The second term is an indirect effect resulting from reduced entry in the secondary market. The endogenous change in market tightness under free entry thus further depresses prices in response to a more appealing outside option. Turning to the value of ownership, V^m, similar derivations yield

$$\begin{aligned}\frac{dV^m}{dV^x} &= -\frac{\beta\delta}{(1-\delta)\phi}\left(\frac{(1-\phi)\theta\eta_p(\theta)}{\beta(1-\phi)p(\theta) + [1-\beta(1-\delta)](1-\eta_p(\theta))}\right)\\ &= \frac{\beta\delta}{\beta\delta + (1-\beta)\phi}\left[1 + \frac{dP}{dV^x}\right] < 0. \end{aligned}\tag{40}$$

An increase in the value of exit is beneficial to an asset holder because they anticipate exiting the market in the future, but this expected benefit is more than offset by the negative price effect.

The results in (39) and (40) thus summarize the implications of the *innovation effect* under a binding free-entry condition. Under free entry, the negotiated price is highly sensitive to the value of the outside opportunity. For this reason, the innovation effect reduces the financial value of TL ownership despite improving the value of exit. This differs from the comparative static result when the free-entry condition is slack (i.e., part (iv) of Proposition 1) in which the negative price effect only partly offsets the positive impact of an improvement in the value of exit.

To summarize, we have therefore characterized the farebox and innovation effects on equilibrium prices, which hold regardless of whether the measure of market participants is fixed or pinned down by free entry. More specifically, prices are lower when dividends are small and the value of the outside option is high. The farebox effect is even stronger when we consider the value of a TL to its owner rather than its market price. The innovation effect on the value of TL ownership, in contrast, involves offsetting forces and the net effect could be either positive or negative depending on whether the free-entry condition binds.

Our model features these two channels through which Uber can affect TL owners and the market value of their TLs. These two channels guide the counterfactual analysis in Section 7. We next describe the data that we use for the calibration exercise presented in Section 6.

5 Data

As mentioned in Section 2, TL transfers and lease agreements (until 2016) are recorded by the City of Toronto's Municipal Licensing and Standards division. This information about ownership transfers and lease agreements is our main source of transaction-level data.

Transaction prices. There were 1,164 TL transfers between April, 2011, and March, 2018. These potentially include transfers to family members for prices less than market value.[9] In order to focus on transactions between buyers and sellers in the secondary market, transfers for amounts less than or equal to $2 are hereinafter excluded from the sample of market transactions.[10]

[9]The City of Toronto's 2012 review of the taxicab industry states that "standard taxicabs cannot be inherited; however, they are often sold to family members for a token amount of 1 dollar."

[10]In the full sample of 1,164 transactions, there are 14 transfers with a price of $1 and 81 transfers with a price of $2.

We define a *before-Uber period* from April 2011 to March 2012, and an *after-Uber period* from April 2017 to March 2018. Figure 2 plots the empirical cumulative distribution functions of the logarithm of before- and after-Uber transaction prices of TLs. Our before- and after-Uber periods contain 71 and 295 transactions. Notice that the after-Uber price distribution appears to the left of the before-Uber price distribution, reflecting the decline in the market price of a TL. The amount of price depreciation is striking: the average price during the before-Uber period is $248,923, whereas the average price in the after-Uber period is only $76,797.

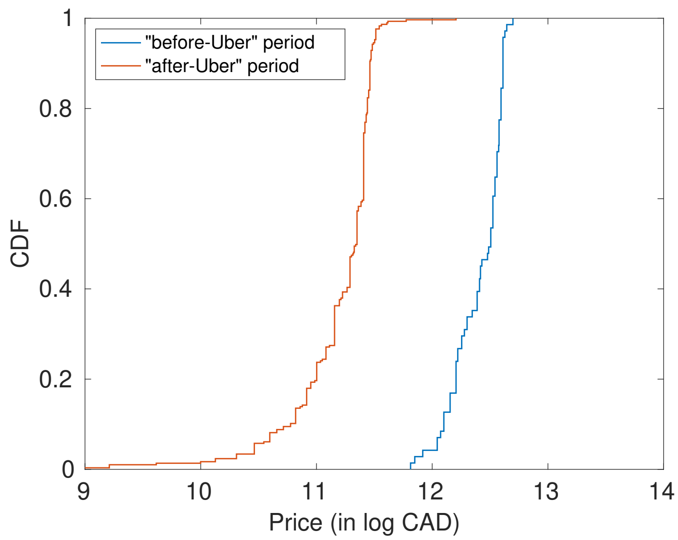


Figure 2: Transaction price distributions.

Monthly lease payments. Recall that a TL provides the right to operate a taxicab vehicle in Toronto. While many license holders operate the taxicab themselves, a TL can also be rented to shift drivers or leased longer term. The monthly payment specified in the lease agreement between the licence owner and the taxicab operator, along with lease start and end dates, were recorded by the city until June, 2016. Unfortunately, the city stopped collecting leasing information in July 2016. In order to extend the analysis beyond June 2016, we collected monthly amounts advertised by non-driver TL owners on `Kijiji.ca`, an online platform for classified advertisements owned by eBay. Online classified advertisement data were collected from January 2016 to March 2018. For the period of overlap (i.e., January to June 2016), the distribution of reported lease payments coincides with the distribution of advertised lease payments less $100 (see Figure 3). The $100 price adjustment could reflect, for example, negotiated discounts relative to the monthly amounts conveyed in the classified ads. We therefore use the advertised lease payments less $100 to extend the sample of monthly lease payments beyond June 2016. We have a total of 1,512 lease payment observations from April 2011 to March 2018.[11]

We view the monthly lease payment as a proxy for the dividend (i.e., the economic rent attributable to TL ownership). In other words, we compare the monthly lease payments before- and after-Uber to get a sense of the farebox effect. The average monthly lease payments for the before- and after-Uber periods are $1,392 and $871, respectively, and the empirical distributions are plotted in Figure 4. This overall decline in the monthly payment for a TL is consistent with the hypothesized farebox effect of Uber.

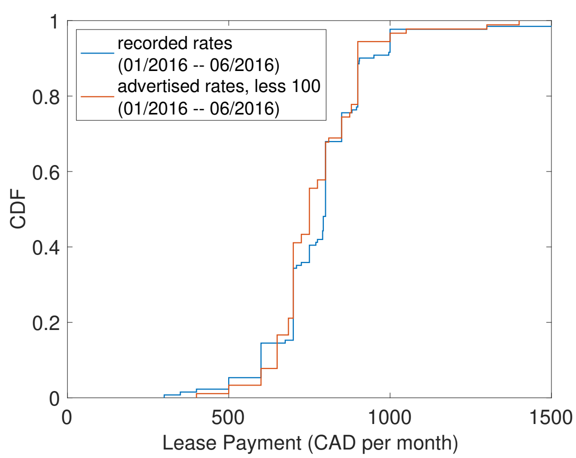


Figure 3: Distributions of advertised and reported lease payments.

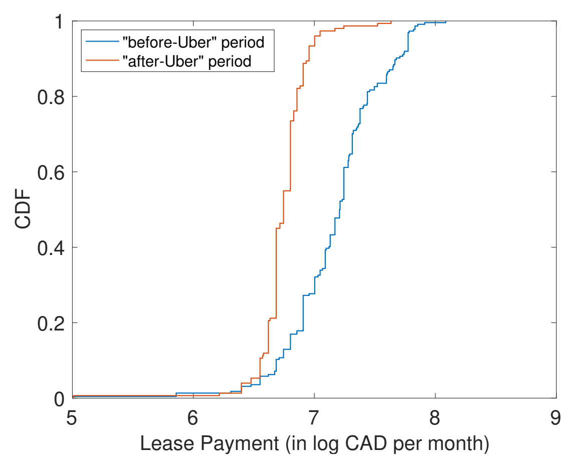


Figure 4: Lease payment distributions.

Uber's market presence. The introduction of Uber is more than just an increase in the number of rides-for-hire. Uber's innovative mobile technology-based approach to ride-

[11]There were 1,315 lease agreements initiated between April 2011 and June 2016. Monthly payments reported to be less than or equal to $2 are once again excluded from the sample. Among the 1,315 lease agreements, only 11 purportedly feature a monthly payment of less than $2. Another 208 lease payment observations come from the advertised lease payment data.

hailing renders the traditional taxicab market relatively less appealing and partially obsolete, which may further depress the market value of licensed taxicabs. This is the hypothesized innovation effect. While the relative appeal of the traditional taxicab approach cannot be directly observed, we conjecture that it is closely linked to Uber's presence in Toronto's ride-hailing market.

We use search intensity data from Google Trends as a proxy for Uber's share of the Toronto market for private car-for-hire transportation services. Specifically, we use an index for the number of Google searches for "Uber" in Ontario, Canada.[12,13] Figure 5 displays the (natural log of the) Google Trends index from April, 2011, until March, 2018. Reassuringly, the launch of UberX in September 2014 coincides with the steepest increase in search intensity. The dashed line is a sequence, $\{G_t\}$, generated by a generalized logistic function parameterized to fit the Google Trends data:

$$G_t = \alpha_1 + \frac{\alpha_2 - \alpha_1}{1 + \exp\left(-\alpha_3\left(t - \alpha_4\right)\right)}. \tag{41}$$

[12]Unfortunately, Google Trends does not currently provide results at the city level for Canada. However, Google Trends lists municipalities in the Greater Toronto Area for 9 out of the 10 locations within Ontario with the most popularity (defined based on the number of "Uber" searches relative to total searches).

[13]The number of Google searches for "Uber" as a proxy for Uber penetration in the local market is an idea borrowed from Hall et al. (2018).

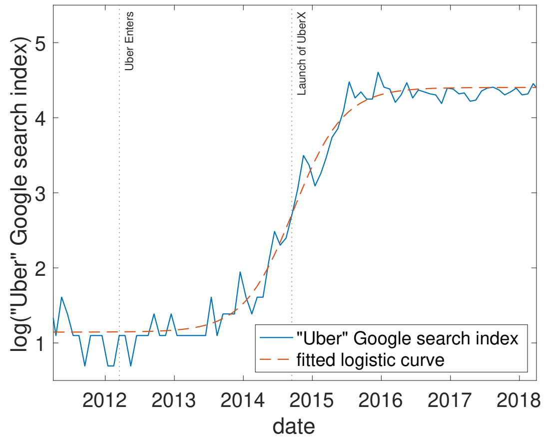


Figure 5: Google Trends search intensity index for "Uber."

We use features of the transaction and lease data from the before- and after-Uber periods to discipline the choice of parameters in our calibration of the model. We use the Google Trends search intensity index for "Uber" to guide the transition of the market during the pre- and post-innovation regimes. The next section details the calibration and simulation exercise.

6 Calibration

The model is calibrated to match several features of the secondary market for TLs in Toronto (including prices, quantities, and time-to-sell), as well as the plate leasing market (including monthly lease payments and lease agreement duration). The aim is to simulate prices that mimic, to the extent possible, the price trends observed in the secondary market for TLs as Uber launched and gained momentum in Toronto's ride-hailing market. We use this calibrated version of the model to assess the relative importance of the farebox and innovation effects of Uber on the market value of licensed taxicabs. We then use it to study the implications of the ridesharing innovation for the financial well-being of TL owners.

6.1 Methodology

We calibrate the post-innovation stationary equilibrium of the model to correspond to the after-Uber period defined in Section 5. By the after-Uber period, both the new ridesharing technology and traditional taxicab services coexist in a new regime of the ride-hailing market. Moreover, the Google Trends search intensity index for "Uber" remains relatively flat at the top end of the scale (Figure 5). These reasons justify our interpretation of the after-Uber period as a close approximation of the post-Uber stationary equilibrium.

We use pre-innovation and post-innovation equilibrium equations to solve for the transition path that converges to the post-innovation stationary equilibrium. In order to characterize the transition, we need an initial distribution of traders and assets. To that end, we consider the stationary equilibrium of a *no-innovation* market in which the innovation is never expected to occur (i.e., $\mu_t = 0$ for all t). The dynamic system of equations in the no-innovation regime is similar to that in a post-innovation market because, in both cases, traders do not anticipate any current or future innovations. However, the no-innovation Bellman equations and price equation are different from their post-innovation counterparts because they reflect pre-innovation market fundamentals: namely, $\hat{\mathbf{\Pi}}$ and $\{\hat{V}_t^x\}$. If the value of the outside option in a no-innovation environment is constant at $\hat{V}^x$, the market admits a *no-innovation stationary equilibrium*[14] in which the distribution of assets is the stationary distribution associated with the pre-innovation Markov transition matrix $\hat{\mathbf{\Pi}}$, given by the distribution of dividends with probability mass function $\hat{\pi}(d_j) = \hat{\pi}_j$, $j = 1, \ldots, J$.

We calibrate the no-innovation stationary equilibrium of the model to match features of the data in the before-Uber period. We provide a similar justification as above: the before-Uber period is a suitable approximation of a no-innovation market if traders in the secondary market for Toronto TLs did not fully or correctly anticipate the arrival of ridesharing and its impact on the traditional taxicab market. Suggestive evidence that Uber's launch was unanticipated during the before-Uber period is the relatively flat and near-zero Google Trends search intensity index for "Uber" (see Figure 5).

[14] See Appendix B for a formal definition of a stationary equilibrium.

With the initial distribution of traders and assets derived from the no-innovation stationary equilibrium, we simulate the transition path between the two stationary equilibria based on the timing of the launch of Uber and UberX in Toronto and our measure of Uber's presence in the Toronto ride-hailing market from Figure 5. In the following two subsections, we discuss the calibration of the stationary equilibria and the numerical simulation of the equilibrium transition path in more detail.

6.2 Calibration of Stationary Equilibria

The model is calibrated to quarterly frequency.[15] We use the following functional form for the meeting process between buyers and sellers:

$$\mathcal{M}(b, s) = \frac{bs}{b+s}. \tag{42}$$

This matching function satisfies the properties described in Section 3.1.

Table 1 contains calibrated parameter values along with closely related market statistics. The quarterly discount factor is set to 0.9873, which corresponds to an annual discount rate of 5 percent. We impose the axiom of symmetry in the bilateral Nash bargaining problem by setting $\phi = 1/2$, so that the buyer and seller each receive half of the total surplus from transferring ownership of the TL.

We choose a 50-point distribution for lease payments. The 50 possible draws are equally spaced between the highest and lowest recorded amounts, and the corresponding pre- and post-innovation probabilities, $\hat{\boldsymbol{\pi}}$ and $\boldsymbol{\pi}$, are selected to minimize the squared differences between the simulated distributions and the empirical CDFs generated from the observed before- and after-Uber lease payments. The resulting CDFs are plotted in Figures 6a and 6b. We set the initial value of exit to zero, $\hat{V}^x = 0$, and calibrate the terminal value, $V^x = 129{,}631$, so that the post-innovation stationary equilibrium features an average price that matches the price statistic from the after-Uber sample period.

[15] We aggregate to quarterly frequency because there are some months with no transactions.

The severity of the preference shock, σ, is set to 0.5543 so that the average price in the no-innovation stationary equilibrium matches the average price in the before-Uber period. Whereas the dividend probabilities and value of the outside option change with the entry of Uber, σ is assumed unaffected by the innovation. The same is true for the remaining parameters, which are calibrated using data that span the before- and after-Uber periods. We set $\delta = 0.0077$ so that the average number of market transactions per quarter, relative to the number of outstanding TLs, is $0.0076 = 38.1487/5000$.

Recall that our lease agreement data also contain durations (i.e. start and end dates). We use these to construct a distribution of lease durations in Figure 7. We calibrate the probability of a renewal shock, $\rho = 0.0832$, to target an average time between renewals equal to the mean lease duration: namely, three years. Probability ρ along with the probabilities contained in $\hat{\boldsymbol{\pi}}$ and $\boldsymbol{\pi}$ are used to construct the transition matrices $\hat{\mathbf{\Pi}}$ and $\mathbf{\Pi}$ as per equation (1).

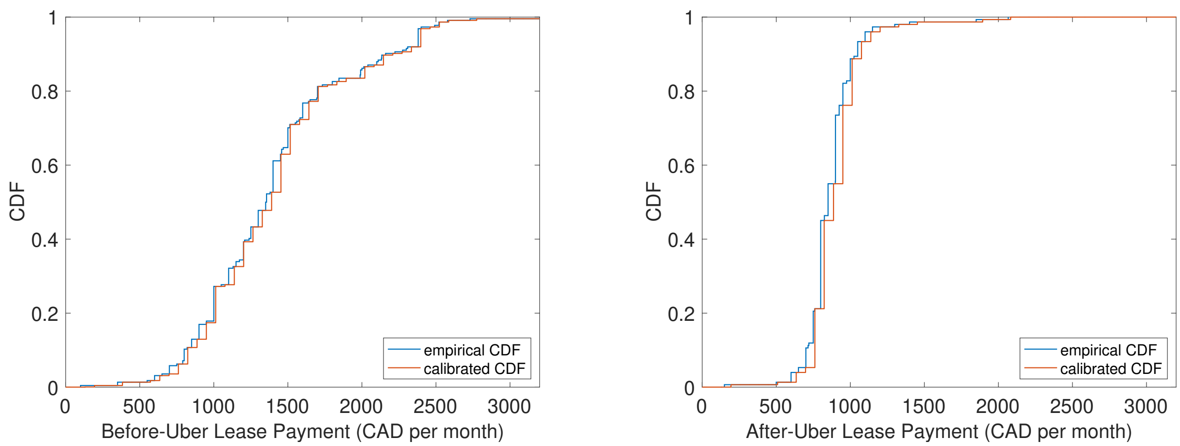
The final parameter to be calibrated is $\mathcal{N}$: the measure of potential market participants. When the free-entry condition is slack, $\mathcal{N}$ determines the tightness of the market and hence the average time it takes to buy or sell a TL.[16] To calibrate $\mathcal{N}$, it would therefore be helpful to have a sense of the severity of search frictions, as captured by time-on-the-market, for example. In Appendix C, we augment our analysis using information contained in the database of Business Licence Renewals and New Issues maintained by the City of Toronto's Municipal Licensing and Standards division. Our approach is based on the observation that estate ownership duration is typically longer when the TL is ultimately sold in the decentralized market compared to the case where the license is transferred to a family member. This analysis yields suggestive evidence that expected time-on-the-market for sellers (*i.e.*, average time spent searching for a buyer) is nearly half a year. Consistent with anecdotal evidence, search frictions are rather severe, which is not too surprising given that the secondary market for TLs is a thin, decentralized market. Accordingly, the total measure of traders relative to the measure of assets, $\mathcal{N}$, is set to 1.0169 so that average time-to-sell is five and a half

[16] Since market participation is initially costless, $\hat{V}^x = 0$, the free-entry condition will not bind in the no-innovation stationary equilibrium.

months.

Table 1: Calibrated Parameters

statistic	target	parameter	value
annual interest rate	5%	β	0.9873
TL price (before-Uber)	\$248,923	σ	0.5543
# of transactions (before- & after-Uber)	38 per quarter	δ	0.0077
TL price (after-Uber)	\$76,797	V^x	129,631
equal splitting of match surplus	1/2	ϕ	0.5000
time-to-sell	11/6 quarters	$\mathcal{N}$	1.0169
lease payments (before-Uber)	Figure 4	$\hat{\boldsymbol{\pi}}$	Figure 6a
lease payments (after-Uber)	Figure 4	$\boldsymbol{\pi}$	Figure 6b
lease duration (2011–2016)	12 quarters	ρ	0.0832



(a) Before-Uber lease payments.

(b) After-Uber lease payments.

Figure 6: Calibrated lease payment distributions.

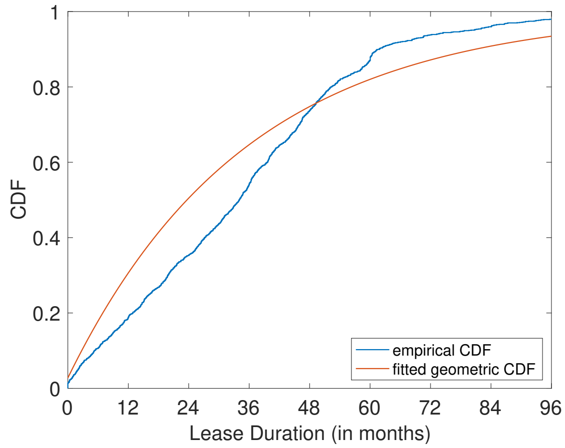


Figure 7: Distribution of lease agreement durations.

6.3 Simulation of Transition Path

We simulate the transition path between the no-innovation and post-innovation stationary equilibria. Along the transition path, the market switches from the no-innovation to the pre-innovation and, finally, to the post-innovation regime to mirror the launch of Uber in the Toronto ride-hailing market. Specifically:

(i) Suppose the secondary market for TLs is well-approximated by the no-innovation stationary equilibrium until Uber first entered the Toronto ride-hailing market in March 2012.

(ii) From March 2012, until the launch of UberX in September 2014, the market for TLs evolves along a pre-innovation transition path.

(iii) Following introduction of freelance UberX ridesharing services in September 2014, the market converges along a transition path to the post-innovation stationary equilibrium.

To compute the transition path, the simulation is based on the following additional assumptions:

(iv) The sequence of probabilities associated with Uber's Toronto market début, $\{\mu_t\}$, evolves from zero to $\mu > 0$, in tandem with Uber's presence in the Toronto ride-hailing market, as proxied by the smoothed Google Trends internet search intensity index, $\{G_t\}$, plotted in Figure 5.

(v) The time series for the outside option, $\{\hat{V}_t^x\}$ and $\{V_t^x\}$, also change over time with Uber's Toronto presence.

Specifically, the probabilities associated with Uber's launch are set according to

$$\mu_t = \frac{\mu}{1 + \exp\left(-\alpha_3(t - \alpha_4)\right)}, \tag{43}$$

where α_3 and α_4 are the parameterized values for the generalized logistic function from equation (41) and Figure 5. Initially, the probability of Uber entering the market is low. The probability rises steeply around the time of the actual launch of UberX. The probability thereafter converges to a positive constant, $\mu = 0.7876$, so that the expected duration of the pre-innovation period from a March 2012 perspective equals the actual time elapsed until the launch of UberX in September 2014. That is, μ is calibrated so that the sequence of probabilities, $\{\mu_t\}$, reflect an early pre-innovation belief that Uber will ultimately enter Toronto's ride-hailing market, but probably not for another two or three years. By the time Uber does enter in September 2014, the belief just beforehand was that Uber's launch was imminent.

The premise underlying item (v) is that the relative value of participating in the traditional taxicab market is deteriorating as the ridesharing innovation takes hold in the Toronto market. Since the value of exit governs the relative appeal of TL ownership, it stands to reason that the value of exit would increase as Uber gains momentum in Toronto's ride-hailing market. In other words, the prospect of partnering with a ridesharing company may enhance the value of exiting the traditional taxicab market for an owner-driver. This is precisely the innovation effect. Accordingly, we allow the value of exit to increase with Uber's presence in Toronto's ride-hailing market, as proxied by the Google Trends search intensity index. In particular, we set

$$\hat{V}_t^x = V_t^x = \frac{V^x}{1 + \exp\left(-\alpha_3(t - \alpha_4)\right)}, \tag{44}$$

where V^x is the calibrated value from Table 1, and α_3 and α_4 are defined as above. We set $\hat{V}_t^x = V_t^x$ for two reasons. First, even the pre-innovation value $\hat{V}_t^x$ changes with Uber's presence because it is a present discounted value that reflects expectations of the upcoming launch of UberX. Second, we do not observe the counterfactual time path of our proxy variable for Uber's presence in Toronto's ride hailing market to which we could separately calibrate $\hat{V}_t^x$ for time periods after the third quarter of 2014.

In order to compute the simulated equilibrium transition path, we implement the following algorithm. For the distributions of trader types and assets as well as market tightness, we use (4), (5) , (6) and (7) to solve for their evolution starting from the initial no-innovation stationary equilibrium as of the first quarter of 2012. To do so, we guess a time path for the measure of buyers, $\{n_t^b\}$, where $0 < n_t^b \leq \mathcal{N} - 1$ for all t.[17] We solve forward 60 quarters. At that point in time (12 years after the launch of UberX), we assume that the economy closely approximates the post-innovation stationary equilibrium calibrated in Section 6.2. Present discounted values and prices are then calculated recursively as per equations (9), (10), (11) and (12) for the post-innovation time periods; and equations (13), (14), (15) and (16) for the pre-innovation time periods. Having now solved for the equilibrium transition path from the pre-innovation to the post-innovation stationary equilibria under the initial guess, we check the quasi-free-entry conditions and adjust the conjectured time path for n_t^b accordingly: if the free-entry condition is violated in period t (i.e., if $V_t^b < V_t^x$), the measure of participating buyers is reduced; otherwise (i.e., if $V_t^b > V_t^x$), n_t^b increases toward $\mathcal{N} - 1$. This entire process is repeated until the participation of buyers is consistent with quasi-free entry in every period.

[17] The measure of buyers is positive but cannot exceed $\mathcal{N} - 1$. If the free-entry condition binds (i.e., $V_t^b = V_t^x$), the number of buyers is less than $\mathcal{N} - 1$.

7 Results

Figure 8 plots the (natural log of the) average quarterly price (in CAD) along the transition path from the no-innovation stationary equilibrium to the post-innovation stationary equilibrium, as well as the observed quarterly average price. The circles in the figure represent the raw quarterly averages for our full sample of transactions, where the size of the circle is proportional to the number of transaction. The small outlier circles in the first half of 2016 likely reflect uncertainty among market participants surrounding Toronto City Council's vote in March 2016 to allow Uber and other ridesharing companies to operate in the regulated market.[18] The blue line applies a smoothing algorithm to help visualize the evolution of the average price despite noisy quarterly data owing to the thin and opaque nature of the secondary market.[19]

The calibrated model accounts well for the dynamic changes in the value of a licensed taxicab. The sudden decline in the simulated equilibrium price in 2012 reflects the unexpected realization that freelance UberX drivers may enter the Toronto market each period with positive probability. Market participants suddenly anticipate future farebox and innovation effects. For our calibration, the initial fall in price is almost entirely driven by expectations of future dividends (i.e., the farebox effect). The gradual decline thereafter reflects both the changes in dividends following the launch of UberX in 2014 (the farebox effect), and the growing value of exit as Uber gains popularity in the ride-hailing market (the innovation effect).

In the initial no-innovation stationary equilibrium, the free-entry condition is slack so that $\hat{V}^b$ exceeds $\hat{V}^x$ and all $\mathcal{N}$ agents participate in the secondary market for TLs. As market participants anticipate and experience the change in farebox revenues coinciding with the launch of UberX, and as the value of exit rises with Uber's presence in the ride-hailing market, the sequences of values $\{V_t^b\}$ and $\{V_t^x\}$ converge so that the free-entry condition ultimately

[18] The second quarter of 2016 reflects a short period of market inactivity; only four transactions were recorded between April and June 2016.

[19] We use a robust quadratic regression over each window of 20 quarterly observations.

starts to bind in the third quarter of 2016. This implies an endogenous reduction in market participation as TL ownership becomes less appealing in terms of the economic rents and opportunity costs. The measure of buyers is about one-sixth less in the post-innovation stationary equilibrium relative to the no-innovation equilibrium, and average time-to-sell increases by about a month. Despite an endogenous response in entry/exit, the volume of transactions per quarter remains virtually unchanged[20] between the post-innovation and no-innovation stationary equilibria. Quasi-free entry is an important feature of the model for replicating the striking drop in the average price of a TL from 2011 to 2017 without also predicting a marked reduction in market transactions and a more severe increase in time-to-sell that contradicts the evidence presented in Appendix C. In Section 7.1, we assess the sensitivity of our results to various parameter changes, including increases in $\hat{V}^x$, that generate simulated transition paths with free-entry conditions that bind earlier.

Figure 9 displays the before-Uber and after-Uber price distributions, along with the simulated price distributions that correspond to the pre- and post-innovation stationary equilibria of the calibrated model. Prices are more dispersed in the data than in the model. In the model, price dispersion is generated from the idiosyncratic dividend process, which we calibrated using the monthly lease payments. Figure 9 reveals that the dividend heterogeneity observed in the recorded lease agreements is insufficient to account for all of the observed price dispersion. Other potential sources of price dispersion include trader heterogeneity in terms of their intrinsic preference for asset ownership, asset holding cost, rate of time preference, continuation value upon exit, or bargaining strength. Since we are focusing on the *overall* or *average* impact of Uber on the financial value of TLs (e.g., their *average* quarterly price), we do not view unexplained residual price dispersion as a consequential shortcoming of our calibrated model.

We use the calibrated model to decompose the price patterns into the farebox and innovation effects. In the complete absence of Uber, all prices and values, as well as the distribution of traders, would have remained the same as in the no-innovation stationary

[20]The volume of transactions declines by less than one percent between the two stationary equilibria.

equilibrium calibrated to the market for TLs in the before-Uber period. In Figure 10a, we plot the counterfactual price path that would have prevailed if the only impact of Uber on the market for TLs was via its adverse effect on dividends (i.e., the farebox effect). For this counterfactual simulation, we keep the value of exit constant at zero: $\hat{V}_t^x = V_t^x = 0$ for all t. As shown, most of the price adjustment occurs when market participants realize the possibility of Uber's Toronto market début. Since prices reflect the present value of future dividends, prices adjust immediately in the first quarter of 2012 to reflect the anticipated future impact of Uber on farebox revenues. The average price continues to decline gradually thereafter, followed by another slight downward movement coinciding with the launch of UberX in 2014 when the distribution of new dividends changes from $\hat{\boldsymbol{\pi}}$ to $\boldsymbol{\pi}$.[21] Prices decline slightly even after the launch of UberX because it takes time for current lease agreements to expire before a new lease payment is negotiated. The average equilibrium price converges to a stationary level that is \$90,525 below the initial no-innovation average price, consistent with the comparative static with respect to the dividend payment in Section 4 (i.e., part (i) of Propositions 1 and 2). The farebox effect accounts for 53 percent of the total price decline.

In addition to the changing dividend process, the price patterns in Figure 8 reflect the changing value of non-participation in the taxicab market (the innovation effect). This latter effect is isolated in a counterfactual simulation that features the change in the value of the outside option but keeps the dividend process constant. The resulting average price decline is plotted in the Figure 10b. Consistent with the comparative statics results in part (ii) of Propositions 1 and 2, an appealing continuation value enhances the net surplus for sellers exiting the market and lowers the net surplus for buyers acquiring a TL in the secondary market, which lead to price reductions under Nash bargaining. The innovation effect accounts for \$60,453 (35 percent) of the total price decline.

As discussed previously, the farebox and innovation effects can further affect prices

[21] This slight decline is barely detectable in Figure 10a because of the logarithmic vertical scale, but amounts to an average price drop of \$12,039 from the third quarter of 2014 to the post-innovation stationary equilibrium.

through an endogenous change in market participation when the free-entry condition binds. The free-entry condition turns out to be slack when we simulate the farebox and innovation effects in isolation. Neither effect on its own is sufficiently severe to drive away market participants. With both effects together, the endogenous response in market tightness amplifies the farebox and innovation effects to account for the rest of the $172,125 price decline.

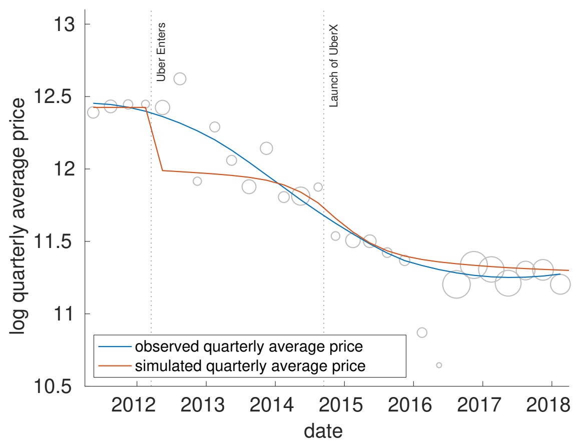


Figure 8: Observed and simulated average prices.

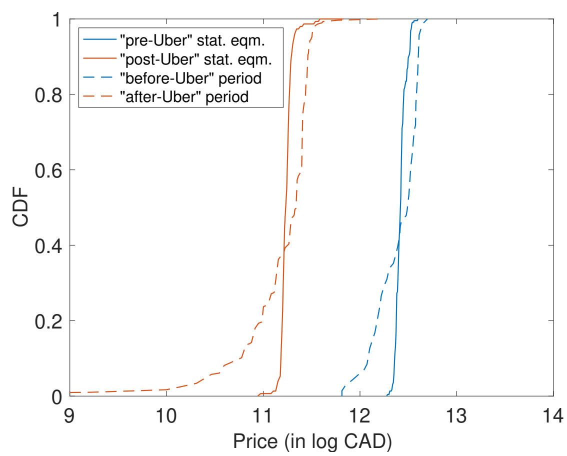
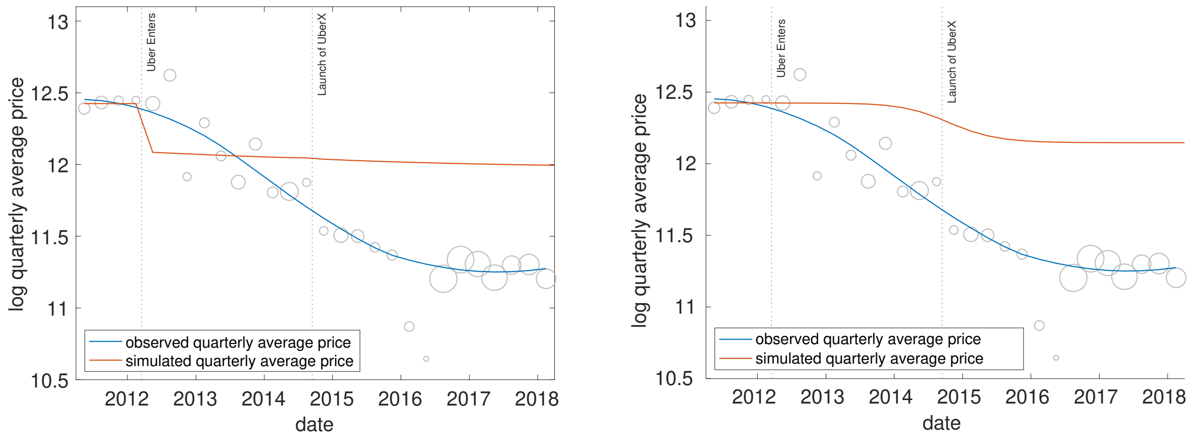


Figure 9: Observed and simulated price distributions.

In summary, the farebox effect alone can account for more than half of the observed price decline. The innovation effect can account for the rest, once the endogenous change



(a) Farebox effect only.

(b) Innovation effect only.

Figure 10: Counterfactual price simulations.

in market tightness takes effect. Both the farebox and innovation effects are thus important determinants of the declining market value of a licensed taxicab.

7.1 Sensitivity to Calibrated Parameters

We consider several alternative choices for calibrated parameter values to assess the sensitivity of our findings in terms of the decomposition of Uber's adverse impact into farebox and innovation effects. More specifically, this section summarizes a series of robustness checks to gauge to what extent the magnitude of the farebox effect depends on the choice of parameter values for β, ϕ, δ and $\hat{V}^x$.

To start, we assess the importance of our choice of parameter value for the discount factor, β. With an increase in β, expectations about future dividends become relatively more important in the determination of equilibrium prices. In 2012, when TL owners begin to anticipate the launch of UberX and its implications for future farebox revenues, a higher discount factor would cause an even more pronounced sudden drop in the average price of a TL. In the baseline calibration with β set according to a five percent annual interest rate, $\beta = 0.95^{1/4} = 0.9873$, the farebox effect alone accounts for a \$90,525 decline in the average price of TL. With the remaining parameters recalibrated to match the same targets as specified in Table 1, β can be increased to instead target an annual interest rate that is lower by 50 or 100 basis points. The farebox effect then increases only very slightly from \$90,525 to \$90,620 or \$90,739. The innovation effect along with any endogenous adjustment to market participation then account for only \$81,505 or \$81,386 of the overall \$172,125 price decline instead of \$81,600.

Alternative parameter values for the relative bargaining strength of the buyer, ϕ, yields similarly negligible changes in the relative magnitudes of the farebox and innovation effects. When sellers capture a larger share of the surplus in a transaction because of a lessening of buyers' bargaining strength, the current price of a TL is more sensitive to expectations about the future value of a TL and hence future dividends. When ϕ is decreased from 1/2 in the baseline calibration to 1/4, for example, the farebox effect increases to \$93,982, which leaves \$78,143 instead of \$81,600 to be accounted for by the innovation effect along with endogenous market participation. With either the increase in β discussed previously or this change in ϕ, the parameter value governing the severity of the preference shock, σ, is recalibrated to match the before-Uber average price of a TL. This mostly offsets the effects of the parameter change of interest on the relative importance of the farebox and innovation effects in accounting for the declining price of a licensed taxicab during the launch and rise of Uber.

Recall that the arrival rate of the preference shock, δ, is calibrated to match the average number of market transactions per quarter. The secondary market for TLs is a thin market, and the number of transactions per quarter varies considerably. For instance, the average number of transactions per quarter in the before-Uber period (17.7015) is considerably less than in the after-Uber period (73.7500). This could be merely a coincidence or for reasons unrelated to the ridesharing innovation.[22] It could also reflect a build-up of would-be buyers and sellers that were hesitant to transact until the uncertainty was resolved surrounding the vote to allow Uber to operate in the regulated ride-hailing industry. Whatever the reason, we are cautious about interpreting the increase in transactions as an Uber-induced

[22]Even the numbers of TL transfers to and from deceased license holders' estates are considerably higher in the after-Uber period, which should be independent of Uber and ridesharing.

structural change in TL ownership turnover and therefore keep δ constant along the simulated transition path. Instead, we explore the sensitivity of our results to changes in parameter δ. When δ is set to 0.0036 to match the volume of transactions in the before-Uber period, the farebox effect is 90,413 and the innovation effect along with endogenous market participation account for the remaining \$81,712 average price decline. If instead δ is set to 0.0152 to match the volume of transactions in the after-Uber period, the recalibrated model features a slightly higher farebox effect amounting to \$90,710, and the other price effects can explain the remaining \$81,415 decline. Parameter δ affects churning in the market and hence the endogenous composition of market participants, but the price implications remain relatively unchanged.

Finally, recall that the initial value of the exogenous outside opportunity, $\hat{V}^x$, is set to zero so as to achieve full market participation (i.e., $n^b + n^m + n^s = \mathcal{N}$) in the no-Uber stationary equilibrium. Under the baseline calibration, the no-Uber stationary equilibrium present discounted expected value of a buyer, $\hat{V}^b$, exceeds the value of the outside option by \$50,399. We now consider approaching a binding free-entry condition by increasing $\hat{V}^x$ from zero towards $\hat{V}^b$ to remove slack in buyers' participation constraint, $\hat{V}^b \geq \hat{V}^x$. An initial value of the outside option equal to \$10K, for example, increases the farebox effect from \$90,525 to \$92,208. With $\hat{V}^x$ set to \$50K, the farebox effect is \$98,938 and thus accounts for 57 percent of the overall price decline, compared to 53 percent in the baseline calibration. A larger farebox effect and hence smaller innovation effect, however, would cause the simulated equilibrium transitional dynamics to feature an average price path that less closely resembles the observed quarterly average price series plotted in Figure 8. The initial fall in price coinciding with the launch of Uber in March 2012 would be too pronounced, and the gradual decline thereafter would be too modest. In other words, the equilibrium price dynamics along the simulated transition path under the baseline calibration more convincingly replicate the price series observed in the secondary market for TLs.

7.2 Delaying the Launch of UberX

In addition to the decomposition of Uber's price effect on TLs, the calibrated model allows us to consider other counterfactual scenarios. To shed light on the impact of Uber on the financial well-being of licensed taxicab owners, we study two scenarios involving alternative timing assumptions about when Uber's freelance ridesharing services become available in Toronto.

Note that unregulated UberX drivers provided ridesharing services with private vehicles in Toronto for a year and a half before Toronto City Council voted on March 3, 2016, to allow ridesharing companies to operate in the regulated market. What if the Toronto Taxicab Alliance had been successful in convincing the City of Toronto to uphold the regulatory supply constraint by cracking down on unlicensed private vehicles-for-hire until the new bylaw was approved in 2016? Relatedly, how sensitive are pre-innovation values to beliefs about the timing of Uber's Toronto intrusion? To shed light on this issue, we consider changes in the actual and anticipated timing of the farebox and innovation effects associated with the launch of UberX, and calculate the impact of these counterfactual specifications on the financial wealth of licensed taxicab owners.

In our benchmark calibration, the sequence of transition probabilities, $\{\mu_t\}$, are such that TL owners entering the second quarter of 2012 expect the new farebox regime to take effect in two and a half years, on average. More specifically, parameter μ is calibrated so that the expected time between the launch of Uber and UberX corresponds to the actual timing. As an experiment, we consider an exogenous force that could postpone, in expectation, the launch of UberX. We recalibrate parameter μ to obtain an expected pre-innovation duration of four years instead of two and a half. A four-year pre-innovation period would coincide with the timing of the vote to regulate Uber drivers in 2016. One possible interpretation is that more coordinated lobbying efforts and public demonstrations could have succeeded in maintaining and enforcing the barriers to entry in the taxicab industry until such time as the regulations were amended to include drivers offering ridesharing services.

We compute two equilibrium transition paths: one in which the launch of UberX is delayed only in expectation, and another in which we simulate a delayed transition path with a prolonged pre-innovation period. The first simulation is the same as the baseline calibration except for the aforementioned recalibration of the sequence of probabilities for the launch of UberX. The parameter value for μ in this scenario is 0.1186. The realized timing of Uber's ridesharing services and the time series for the value of the outside option, $\{\hat{V}_t^x\}$ and $\{V_t^x\}$, remain unchanged relative to the baseline. In other words, only *beliefs* or expectations about the timing of the transition to the post-innovation dividend regime have been modified in this first scenario.

The second counterfactual simulation explicitly delays the launch of UberX by a year and half. Specifically, the sequence of probabilities and the time series for the value of exit are shifted as follows:

$$\mu_t = \frac{\mu}{1 + \exp\left(-\alpha_3((t-\Delta) - \alpha_4)\right)}$$
$$\hat{V}_t^x = V_t^x = \frac{V^x}{1 + \exp\left(-\alpha_3((t-\Delta) - \alpha_4)\right)},$$

where Δ is set to one and a half years so that the sharpest increase coincides with Toronto City Council's vote in 2016. Parameter μ is recalibrated again so that four years is the expected duration of the pre-innovation period. In this scenario, the timing of the farebox and innovation effects (and expectations thereof) align with the first quarter of 2016 rather than the actual 2014 launch of UberX. This simulation aims to compute the equilibrium transition path that would have transpired if market participants correctly anticipated an additional delay in the launch of UberX until city bylaws were amended to include the provision of ridesharing services.

The transition paths for the (log of the) quarterly average price are plotted in Figure 11. The simulation from the baseline parameterization is the red line, and the simulation that adjusts only expectations about the timing of the farebox effect is plotted in purple. The price drop between the first and second quarter of 2012 is $87,998 in the baseline, but only \$80,375 when the farebox effect associated with the launch of UberX could have been postponed by an additional year and a half (in expectation). The counterfactual simulation that delays both the farebox and innovation effects until 2016 is plotted in green. It reveals a similar initial price decline of \$81,467, but further declines unmistakably occur much later than in the simulation with counterfactual beliefs only.

Of greater interest than the price effects under these alternative parameterizations are the implications for the value of TL ownership (i.e., the $\{\hat{V}_t^m\}$ and $\{V_t^m\}$). These series, plotted in Figure 12, determine the present discounted expected value of the financial repercussions of Uber for the owners of traditional licensed taxicabs. Given the linear preference specification of the model, these financial values also summarize the welfare implications for TL holders.

Figure 12a reveals that most of the decline in the average value of TL ownership occurs initially with Uber's Toronto market début. The dramatic initial decline and further declines thereafter are attributable primarily to the negative farebox effect. This is similar to the farebox effect on prices (see Figure 10a). The innovation effect, on the other hand, raises the value of TL ownership because of the enhanced continuation value upon exit. As we saw in Figure 10b, however, the innovation effect also causes a gradual decline in prices. The negative impact on the value of TL ownership via prices only partly offsets the positive continuation value effect when the free-entry condition is slack. The net innovation effect is therefore positive, as shown with the comparative static result in part (iv) of Proposition 1. The overall impact of Uber on the financial well-being of TL owners would be more severe in the absence of the innovation effect. It follows that the initial impact is more severe as the innovation effect is shifted further into the future (i.e., the green line in Figure 12a as compared to the purple line).

Figure 12b focuses on the cross-sectional distribution of the financial value of owning a TL from the perspective of the second quarter of 2012. The distribution of $\hat{V}_t^m$ in the baseline calibration is plotted in red. When only the beliefs about the timing of the farebox effect are adjusted (the purple line), the distribution shifts to the right by \$8,458. When the timing of both the farebox and innovation effects are adjusted (i.e., the green line), the shift in the distribution relative to the baseline calibration is less pronounced: only $4,455. Once again, the innovation effect partly offsets the farebox effect in terms of the financial value of TL ownership because a more appealing alternative is beneficial to supply-side participants in the hide-hailing market. TL owners anticipate capitalizing on the innovative approach to ride-hailing upon selling their TL at a later date, and are better off when they can expect to do so sooner.[23]

A brief discussion of the magnitude of these numbers is in order. Put simply, these sums of funds are far from inconsequential. With approximately 5,000 city-issued taxicab licenses outstanding, TL owners would have benefited tremendously from an expected one and a half year delay in the launch of UberX. A back-of-the-envelope calculation yields a collective willingness to pay among TL owners in 2012 upwards of $40M for the anticipated delay. It is then not surprising that there were coordinated efforts among TL owners to prevent or postpone the erosion of economic rents earned from the provision of traditional taxicab services prior to the new rules approved in 2016. Toronto taxi drivers held numerous demonstrations, strikes and protests against the circumvention of Toronto's ride-hailing regulations by UberX drivers, including rush hour road blockages (see, for example, Mangione and Balca, 2015). Anti-Uber spokespersons quoted in the media complained about *stolen business* (CBC News, 2015), and likened Uber's private-vehicles-for-hire to *bandit taxis* (Csanady, 2015), which clearly point to concerns about the farebox effect specifically.

8 Conclusion

In this paper we study the effect of Uber on the market value of a traditional taxicab license. We develop a random search and bargaining model of the secondary market for TLs to highlight two potential channels through which Uber can affect equilibrium prices. What we

[23] In reality, some TL owners exit the traditional taxicab market for retirement, in which case the enhanced value of the outside opportunity is of no benefit. The impact of a delay in the launch of UberX on the financial well-being of retiring TL owners may be better approximated by comparing our baseline simulation to the previous counterfactual simulation (i.e., the red and purple lines in Figure 12), which maintains the same assumptions about the timing of the innovation effect.

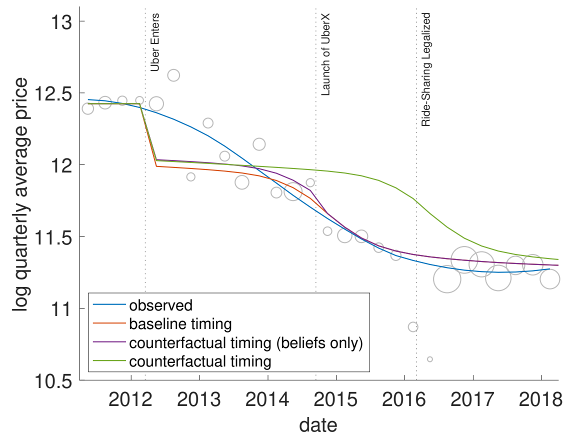
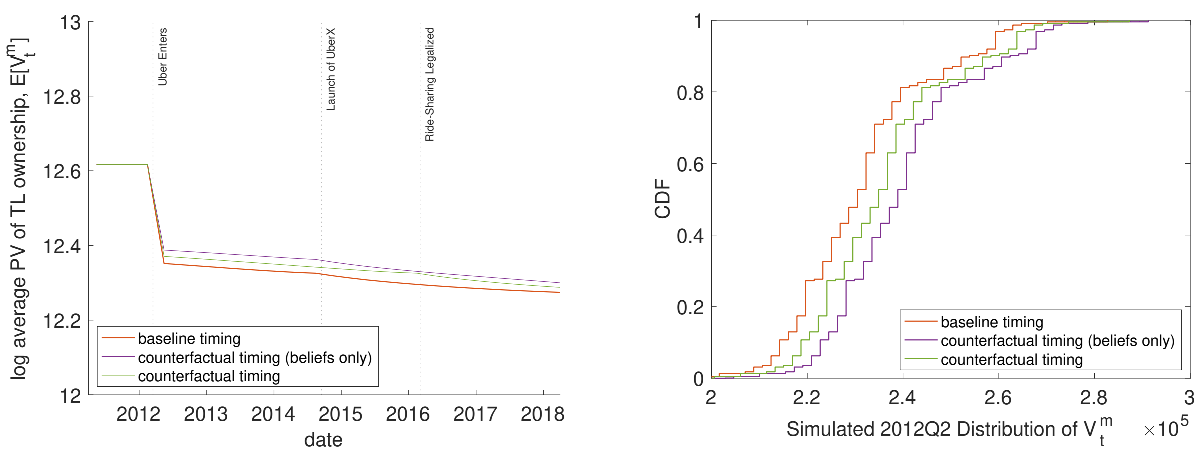


Figure 11: Counterfactual simulations of the average price.



(a) Simulated average value of TL ownership.

(b) Distribution of $\hat{V}_t^m$ in Q2 of 2012.

Figure 12: Simulated present discounted expected values of ownership.

call the farebox effect captures the idea that increased competition from Uber drivers in the ride-hailing market lowers the economic rents associated with TL ownership. The innovation effect, in contrast, reflects the appeal of Uber's innovative technology-driven approach as an alternative endeavor for both current and prospective TL holders. Using transaction-level data and proxy variables for Uber's market presence, we calibrate our model and simulate a transition path from a stationary equilibrium without Uber to one in which Uber is well-established. The simulated prices replicate, to a great extent, the prices actually observed. We then isolate and quantify the key driving forces behind the declining market price of a

TL. We find that the farebox effect accounts for about 53 percent of the price decline. The innovation effect along with endogenous market participation can account for the rest, and are crucial for replicating the observed price patterns.

Whereas both the farebox and innovation effects contribute to the decline in prices, the decline in the present value of TL ownership is attributed predominantly to the farebox effect. Calculating these financial values by means of the calibrated model reveals that an expected delay in the launch of UberX by 18 months would be worth $4,455 or more to each of the 5,000 Toronto TL owners in 2012. It is not surprising, then, that Toronto taxi drivers rallied to protest plans for deregulation and call on the city for bylaw enforcement against unregulated rides-for-hire. Taxi drivers have organized anti-Uber protests in many other cities across the globe, including Paris, Sao Paulo, and Queensland, among others (Lindeman, 2015). This confrontational transition from the traditional taxicab regime to a more innovative regime involving ride-hailing services is therefore not unique to the city of Toronto.

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A Microfoundations for the Idiosyncratic Dividend Process

Licensed taxicab operations. Suppose the operation of a licensed taxicab in a given time period requires capital and labor inputs, denoted k and h, to generate farebox revenue governed by the following production function:

$$F(k,h) = \begin{cases} F(\bar{k},h) \equiv f(h) & \text{if } k \geq \bar{k} \\ 0 & \text{otherwise} \end{cases} \tag{45}$$

where $\bar{k}$ represents the vehicle and dispatch equipment necessary for taxicab operations. Let $f : \mathbb{R}_+ \rightarrow \mathbb{R}_+$ satisfy $f' > 0$, $f'' < 0$, $\lim_{h\rightarrow 0} f'(h) = \infty$ and $\lim_{h\rightarrow\infty} f'(h) = 0$. Letting w and r represent the opportunity costs of labor and capital, the current surplus, or *dividend*, enjoyed by an owner-operator is given by:

$$d = \max_h f(h) - wh - r\bar{k}. \tag{46}$$

Periodic shocks to labor productivity, as captured by f, and/or the opportunity costs of labor and capital, r and w, would generate idiosyncratic variation in the stream of dividends:

$$d_j = \max_h f_j(h) - w_j h - r_j \bar{k}. \tag{47}$$

Leasing arrangements. Consider instead a non-driver TL owner paired with a driver of type j: that is, a driver with idiosyncratic but observable characteristics described by a farebox generating function, f_j, and opportunity costs w_j and r_j for labor and capital. Suppose the monthly payment for the lease of the license is proposed by the TL owner in the form of a take-it-or-leave-it (TIOLI) offer. The optimal TIOLI offer binds the driver's participation constraint, yielding the same expression for the TL owner's dividend as in (47).

Suppose further that lease agreements expire each period with probability ρ. Conditional on lease termination, let π_j denote the probability of partnering anew with a driver of type $j = 1, \ldots, J$. We can now construct the transition matrix for current dividends, taking into account the lease agreement *renewal shocks*:

$$\mathbf{\Pi} = \begin{bmatrix} (1-\rho) + \rho\pi_1 & \rho\pi_2 & \cdots & \rho\pi_J \\ \rho\pi_1 & (1-\rho) + \rho\pi_2 & \cdots & \rho\pi_J \\ \vdots & \vdots & \ddots & \vdots \\ \rho\pi_1 & \rho\pi_2 & \cdots & (1-\rho) + \rho\pi_J \end{bmatrix} \tag{48}$$

B Equilibrium Definitions

Given $V_t^x = V^x$ for all t, the post-innovation market admits a stationary equilibrium satisfying the following definition.

Definition 1. A *post-innovation stationary equilibrium* is a set of values, $\{\boldsymbol{V}^m, \boldsymbol{V}^s, V^b\}$; a vector of prices, $\boldsymbol{P}$; a distribution of assets, $\boldsymbol{a}$; a distribution of trader types, $\{n^m, n^s, n^b\}$; and a market tightness, θ; such that

(i) values satisfy:

$$\boldsymbol{V}^m = \mathbf{\Pi}\big\{\boldsymbol{d} + \beta\big[(1-\delta)\boldsymbol{V}^m + \delta\boldsymbol{V}^s\big]\big\} \tag{49}$$

$$\boldsymbol{V}^s = \mathbf{\Pi}\big\{(1-\sigma)\boldsymbol{d} + \beta\big[\,(1-p(\theta))\,\boldsymbol{V}^s + p(\theta)\big(V^x\mathbf{1} + \boldsymbol{P}\big)\big]\big\} \tag{50}$$

$$V^b = \beta\big[\delta V^x + (1-\delta)(1-q(\theta))V^b + (1-\delta)q(\theta)\boldsymbol{a}\mathbf{\Pi}\big(\boldsymbol{V}^m - \boldsymbol{P}\big)\big] \tag{51}$$

(ii) prices satisfy the Nash bargaining solution:

$$\boldsymbol{P} = \boldsymbol{V}^m - V^b\mathbf{1} - \phi\big[\boldsymbol{V}^m - V^b\mathbf{1} + V^x\mathbf{1} - \boldsymbol{V}^s\big] \tag{52}$$

(iii) the distribution of assets is stationary:

$$\boldsymbol{a} = \boldsymbol{a}\mathbf{\Pi} \tag{53}$$

(iv) the distribution of traders and market tightness satisfy aggregation, stationarity, quasi-free entry and the definition of market tightness:

$$n^m + n^s = 1 \tag{54}$$

$$\delta n^m = \mathcal{M}((1-\delta)n^b, n^s) \tag{55}$$

$$n^b \leq \mathcal{N} - 1 \quad \text{and} \quad V^b \geq V^x \quad \text{(with complementary slackness)} \tag{56}$$

$$n^b = \frac{\theta n^s}{1-\delta} \tag{57}$$

All equations in the above definition are stationary versions of equations (9), (10), (11), (12), (6), (4), (5), (8) and (7).

The definition of a *no-innovation stationary equilibrium*, introduced in Section 6.1, closely resembles Definition 1, except that $\hat{\mathbf{\Pi}}$ and $\hat{V}^x$ replace $\mathbf{\Pi}$ and V^x.

C Supplementary Data and Time-to-Sell

Database of Business Licence Renewals and New Issues. It would be of interest to document time-on-the-market for each buyer and seller in the secondary market for TLs. Unfortunately, information about the length of the search process for all traders is not readily available. Nevertheless, investigation of the database of Business Licence Renewals and New Issues maintained by the City of Toronto's Municipal Licensing and Standards division provides some clues about the severity of search frictions. In particular, the time elapsed between an estate transfer and a subsequent market transaction can be recovered from the information recorded in this database. As described in the 2014 report of the taxicab industry prepared by the City of Toronto, the TL is first transferred to the estate of a deceased license holder, but must then be sold to a licensed taxicab driver within 12 months. In practice, many estate ownership durations exceed 12 months, although some personal representatives of deceased TL owners scramble to transfer ownership of the TL right as the 12-month period draws to an end.

Figure 13 plots the empirical cumulative distribution functions for the time elapsed between two consecutive changes in TL ownership when the first transfer follows the death of a license holder. Data for Figure 13 include all estate sales recorded in the before-Uber period (i.e., between April 2011 and March 2012) and after-Uber period (i.e., between April 2017 and March 2018). As can be seen, the distribution of estate ownership durations are quite similar between the two periods, although the aforementioned bunching of estate transfers just prior to the 12-month mark is more pronounced in the after-Uber period.

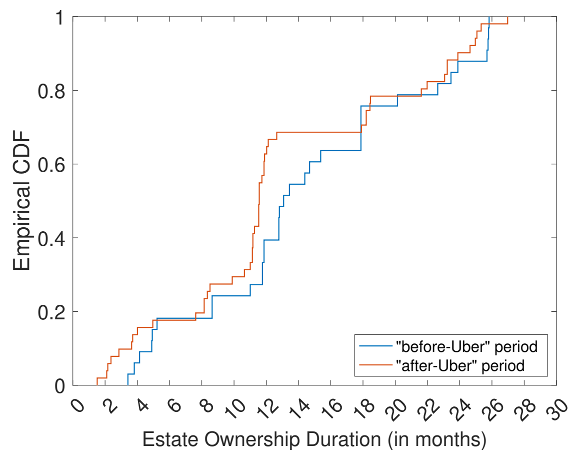


Figure 13: Distributions of estate ownership duration.

The time between these changes in ownership likely reflects (i) the time required to sort out the deceased license holder's estate, and (ii) the difficulty in finding a buyer. Both sources of delay are potentially relevant when the TL is sold in the secondary market, whereas only the first is important when the TL is ultimately transferred to a family member. Comparing the time between transfers for these two groups provides some insight about time-on-the-market for sellers. In what follows, we attribute longer estate ownership durations preceding market transactions to the time required to meet a potential trading partner and negotiate the terms of the transaction.

The before- and after-Uber samples are each divided into two groups according to market transactions and family transfers.[24] Differences after the first 12 months of estate ownership

[24]A *family transfer* satisfies at least one of the following two conditions: (i) the new owner has the same

might be particularly relevant because some personal representatives of deceased TL owners' estates may deliberately delay the transfer of the license until the end of the initial 12 month period.[25] Moreover, it should be easier to manipulate the date of a family transfer than a market transaction if the latter can only transpire after a lengthy and uncertain period of searching for and negotiating with a buyer. Consistent with this line of reasoning premised on search frictions in the secondary market for TLs, the histograms plotted in Figure 14 display evidence of bunching just under 12 months for the pooled (i.e., before- and after-Uber) sample of family transfers but not market transactions. To circumvent these bunching-related issues in our identification and estimation of time-to-sell, we now restrict our attention to estate ownership durations exceeding 12 months. Figure 15 plots these truncated distributions for market transactions and family transfers for estate ownership durations that end in the before-Uber period (Figure 15a) and after-Uber period (Figure 15b). As expected, these truncated empirical CDFs provide some evidence that market transactions take longer than family transfers.

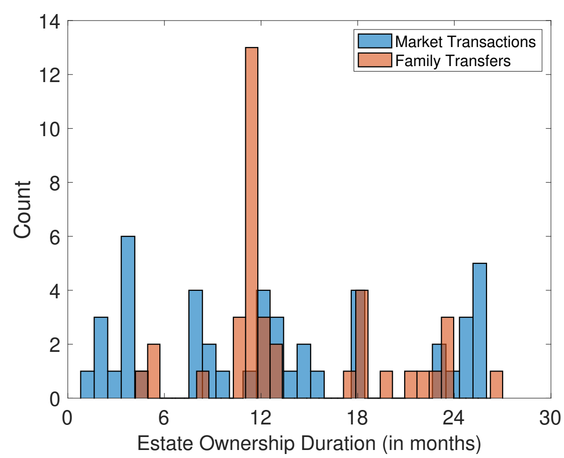
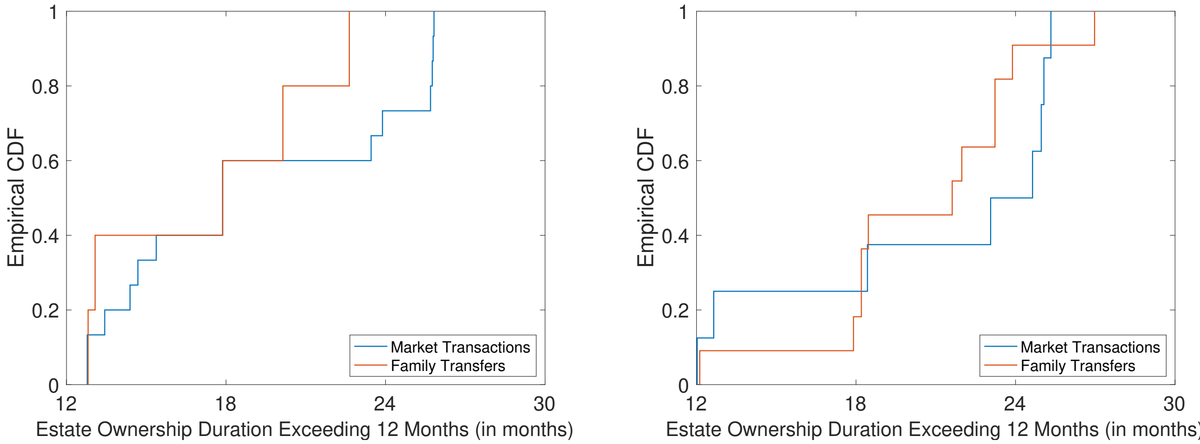


Figure 14: Histograms of estate ownership duration.

surname as the deceased, or (ii) the new owner is a business with the same six-digit postal code as the estate of the deceased owner. Admittedly, a transfer to a family member with a surname different from that of the deceased TL owners will be incorrectly categorized as a market transaction.

[25] There could even be reasons to delay the transfer within the first year if, for example, the intended beneficiary is not yet a licensed taxicab driver, or if the revenue generated from leasing the TL in the interim can be allocated to someone else. Maintaining estate ownership beyond the first year, however, could be viewed as risky or costly because it requires approval by the Toronto Licensing Tribunal.



(a) Before-Uber period.

(b) After-Uber period.

Figure 15: Truncated time until new ownership following death of previous TL owner.

Our approach for deriving estimates of the average time-on-the-market for sellers from estate ownership duration data can be described as follows. Suppose that sorting out a deceased TL holder's estate is a process that terminates each period with probability γ. Afterwards, absent a family transfer, a suitable buyer is found and ownership of the TL is transferred from the estate to the buyer by means of a transaction in the secondary market each period with probability $p(\theta)$. Let x^i denote the duration of estate ownership for a TL that is ultimately transferred to a family member ($i = F$) or sold in the decentralized market ($i = M$). Conditional on the transfer being more than 365 days after the death of the previous license holder, duration x^F is a geometrically distributed random variable with probability mass function (PMF)

$$\text{Prob}\left\{x^F = x | x^F > 365\right\} = \begin{cases} \gamma(1-\gamma)^{(x-1)-365} & \text{if } x > 365 \\ 0 & \text{otherwise.} \end{cases} \tag{58}$$

Duration x^M exceeding 365 days, on the other hand, is a random variable with PMF

$$\text{Prob}\left\{x^M = x | x^M > 365\right\} = \begin{cases} \dfrac{\gamma p(\theta)\left[(1-p(\theta))^{x-1} - (1-\gamma)^{x-1}\right]}{\gamma(1-p(\theta))^{365} - p(\theta)(1-\gamma)^{365}} & \text{if } x > 365 \\ 0 & \text{otherwise.} \end{cases} \tag{59}$$

Probabilities γ and $p(\theta)$ can then be estimated from the estate ownership duration data by maximizing the following log-likelihood function:

$$\log \mathcal{L}(\gamma, p(\theta)) = \sum_{x \in \mathbb{X}^F_{>365}} \log\left(\gamma(1-\gamma)^{(x-1)-365}\right) + \sum_{x \in \mathbb{X}^M_{>365}} \log\left(\frac{\gamma p(\theta)\left[(1-p(\theta))^{x-1} - (1-\gamma)^{x-1}\right]}{\gamma(1-p(\theta))^{365} - p(\theta)(1-\gamma)^{365}}\right), \tag{60}$$

where $\mathbb{X}^F_{>365}$ represents the set of estate ownership durations exceeding one year recorded for family transfers, and $\mathbb{X}^M_{>365}$ is the same for market transactions.

Using the samples of transfers and transactions from the pre-Uber period, this procedure yields parameter estimates $\hat{\gamma} = 6.1189 \times 10^{-3}$ and $\hat{p} = 5.9286 \times 10^{-3}$. The implication for expected time-on-the-market for sellers (*i.e.*, average time spent searching for a buyer) is therefore $1/\hat{p} = 169$ days. When we repeat this exercise using the sample of market transactions and family transfers from the after-Uber period, the parameter estimates are $\hat{\gamma} = 4.0557 \times 10^{-2}$ and $\hat{p} = 6.0383 \times 10^{-3}$. The implied expected time-on-the-market for sellers in the after-Uber period is therefore remarkably similar to that implied by our before-Uber period estimate: $1/\hat{p} = 166$ days. Based on these calculations, expected time-to-sell for a personal representative of a deceased license holder's estate is around five and a half months in both the before- and after-Uber periods. These estimates are in line with anecdotal evidence from retiring taxicab owner-drivers.