Market dynamics between public transport and competitive ride-sourcing providers

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1 Introduction

Recent advances in communications and IT technology have underpinned the rapid development of transportation network companies (TNCs) in recent years [8]. Although the competitive prices offered by TNCs have been well-received by users, recent studies indicate that the resulting increase in public welfare [6] is temporary, as passengers are likely to be steered away from public transport. Indeed, a recent study by [5] has presented evidence that such shifts have already occurred and can be directly linked to increased congestion in major cities.

Many studies in taxi pricing [e.g. 4, 9] have adopted an economic theory perspective, using aggregate demand and supply models to represent the dynamics of urban taxi operations. Dynamic pricing has also been considered, for example by [7] who adopt a Vickrey-Clarke-Groves (VCG) bidding mechanism for shared autonomous taxi rides to maximise social welfare. The impact of dynamic pricing to TNC operations was investigated in [3], suggesting that a dynamic increase in trip price significantly increases the supply of rides in the system.

However, the relationship between dynamic TNC pricing strategies and public transport provision remains unexplored to this date. To address this issue, we propose a novel, game-theoretic, dynamic pricing model that accounts for multiple TNCs operating alongside public transport services. This is applied to a city-wide service scenario, and compared to an alternative static pricing model that serves as a baseline. Finally, we perform a comparative analysis of expected utilities for travellers and operators, while monitoring mode share fluctuations across a range of competitive scenarios and market structures.

2 Model Description

The key actors in our model are two symmetric TNC firms offering an identical product (rides) of equivalent quality. A centralised platform receives ride requests from the public. Both firms are expected to respond to these requests, with quotes for service and estimates of anticipated wait and travel times. Travellers can then decide (using a generalised costing mechanism) whether to accept an offer or to revert to public transport.

TNCs are expected to operate with a profit maximization objective and are allowed to introduce surcharges upon the base prices for each trip. These are based upon current demand levels, and a TNC's perception on the ability of its competitors to serve a specific trip request. Using dynamic pricing, the final bid price is the sum of a variable base price r per time of travel set by the platform, and the TNC's choice of an extra variable tariff per time of travel f_i.

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The price p_i for company i is calculated using (1) and (2):

$$p_i = f_i + r \qquad \forall\ i \tag{1}$$

$$f_i \in \mathbb{R}^+ \qquad \forall\ i \tag{2}$$

The variable base price level r is set by the platform and assumed to apply to both firms. This depends upon the number of available vehicles Q_i for each firm i, and the total number of trip requests D currently in the queue. The minimum value of r, denoted r_0, is the lowest value in the set C of marginal costs per unit travel time, with c_i being the cost for each TNC i.

We use equations (3), (4) and (5) to determine r, with α, β and γ determined through calibration:

$$r = r_0 + \frac{\alpha}{\beta(\frac{\sum_i Q_i}{D})^2 + \gamma} \tag{3}$$

$$r_0 \geq \min C \tag{4}$$

$$D \in \mathbb{Z}^+,\ Q_i \in \mathbb{N} \qquad \forall i \tag{5}$$

Equation (3) stipulates that for high ratios of vehicle availability against demand, r approaches r_0. Where very low availability levels are observed, the value of r approaches $r_0 + \frac{\alpha}{\gamma}$. It is assumed that firms do not adjust their value of Q_i at each request. Vehicle availabilities in our model are influenced by traveller origins and vehicle proximities. As such, following from Bertrand competition [2], firms can only control bid values through f_i.

In turn, travellers in our model evaluate the utility of each company bid using a nested logit model with a degree of stochasticity to account for heterogeneity in traveller preferences. Customer utilities for each modal options are calculated using (6) for TNC firms U_{T_i} and (7) for public transport U_P:

$$U_{T_i} = V_{T_i} + \varepsilon_{T_i} = \alpha_i - \beta_1\ w_i - \beta_2\ t_T - \beta_3\ p_i \times t_T + \varepsilon_{T_i} \qquad \forall i \tag{6}$$

$$U_P = V_P + \varepsilon_P = -\beta_1\ w_P - \beta_2\ t_P - \beta_3\ p_P + \varepsilon_P \tag{7}$$

where p_P and w_P are the price and waiting times for trips using public transport, w_i is the waiting time for firm i, t_P and t_T are the in-vehicle travel times via public transport and TNC respectively. The parameter α_i is used to represent the inherent preferences for the TNCs due to unobserved factors such as comfort, brand image and trust. In turn, β_1, β_2 and β_3 are random variables representing the marginal disutility of waiting time, travel time and travel cost, and are assumed to vary across the client population following a normal distribution with standard errors σ_{β_1}, σ_{β_2}, σ_{β_3}.

The stochastic error terms ε_{T_i} and ε_P are randomly distributed variables following a type 1 extreme value distribution, which is the assumption underlying the nested logit model structure. The latter assumes a heightened correlation between the stochastic error terms for the TNCs (i.e. ε_{T_i}) thus allowing for a greater elasticity between the TNC alternatives. The values of p_P, w_P, w_i, t_P and t_T vary between clients and depend on network characteristics and vehicle distributions across the network at the time of the request.

For the nested logit model choice probabilities are computed as follows for the high level choice of TNC T or public transport P [1]:

$$P(b) = \frac{e^{\mu\ V_b}}{e^{\mu\ V_T} + e^{\mu V_P}} \qquad \forall\ b = \{T,\ P\} \tag{8}$$

Where μ is the scale of the stochastic error terms, assumed to be 1 between the high-level options (TNCs versus public transport). The probability of choosing one of the TNC firms is given by:

$$P(T_i) = P(T_i|T)P(T) \qquad \forall\ i \tag{9}$$

$$P(T) = \frac{e^{\mu\ V_T}}{e^{\mu\ V_T} + e^{\mu V_P}} \tag{10}$$

$V_T = IV_T$ is the inclusive value of the TNC nest and is calculated using equation (11):

$$IV_T = \frac{1}{\mu_T} \ln \left[\sum_i e^{\mu_T \times V_{T_i}} \right] \tag{11}$$

Where μ_T is the scale of the error terms for the TNC options, which captures the heightened correlation between the different TNC choices as shown in equation (12):

$$corr = 1 - \left(\frac{\mu}{\mu_T} \right)^2 \tag{12}$$

The value of $P(T_i|T)$ is calculated using equation (13):

$$P(T_i|T) = \frac{e^{\mu_T \ V_{T_i}}}{\sum_{j=1}^{n} e^{\mu_T \ V_{T_j}}} \tag{13}$$

For each trip request, the firms evaluate the probability of winning the bid based on the estimated traveller utilities for each option. Estimates are required as firms are not privy to the real value of client-specific parameters $\alpha_i, \beta_1, \beta_2$ and β_3, nor the real values of their competitors w_i. To estimate the traveller utilities, each firm i uses random variables from the distributions of the parameters calibrated from observed behaviour, denoted as $\hat{\alpha}_i, \hat{\beta}_1, \hat{\beta}_2, \hat{\beta}_3, \hat{\sigma}_{\beta_1}, \hat{\sigma}_{\beta_2}, \hat{\sigma}_{\beta_3}$ and $\hat{\mu}_{TNC}$. Firm i also uses an estimate $\bar{w}_{j,i}$ for the waiting time of firm j, weighted by firms i waiting time and their ratio of vehicle availabilities as shown in equation (14):

$$\bar{w}_{j,i} = w_i \times \frac{Q_i}{Q_j} \qquad \forall\ i, j \tag{14}$$

Hence the estimate by firm i of the utility $\bar{V}_{j,i}$ of choosing firm j to the customer in question is given by equations (15), (16) and (17):

$$\bar{V}_{j,i} = \hat{\alpha}_i - \hat{\beta}_1\ \bar{w}_{j,i} - \hat{\beta}_2\ t_T - \hat{\beta}_3\ \bar{p}_{j,i} \times t_T \qquad \forall\ i, j \tag{15}$$

$$\bar{p}_{j,i} = \bar{f}_{j,i} + r \qquad \forall\ i, j \tag{16}$$

$$\bar{f}_{j,i} \in \mathbb{R}^+ \qquad \forall\ i, j \tag{17}$$

Similarly, the estimate by firm i of the utility $\bar{V}_i$ of choosing firm i to the customer and the estimate of the utility $\bar{V}_P$ of choosing public transport to the same customer is given by equations (18) and (19) respectively:

$$\bar{V}_i = \hat{\alpha}_i - \hat{\beta}_1\ w_i - \hat{\beta}_2\ t_T - \hat{\beta}_3 p_i \times t_T \qquad \forall\ i \tag{18}$$

$$\bar{V}_P = -\hat{\beta}_1\ \ w_P - \hat{\beta}_2\ t_P - \hat{\beta}_3 p_P \tag{19}$$

Firms choose the price of their bids to maximise their expected profit. Since the utility values used in the probability calculations are estimates, so is the expected profit. For simplicity, we assume a scenario where only two TNCs operate. Hence, the expected profits $\mathbb{E}(\bar{P}r_{T_i})$ and $\mathbb{E}(\bar{P}r_{T_{j,i}})$, given the marginal cost c_i per time of travel for each firm are:

$$\mathbb{E}(\bar{P}r_{T_i}) = \bar{P}(T_i \mid \bar{f}_{j,i}) \times ((f_i + r) - c_i) \qquad \forall\ i \tag{20}$$

$$\mathbb{E}(\bar{P}r_{T_{j,i}}) = \bar{P}(T_{j,i} \mid f_i) \times ((\bar{f}_{j,i} + r) - c_j) \qquad \forall\ i, j \tag{21}$$

If a pair of values f_i^* and $\bar{f}_{j,i}^*$ exists for which both $\mathbb{E}(\bar{P}r_{T_i})$ and $\mathbb{E}(\bar{P}r_{T_{j,i}})$ are maximised, this constitutes a Nash Equilibrium. Hence, the algebraical solution for the Nash Equilibria, if they exist, could be found by solving the system of non-linear equations for f_i and $\bar{f}_{j,i}$ as defined in equations (22) and (23). Fixed costs are not considered in equations (20) and (21) since they do not influence the choice of f_i which is defined by (22) and (23):

$$\frac{\partial(\mathbb{E}(\bar{P}r_{T_i}))}{\partial f_i} = g(f_i,\ \bar{f}_{j,i}) = 0 \qquad \forall\ i \tag{22}$$

$$\frac{\partial(\mathbb{E}(\bar{Pr}_{T_{j,i}}))}{\partial \bar{f}_{j,i}} = h(f_i,\ \bar{f}_{j,i}) = 0 \qquad \forall\ i, j \tag{23}$$

3 Expected Results

The Nash Equilibrium in the proposed model is expected to be different than the Bertrand model [2], where equilibrium price is the marginal cost. This is due to allowing for variation in the inherent preference and waiting times between TNCs. This variation gives the competitive advantage to the firm with the highest sum of the inherent preference and waiting time terms in equations (15) and (18) to set the equilibrium value of extra variable tariff above 0. We test the model for the presence of Nash Equilibria, solving the system of non-linear equations (22) and (23). Simulation is used to evaluate the impact of this model in realistic network scenarios.

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