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The limits of network effects: Modelling competition in ride hailing platforms

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Abstract

Hotel companies not owning a single bed, taxi companies not owning a single car, the worlds' most diverse store not owning a single till; in the 21st century we are witnessing a rapid transformation of our way of life, greatly driven by such digital platforms. Ride hailing services in particular have been quite present in our lives, disrupting how we think about transport. As a platform business these services benefit from network effects: their value increases according to their number of users. Due to the existence of network effects, these services are believed to benefit a lot from first mover advantage. However, no one has studied whether there are limits in the network effect for ride hailing services, something crucial to competition watchdogs when deciding if they should let a service like this into the city. The current literature presents extensive analysis and modelling of various graph based methods, looking at the apparition of "small-world" or "scale-free" phenomena, as well as some structural properties. Although very useful, these models are often very abstract and rarely lend themselves to empirical falsification. Here we study the limits of network effects in ride hailing platforms. Using agent based graphical models we find the sensitivity of riders and drivers to waiting and idle time to be decisive factors in the growth of these platforms. We validate our results using real ride hailing data from the New York City Taxi and Limousine Commission dataset. We find that our model can accurately capture the growth of ride hailing platforms both in terms of market-share and population. Finally, we explore alternative "worlds" where the tension between first mover advantage and increasing waiting or idle time is readily observable. This work is a first look into how empirical findings could be used to aid data driven regulation, ultimately allowing policy makers greater insights in their decision making process.

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Chapter 1

Introduction

Today, with our the ever-increasing degree of digitisation in cities, the market for ride-hailing platforms (RHP) has exploded [1]. In about a decade we have seen dozens of such companies (Uber, Lyft, Kapten, ViaVan, ...) grow to form a multi-billion dollar industry. This is not only a feature of developed markets. Indeed in many developing countries such as China (DiDi Chuxing), Iran (Snapp), Russia (Yandex.Taxi) etc, RHPs are an intricate part of everyday life.

Uber-style platforms typically benefit from some form of network effect which results in a rich-get-richer dynamic (Matthew effect) [2], also called preferential attachment [3]. This occurs when an increase in the number of users of a product or service, directly increases its value to existing and new users. For example, additional users riding with a RHP will mean a richer market for drivers which incentivises them to join the platform. With this increase in drivers, waiting times are reduced which in turn attracts additional riders to join the RHP.

However, intuition suggests that for businesses like Uber, there could be some inherent limit to how much they can grow due to this network effect. For example, for Uber passengers, the difference between a waiting time of 30s and 1min is not significant. Therefore, once Uber reaches a saturation such that waiting times are down to 1 minute, any growth in the number of drivers will only have a marginal effect on the number of riders, potentially downgrading the classical dynamics of preferential attachment, to a less potent version.

While extensive studies on network effects and how they induce exponential growth are abundant, the question of their limits is yet to be addressed. There has been work done to model ride-hailing platforms, but none go in detail to describe the fundamental underlying mechanic of their growths: how individuals make their joining decision.

In response to this gap in the literature, here we propose an agent based model that can simulate the network effects acting on various such platforms in a city. Crucially, our model captures the push and pull that users of a platform experience due to variances in waiting and idle time. We then investigate the limits of these network effects, as well as the applicability of our model using freely available ride-level data from New York City.

Our model, inspired by a model that replicates competitive dynamics observed within the immune response to cancer [4]¹, allows us to independently factor in 5 key parameters. These are: the agents' sensitivity to waiting time ($\mu_{waiting}$) and idle time (μ_{idle}); the portion of agents that are riders (usually $\pm 95\%$); the calculation of the price surging coefficient (η); and the delay between platform's entrances to market. The latter allows for studying the power of first movers' advantage.

This novel work brings with it multiple contributions. We are proposing here a simple model that captures micro level intuitions from the agents driving the exponential growths in the ride-hailing platforms: riders and drivers, and are able to reproduce macroscopic intuitions naturally. Taking New York City's ride-hailing market as a baseline, we are able to reproduce the market-share growths from Uber and its competitors in the city. From this point, we conduct a sensitivity anal-

¹In the case of the cancer dynamics, competition is for resources. While here, competition is for new users.

ysis based on the parameters that reflect the real-world situation in NYC. This analysis is akin to the investigations that policy makers could undertake. By analysing the impact of different delays in market entry for different platforms, they could make more informed decisions in their jurisdictions. Finally, as we are sourcing our model from immunology, this work may be able to shine a light on universal competitive dynamics that can be found both in ride-hailing platforms and the human body.

This work shines a much needed, data-driven light on competition between RHPs. The initial empirical validation of our model opens the door for competition authorities in cities to look to empirical research to guide their decision making regarding the introduction of RHPs in their jurisdictions.

Chapter 2

Background

2.1 What are network effects

A network effect (NE) is an economical or business term that describes a situation where the value of a product or service increases with its number of users [5]. Classical examples of such that have been studied extensively include the citation pattern of scientific papers [6], the World Wide Web (WWW), or even the collaboration graph of movie actors [7]. The term “Network Effect” is used because these observed phenomena result from certain dynamical properties that are intrinsic to some particular types of networks.

These examples naturally exhibit NEs. A scientific paper which has been cited thousands of times is present in a substantial amount of other papers, gaining more exposure and increasing its odds of being cited again. Similarly, a website that has a certain reputation and many frequent users is more likely to be shared, increasing its odds of being linked on another page. Finally, a famous actor will naturally be offered more important roles in upcoming movies and therefore will increase his number of co-stars.

In pop-culture, “The rich get richer” is often the term used to describe such apparently unlimited exponential growth. In the literature, one can often find the terms: “Matthew Effect” [8] from the biblical verse “*For to every one who has will more be given, and he will have abundance...*”, “Cumulative Advantage” [9] or more recently “Preferential Attachment” [7].

2.2 Local vs global network effects

The examples laid out in the previous section are all instances of *global* (or *direct*) NEs. Typically, networks that profit from a direct NE have a single type of node, and the addition of a new node directly increases the value of each user. For example, when the telephone was introduced to the public, each additional phone allowed each owner to call an additional person, increasing their individual value for the service [10].

A typical example of a global NE could be the indexing of a search engine such as Google. As far as we know, Google’s indexing grossly works by expanding its graph of known (indexed) websites by crawling through these [11]. What this means is that they go through their known websites in search for new links which they have yet to index. Naturally, having more indexed websites exponentially increases the number of discoverable links, and therefore introducing a global network effect.

Not all networks benefit directly from growth alone: those exceptions are called *local* (or *indirect*) NEs. Platforms that strongly profit from these are ride-sharing or ride-hailing platforms (RHP). If we model Uber as a network, it would be a bipartite network with two different types of nodes. Once the platform has a high number of rider nodes, the business becomes quite lucrative for drivers, increasing the number of driver nodes. This new increase in drivers cuts the waiting time for riders, which in turn increases the number of rider nodes.

Although not as obvious, local network effects are far from being the exception. Take any messaging app such as Facebook Messenger, WhatsApp or Snapchat. The overwhelming majority of their users are only aware of their own contacts, they only interact through the service with people they are directly connected to. In other words, if we were to draw an undirected graph of such a platform, each node would only be aware of its immediate neighbours - essentially creating minuscule local networks [12]. Agents have comparatively low degrees, and are unaware of the overall structure of the graph.

The case of Uber is an interesting one because it also represents a “second” layer of locality: although the increase in drivers is correlated in an increase in users, this is the case only in local geographically areas. RHPs benefit from these local effects, but this has yet to be rigorously studied. In addition to geography, there might also be waiting times that come into effect, which we will study in this paper. Although Uber is a global network, it consists of many smaller local clusters of bipartite graphs, within which we observe indirect NEs.

2.3 The implications for competition

Network effects have always had a considerable impact on financial markets. Historically, economists and competition watchdogs viewed NEs as a significant barrier to entry and protective of strong market positions. Now, more modern economic has recognised the various limits of NEs and negative consequences of platform growth [13]. Old literature suggested that networks exhibiting direct network effects (such as the telephone network) rapidly scaled to a monopoly. The widespread view was that once a particular platform reached a certain scale, it wasn’t profitable to build a competing company [14]. As a result, the former would have significant market power, and competition enforcers tended to share this view.

As the understanding of multi-sided platforms advanced, so did the economic literature on both direct and indirect network effects [15]. Rapidly, economists recognised that the existence of NEs didn’t necessarily ensure a strong first mover advantage: they could suffer from negative externalities just as much as positive ones. For example, as a search engine gains users it becomes attractive to advertisers, which are beneficial for the business. On the other hand, having more advertisers (or even users) has no effect on user demand [16]. In other cases, this impact might even be negative. Take paper or online newspapers, the increase in number of readers is correlated with the number of potential advertisers, but more advertising diminishes the value for the readers [17]. For social networks, which are an ever-expanding class of NE-prone platform, growth can even invite competition [18]. As the number of profiles gets large, the number of users who are trying to use the platform for disruptive or illegal activities also becomes problematic. This also naturally comes at a higher infrastructural, network and maintenance cost.

The explosion of digital platforms also brings its own set of problem for network effects. With social media, ride-hailing and dating platforms being free to use, there is no consumer “lock-in”: the cost of moving to a competing service is often close to none. Additionally, while they may have a preference, users are not exactly limited to using a single platform (e.g. always using Uber instead of Black Cabs). This concept is called “multi-homing” and has been investigated by Rochet & Tirole [15].

All things considered, profiting from a network effect is not the one single secret to a successful business. Platforms on a multi-sided market must capture as many positive externalities, while also mitigating the negative effects that naturally come with growth. Such examples would be Facebook, that all-the-while competing with the (at the time \approx 2004) giants Myspace and Friendster, enforced its strict policy for “real” profiles, requiring a valid college email addresses. It also rigorously enforced its terms of service, banning what it thought was obscene and nude content [19]. On the other hand at Myspace, news reports of minors who lied about their age and child sex predators who preyed on them caused public concern. Advertisers subsequently abandoned the platform and the site floundered [13].

With the development of online platforms benefiting from NE, some may seem to hold a monopoly. This seems to be the case in the mind of most people when they think about Uber, although in cities

like London or New York, the competition is considerable. On the other-hand, this competition might not exist in smaller cities such as Clermont Ferrand in France, leading to a real monopoly. Research has yet to determine the reason for this divide, and give a model for predicting when each situation is most likely to occur.

2.4 Graph-based models of network effects

At first, networks of complex topology have been explained using Erdős and Rényi’s (ER) random graph theory [20]. Their model starts by generating N vertices, and connects each pair of vertices with a probability p . From this setup, the probability that a randomly chosen vertex has k edges follows a Poisson distribution $P(k) = e^{-\lambda} \frac{\lambda^k}{k!}$, with parameter:

$$\lambda = N \binom{N-1}{k} p^k (1-p)^{N-1-k}$$

Unfortunately, this research dates back to 1960, where data on large networks was nonexistent. Due to this, the theory couldn’t be tested on real world data. Today, we have access to virtually unlimited data about all kinds of networks. This allows to empirically validate previously proposed models.

A more recent model proposed by Watts and Strogatz (WS) is the small-world model [21]. In this model, N vertices are aligned to form a $1-D$ lattice, each vertex connected to two nearest other ones. An additional edge is then drawn to any other vertex with probability p . Because this can spontaneously generate “shortcuts” between otherwise far-apart vertices, this process decreases the average distance between each of them, leading to a small-world phenomenon [7] (also commonly known as “6 degrees of separation” [22]).

A common point between both the ER and WS models is that the probability of finding a highly connected node decreases exponentially with k , i.e. vertices with high degree are virtually nonexistent. This conflicts with what we can observe in empirical data. Indeed, in (very) large networks, such highly connected vertices actually have a large chance of occurring, following a power-law tail. Barabási and Albert (BA) [7] explain that two generic aspects of real-world networks are missing in these two models.

First, both networks start with N vertices, and no new one are ever added. The models simply attach edges between them using two different methods. In contrast, real-world networks are open, they form by the constant addition of new vertices from their environment. New actors join the industry quite often; the WWW grows exponentially over time with the addition of new websites; and research papers are constantly being published.

Secondly, random networks assume a random and uniform probability for two vertices to be connected. In the real-world we commonly see what BA coin as “Preferential Attachment”. Newly published papers are much more likely to cite well known and peer-reviewed research rather than unknown works. This means that the probability of a new paper citing one that already has many citations (a higher degree node) is much higher than citing a paper with few citations (a low degree node). The variety of such existing examples illustrate that the way a new vertex links to existing ones is far from being uniform.

Barabási and Albert base their model on exactly these two features:

- Continuous growth (of the population size N),
- Preferential Attachment (of new nodes to high degree nodes).

Their network starts with a small number of vertices (m_0) and grows by the addition of a single vertex at each time step. New nodes are then connected by $m(\leq m_0)$ edges to m other (different) vertices. Preferential attachment is then implementing by saying that each new node has a probability Π to be linked to node i depending on the degree k_i of that vertex. That is:

$$\Pi(k_i) = \frac{k_i}{\sum_j k_j}$$

This network evolves into a scale-invariant state with the probability that a vertex has degree k follows a power-law distribution with exponent $\gamma_{model} = 2.9 \pm 0.1$.

From comparing these models, we can see that BA’s work related best to real-world networks. Thanks to this, we will take inspiration in his work to hopefully bring a new insight on NE profiting businesses and their limits.

2.5 Local network effect models

Current local NE models often focus on precise modelling of a complex network, by setting specific rules for individual clusters within them. Arun Sundararajan (AS) bases his model on the fact that individual vertices have no knowledge at all about the underlying structure of the network they are a part of [12]. The model is graph based and contains N fixed vertices which represent agents. Each agent is associated to a set G_i , the neighbour set of vertex i . This can be seen as the friends, or contacts of the agent. If $j \in G_i$, we can say that j is a neighbour of agent i . This creates an undirected graph of agents connected to their respective “close” acquaintances. A visualisation of such a neighbourhood can be seen in Figure 2.1. In addition, each vertex is initialised with an unchangeable parameter $\theta_i \in [0, 1]$ which influences what AS describes as its payoff value. At each time-step, agents make a binary decision a_i to adopt or not a new abstract network good. The decisions are influenced by their neighbours and modifies their reward, or payoff π_i :

$$\pi_i(a_i, a_{i-1}, G_i, \theta_i) = a_i[u(\sum_{j \in G_i} a_j), \theta_i] - c$$

where this payoff is dependent on a value function $u(x, \theta_i)$ that quantifies how many neighbours have adopted the good.

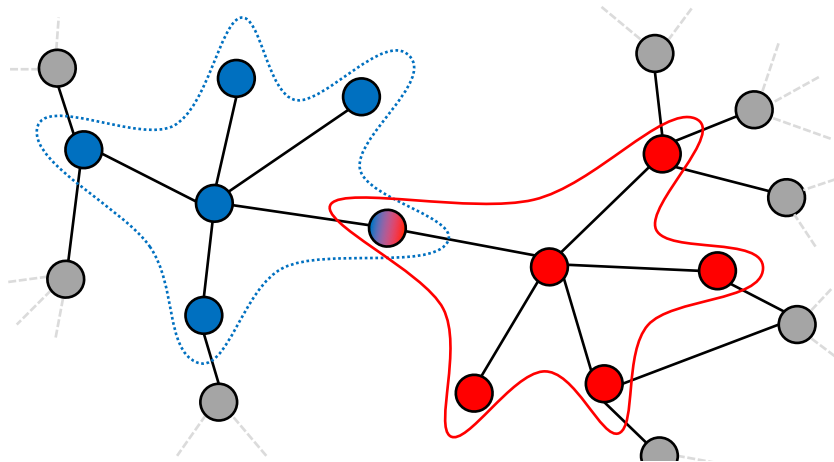


Figure 2.1: Two agents and their neighbourhood clusters G_{blue} and G_{red}

AS’s model successfully represents the fact that if your close family, friends or co-workers adopt something, you will to some extent be incentivised to do the same. His goal was to identify the overall adoption trend of the network, and how local adoption can influence the global result, taking a game theory-like approach.

One notable feature that AS describes in the “future work” section of his paper is that agents could adopt one of many incompatible goods, in a dynamical/evolutionary way. In our model we propose just that, where users are able to join one of n RHPs based on a localised measure of the city’s topology.

2.6 Lack of empirical validation

Throughout each of the models that we’ve seen this far, there has been no empirical work on competition and ride hailing platforms. Furthermore, BA verified their model on networks of at

most a few hundred-thousand vertices, and the same goes for AS and WS [7, 21, 12]. While this can seem like a substantial size, real world networks now easily go above tens of millions of nodes with a good amount of this data now being collected on astronomical scale.

Obviously, most of this real-world data is not made public, but some have used public datasets of millions of records to build alternative simulations.

R. Tachet et al. have built a “shareability” model of rides and tested their findings on empirical data from metropolises ranging from San Francisco, London and Singapore [3]. Their argument is that our increasingly connected urban areas drastically increase the number of unique trips (made in a personal car) that are similar enough to be merged into one car-pooling, all the while keeping the time delay to a minimum. This would reduce congestion as well as societal, environmental and economical cost in a city.

In their model, two trips are defined to be shareable if they would incur a sharing delay of no more than Δ minutes, relative to a single ride. The authors of the paper suggest a formula for the sharability (S) of rides for any given city:

$$S = 1 - \frac{1}{2L^3}(1 - e^{-L})(1 - (1 + 2L)e^{-2L}) \quad \text{with} \quad L = \lambda\Delta^3 \frac{v^2(C)}{|\Omega(C)|}$$

with v the average traffic velocity of the city, λ the average rate at which taxi rides are available, and Ω the city’s area.

What they were able to demonstrate was that in all the metropolises/megalopolises that they studied, sharability rapidly saturated to near 100% as both the average of trips/h or L grew.

2.7 Looking towards biological processes

Preferential attachment is famously seen in a variety of different domains [7]. Interestingly these domains are incredibly different from one-another. From author citation networks, the world-wide-web to the collaboration graph of movie actors or even the human nervous system.

Biological processes are particularly relevant to our case as many of them include two sided feedback loops and vary wildly in complexity. Some examples include the HPA axis¹, that is understood to control reactions to stress and regulate many body processes [23] or more simply the blood sugar regulation process, in which insulin and glucagon raise and lower these levels in a negative feedback loop [24].

A few of these biological processes are described in rigorous mathematical models. In one case, a minimal model correctly predicts the increase in gene expression variability after mutating a particular biological signalling pathway [25]. In another case, modelling is used to study cancer regulation and looks at various elements involved in gene regulation: miR-17-92², E2F³ and Myc⁴ [26]. Although these all involve feedback loops from multiple agent types, it is not immediately clear how they would be applied to ride-hailing platform markets, unsurprisingly.

However, one that would be of particular interest would, in theory, directly replicate competitive dynamics between cells inside the human body with two types of agents. This is done by one group that models the immune response to cancer [4]. They present a mathematical model of cancer-immune competition under immunotherapy. Through the direct modelling of the cell populations they are able to successfully reproduce emergent behaviour of cancer, in which the immune system “guides” the cancer to continuously express new cell types that are unknown to it.

¹The hypothalamic–pituitary–adrenal axis, is a complex set of direct influences and feedback interactions among three components: the hypothalamus, the pituitary gland and the adrenal glands.

²An element of the microRNA family that regulates gene expression.

³A group of genes that are involved in the cell cycle regulation and synthesis of DNA in mammalian cells.

⁴A regulator that increases the expression of genes that contribute to the formation of cancer (through cell proliferation).

Chapter 3

The Model

3.1 The agent population model

Ride-hailing platforms (RHPs) are composed of two types of agents: the riders and the drivers. Each agent has a specific set of criteria that they look for when choosing which platform to join. By considering only a handful of these criteria, our model allows us to analyse some key emergent properties of RHPs.

The dynamics of the two populations are modelled through a system of structured equations where R_{rider} and R_{driver} model the net growth rates of rider and driver populations. We will look into each separately.

We use these rate equations in a custom graph-based model. In particular the model starts out with N -many principal nodes which represent the RHPs (e.g. Uber and Lyft). From there, nodes (agents) are generated and become one of two types: riders and drivers. Figure 3.1 contains an illustrative example: competition between Uber and Lyft.

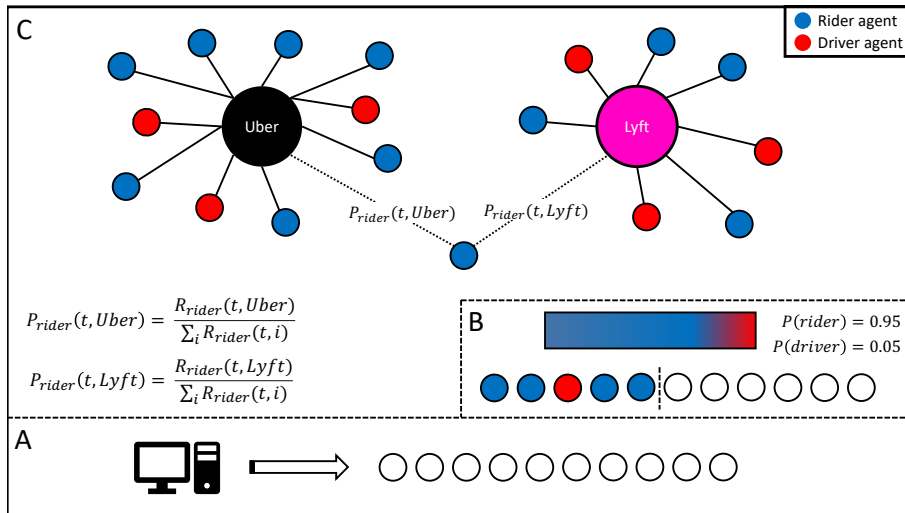


Figure 3.1: The graph based simulation in a two platform market. $P_{rider}(t, u)$ is the probability that at time t a rider agent will join platform u . **A**: A variable number of agents are generated at each time-step. **B**: 95% of them become riders, 5% are drivers. **C**: Each agent joins a platform with probabilities derived from underlying rate equations.

The drawing of edges from new agents to platforms is dictated by the rate equations, $R_{rider}(t, u_i)$ and $R_{driver}(t, u_i)$. As such these equations directly describe the rate of platform growth, in terms of riders and drivers.

3.1.1 Building the rider agent rate equation

$$R_{rider}(t, u_i) := \kappa_{driver}(t, u_i) - \mu_{waiting}\rho_{rider}(t, u_i) - \eta\rho_{rider}(t, u_i) \quad (3.1)$$

$$\rho_A(t, u) = \frac{f_A(t, u)}{f_{rider}(t, u) + f_{driver}(t, u)} \quad \kappa_A(t, u_i) = \frac{\omega_A(t, u_i)}{\sum_{j \neq i}^U \omega_A(t, u_j)} \quad A \in \{rider, driver\} \quad (3.2)$$

When a rider considers which RHP to join, they mainly consider a combination of three criteria, which are defined in equations (3.1) and (3.2). These are:

1. the platform’s popularity,
2. the sensitivity of a rider to the average waiting time experienced by platform users,
3. the average ride price within a platform.

Riders typically have an inherent sensitivity to waiting time. Ask them to wait too long for a ride, and they are likely to check another app, or get to their destination differently. This is modelled through the $\mu_{waiting}$ parameter, and here we assume that this can be modelled as a single parameter for each platform (i.e. $\mu_{waiting}$ is the average sensitivity of users from that platform). Note that this parameter is not the waiting time itself, but the sensitivity of platform riders to waiting time. Almost more importantly, a RHP that has a higher number of riders w.r.t. their drivers will necessarily make their riders wait longer for each ride. This is modelled by the $\rho_{rider}(t, u_i)$ and is completely analogous to over-crowding.

Next, users of RHPs are naturally attracted by more “well-known” platforms. It has been widely studied and it is thought that these platforms benefit from a “rich get richer” effect, also known as “preferential attachment” which allows them to grow exponentially [7]. For many years, if you thought of ordering a taxi from your smart-phone, odds were you would think of Uber first. In our model, we specifically take into account: the riders of RHPs are attracted to those platforms with the highest share of driver agents. This way, if a platform is currently booming amongst drivers, this would mean a relatively high driver-per-rider ratio, thus being attractive to riders. This is all taken into account in the $\kappa_{driver}(t, u_i)$ term. Note that the way this function is being computed is completely identical to the probability of a new edge being attached to a particular node in the Barabási and Albert (BA) model [7]. This has been studied in detail and has been shown to be a key element in exhibiting preferential attachment.

Last and definitely not least, the price of each ride is critical. Everywhere riders are unanimously attracted by low prices. This is represented in our model by $\eta\rho_{rider}(t, u_i)$. This term can be seen as positively correlated to the average platform ride price.

Note that all these terms share an equal weighting in the model. This is a simplifying assumption as the underlying relationship might contain other weightings or even non-linearities. Further, more complex models could segment rider and driver populations based on their price elasticity among a number of other metrics. As a first model, we choose not to make further assumptions about the underlying dynamics.

3.1.2 Building the driver agent rate equation

$$R_{driver}(t, u_i) := \kappa_{rider}(t, u_i) - \mu_{idle}\rho_{driver}(t, u_i) + \eta\rho_{rider}(t, u_i) \quad (3.3)$$

Quite similarly to riders, when a driver chooses which RHP to work with, they consider a combination of criteria which can define how attractive the platform is to drivers.

Drivers, other factors being equal, will always choose to serve the ride which minimises their idle time, modelled through μ_{idle} . This is considered to be the average sensitivity to idle time throughout a platform’s drivers, a factor negatively affected by over-crowding, and applicable to all drivers through the multiplicative term $\rho_{driver}(t, u_i)$.

The next important factor that boosts a platform's attractiveness is having a substantial pool of active riders. This is a positive effect and is represented by the $\kappa_{rider}(t, u_i)$ term. It describes what share of all riders the platform is able to offer the driver.

Lastly, and almost identically to the rider case, $\eta\rho_{rider}(t, u_i)$ involves the price of each ride a driver is able to charge. While this was a negative for riders, who aim to minimise cost, here drivers aim to maximise this same positive amount.

Rates as joining probabilities

R_{rider} and R_{driver} , intuitively represent how attractive a particular platform is to an agent at a specific time. In a monopoly, this is essentially a measure of attractiveness, and defines how likely it is that a newly generated agent joins the platform. That is if 10 agents are being generated and $R_A = 0.8$, then 8 new agents will join the platform. This implicitly means that in a monopoly, not all generated agents will have joined a platform. In a competitive setting, the rates can be used to construct joining probabilities. We assume that there is a total pull of agents in the market (corresponding to $\sum_j R_A(t, u_j)$), so that the probability of joining platform i is equal to its share of the total pull that their rate represents ($\frac{R_A(t, u_i)}{\sum_j R_A(t, u_j)}$). All together, this means that if a second platform joins the market during the simulation, there will be an abrupt change in the way the simulation allocates agents. The consequences of this will be apparent and are discussed in later sections.

3.1.3 Reproduction of known behaviour

Ride-hailing platforms have particularly intuitive behaviours that our model is able to reproduce. First we will see that the exponential growth, typical of businesses that benefit from network effects, is well reproduced here (figure 3.2). Then we will see how increasing the sensitivity to idle and waiting time reduces the total population of their respectively affected agents (i.e. high waiting time sensitivity in a platform implies a lower population of riders) (figure 3.3). Finally an increase in ride price should have a noticeable effect on the number of rider and driver agents, as this is negative for the former and positive for the latter (figure 3.4).

Exponential Growth

It has been well documented that exponential growth, led by network effects, arises when two conditions are met: the population N increases at every time step, and the probability that a specific node in the network grows is proportional to that node's degree. Specifically, the probability that a new edge is drawn on node i should be:

$$\Pi(i) = \frac{k_i}{\sum_{j \neq i} k_j} \quad \text{where } \text{degree}(i) = k_i$$

Our simulation reproduces the first aspect naturally, with new agents being added to the environment at each time-step. Instead of modelling an entire graph, we consider the market-share of each platform to be proportional to the degrees of a graph's node. Explicitly, one could model each platform as a graph's cluster. The centroids would be the platforms, and each edge connecting it to a unique agent. The market-share of each platform is thus directly proportional to the degree of the centroid over the total number of edges in the graph.

Figure 3.2 B shows the population growth of our agents when their decision to join a platform is led solely by the platform's overall market-share, compared to figure 3.2 A where this decision is based on the rate questions from our model. In these plots we can see that the population of agents in platform 1 is identical throughout. A slight difference arises for platform 2, where in our model (A and C) its agents grow much faster than in the Barabási-like model. This growth difference is due to the fact that in our model, riders (resp. drivers) are attracted by the driver (resp. rider) market-share (as apparent in equations 3.1) and 3.3. On the other hand in the Barabási-like model all agents are attracted by the same quantity, the general platform market-share.

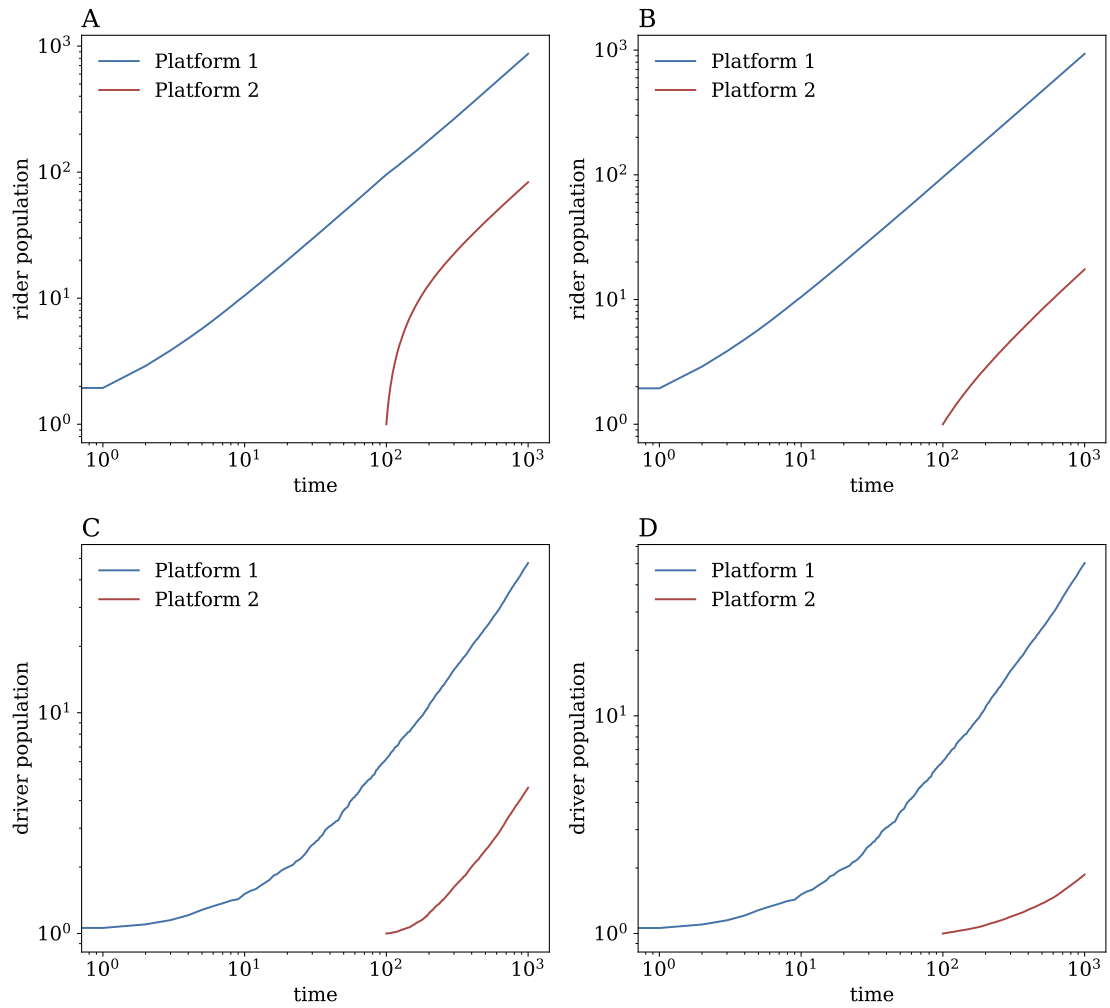


Figure 3.2: Agent population growth in a two platform competitive environment. Platform 2 starts with a 100 time-step delay. All parameters are set to 0 throughout. **A**: Rider population growth with our model. **B**: Rider population growth with Barabási like model. **C**: Driver population growth with our model. **D**: Driver population growth with Barabási like model.

Sensitivity to waiting and idle time

Figures 3.3 **A**, **B** shows how varying $\mu_{waiting}$ and μ_{idle} impacts the total number of riders that join a single RHP. As expected, the sensitivity to waiting time is inversely correlated to the final population, and this is also true for drivers and their sensitivity to idle time. Both of these parameters negatively impact the effective attractiveness of the platform. Intuitively, this models what happens as agents grow more and more impatient; they are less likely to accept a high waiting/idle time, this makes them less likely to join the platform and thus reduces the final population of that platform.

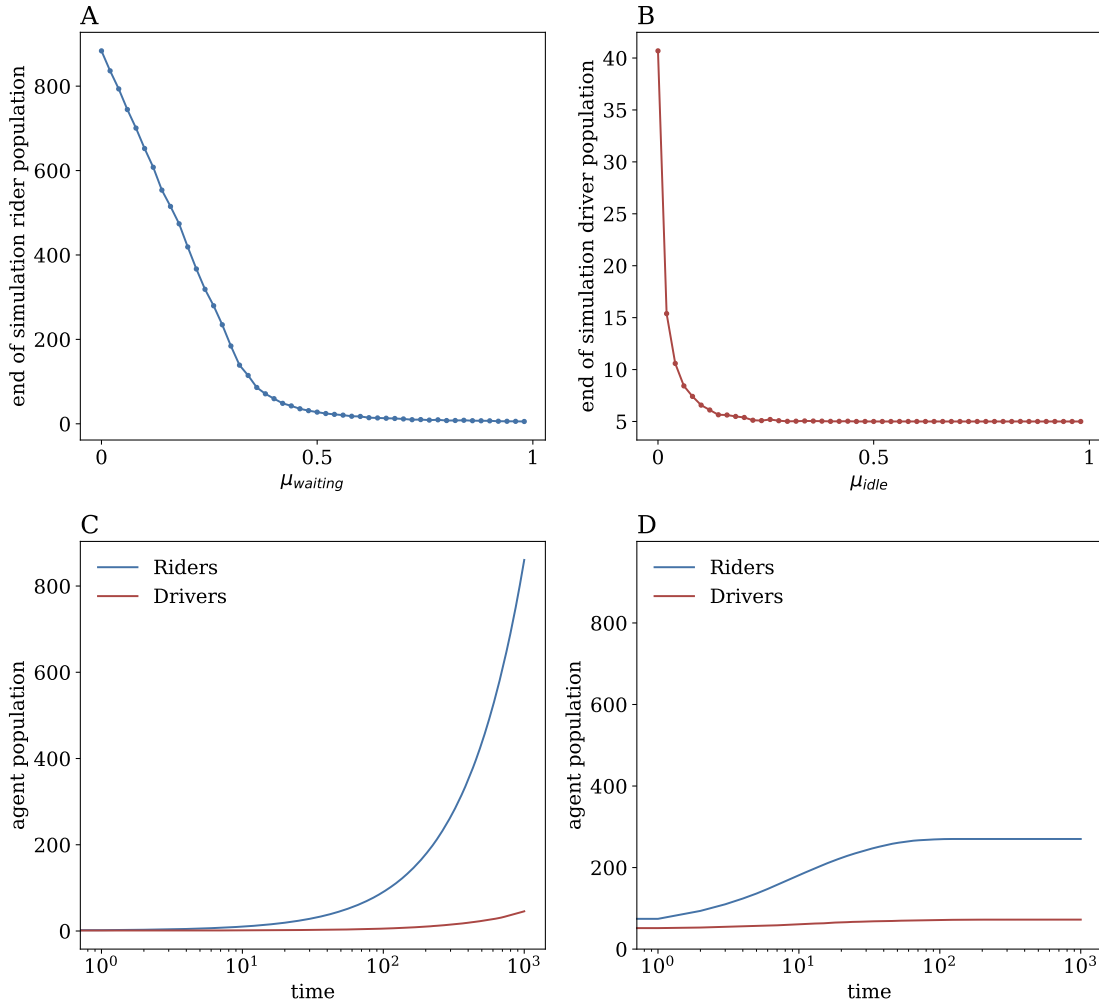


Figure 3.3: The effects of $\mu_{waiting}$ and μ_{idle} on the agent populations as well as two extreme situations of $\mu_{waiting}$ (all in a monopoly). **A**: Rider population at the end of a simulation with $\mu_{idle} = 0.5$. **B**: Driver population at the end of a simulation with $\mu_{waiting} = 0.5$. **C**: The agent populations during a simulation with $\mu_{waiting} = 0.01$ and $\mu_{idle} = 0.5$. **D**: The agent populations during a simulation with $\mu_{waiting} = 0.99$ and $\mu_{idle} = 0.5$.

Figures 3.3 **C**, **D** illustrates the average population growth of both the rider and driver population for $\mu_{idle} = \frac{1}{2}$ and $\mu_{waiting} \in \{0.01, 0.99\}$. The impact of rider waiting-time sensitivity is clear. With high sensitivity, the growth completely disappears and dies out after only 100 time-steps. On top of this, the value is so high that it prevents almost any users from joining the platform at all. This peculiar, seemingly impossible effect that occurs when $\mu_{waiting}$ is high will be touched upon further in section 4.2.3.

Sensitivity to ride pricing

Figure 3.4 illustrates the behaviour of the total rider and driver population as we change η , the factor positively correlated with average platform ride price. The rapid decrease in rider population does validate our first intuition, the riders are less attracted by the platform as the average ride price increases. The way the driver population evolves is much more intriguing. From the plot, we can see that the increase in price is initially favourable for the driver population, rising rapidly, but at about $\eta > 0.4$, the population declines. At first glance this seems counter intuitive, higher prices should be more attractive to drivers and shouldn't lower their population. What we are seeing here is actually that once the price goes past a certain limit, the rider population suffers so greatly, that the loss in customers out-weights the gain from each individual ride price. This indicates an “optimal” price which maximises the driver population.

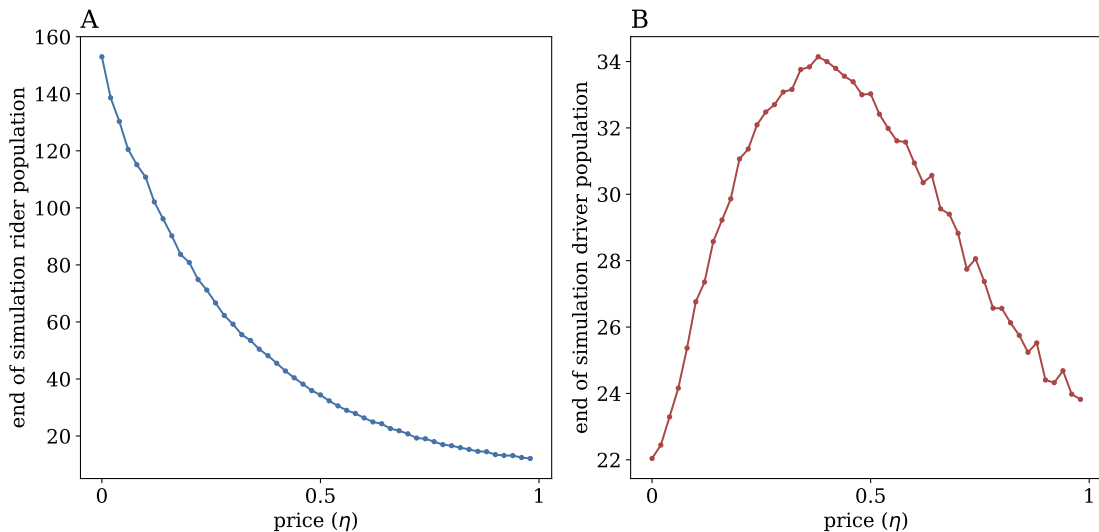


Figure 3.4: The effect of η on the agent populations (with $\mu_{waiting} = 0.5$ and $\mu_{idle} = 0.5$). **A**: Constant decline of the end-simulation rider population due to increased prices. **B**: The end-simulation driver population peaks at an “optimal” ride-pricing value before declining rapidly.

3.2 The links between ride-hailing and biology

Our model as described above, takes its roots from a population model of competition between cancer and T-cells within the human immune response. Here we go into more detail about the reasoning behind this peculiar origin.

Riders and drivers in RHP benefit from a two sided feedback loop which takes into account competition for resources. This kind of phenomenon has been studied extensively, and specifically in the biological literature. One such model comes from immunology and studies the population growth rates coming from the interactions between cancer and T-cells.¹

3.2.1 The original model

Here we will dive into the details of the original model [4], what they were modelling and what each term represents in immunological terms.

Consider a population of cancer cells structured by $u \in U \subset \mathbb{R}^+$ that represent their antigenic expressions, and a population of activated T cells structured by $v \in V \in U$ that represent those antigens that T cells can effectively attack.

¹We leave to the reader any philosophical considerations about comparing the operation of a RHP to the dynamics of cancer.

The local densities of cancer cells and T cells are modelled by the functions $f_C(t, u) \geq 0$ and $f_I(t, v) \geq 0$. The related total densities are:

$$\rho_C(t) = \int_U f_C(t, u) du \quad \rho_I(t) = \int_V f_I(t, v) dv$$

The model aims to simulate the growth of both cells using therapeutic agents boosting proliferation and immune memory: $c_P(t) \geq 0$ and $c_M(t) \geq 0$ respectively. In a sense, these two aspects account for T-cell population and effectiveness respectively.

Cancer cells proliferate, net of apoptosis² with rate $\kappa_C > 0$. This is their “natural” growth rate. Furthermore since cellular proliferation is hampered by the competition for resources, they assume that interactions lead to cancer death with rate $\mu_C > 0$ ³.

Next T-cells undergo rapid clonal expansion which is accounted for by including binary interactions between cancer cells of trait u and activated T-cells with trait v : $\eta_{\theta_E}(|u - v|) > 0, \eta_{\theta_E}(\cdot) \leq 0$. Again due to limited resources, T-cells die on average according to a rate $\mu_I > 0$.

To model the effects of T-cells killing cancer cells, a second binary interaction is described by $\eta_{\theta_I}(|u - v|) > 0, \eta_{\theta_I}(\cdot) \leq 0$.

Again the proliferation rate of immune T-cells is modelled by $\kappa_P > 0$, and the actions of therapeutic agents that boost immune memory is modelled through a reduction in death rate related to homeostatic regulation⁴ by parameter $\mu_M > 0$.

The dynamics of the two cell populations are described by the follow set of equations, where R_C and R_I model the net proliferation rates of cancer cells and T cells respectively:

$$R_C(t, u) := (\kappa_C - \mu_C \rho_C(t)) - \int_V \eta_{\theta_I}(|u - v|) f_I(t, v) dv \quad (3.4)$$

$$R_I(t, v) := \left[\int_U \eta_{\theta_E}(|u - v|) f_C(t, u) du + \kappa_P c_P(t) \right] - \frac{\mu_I}{1 + \mu_M c_M(t)} \rho_I(t) \quad (3.5)$$

These two rate equations are the progenitors of the rate equations described in our model described in sections 3.1.1 and 3.1.2 (equations 3.1 and 3.3).

3.2.2 Modelling RHP competition using ideas from immunology

There are many direct parallels between the resulting dynamics that dictates how riders and drivers behave within the world of RHPs, and how T-cells and cancer cells behave within our bodies.

The most important being competition for resources. Just as cells compete with themselves for the body’s resources, riders compete for a valuable resource: the driver which will take them from their location, to their destination in the least amount of time. On the flip side, drivers also compete with each-other to serve the most customers, thus increasing their revenues. Both of these resources, interestingly being the agents themselves, are indeed finite and variable. Fundamentally, both biological cells and RHP users compete amongst themselves for a limited shared resource, leading to similar dynamics.

Another point of similarity is over-crowding, and it is a direct consequence from the competition for resources. As the density of a single cell-type increases, this also hinders their reproduction and is therefore self-limiting (in a situation with equal resources). This is analogous to a RHP that sees its number of riders explode, while its drivers do not. Eventually, each individual rider will have such a poor experience, that it will lead to slower growth [and identically for a growing number of drivers, with a constant number of riders].

²i.e. taking total death rate into account.

³This death is directly related to the waiting / idle time what we have considered in our model.

⁴This is regulation due to competition for resources required for the cells to remain alive.

While these comparisons may seem to be direct, there does seem to be subtleties. In particular, the death-rate of cells and the way that this factor is increased through over-crowding is known/can be measured empirically in a lab. Importantly, all cells of the same type can be assumed to behave identical. For ride-hailing platforms, this is not true. Each individual agent is unique, and while effects can be measured on the population, it is hard to say anything specific of individuals. An assumption that is necessarily made here is the homogeneity of these rider/driver agents, which must be kept in mind.

3.2.3 Modifications of the original model

As our model is treating an entirely different domain, some modifications of the original model are necessary, while keeping the structure of the model the same, hence preserving the strikingly similar underlying structure between the two domains.

This first modification to be made was altering the way each agent is understood to grow. The basic cell proliferation rates can be considered constant, and this is simply not the case for a ride-hailing platform. Its attractiveness is variable, and thus we have replaced the constants κ with functions $\kappa(t, u)$ to reflect this variable growth. These take into consideration the time (t) and the specific platform (u) in order to give a positive growth rate element, dependent on the RHPs' market-share, replicating preferential attachment.

The next change was regarding the way cell death was amplified due to over-crowding, $\rho_A(t)$. This was originally defined as $\rho_A(t) = \int_U f_A(t, u) du$ $A \in \{C, I\}$, the density of cell type A . In our model, we consider different RHPs, whereas in the original model, they considered different antigenic expressions of a cancer or T-cell. Our solution was to consider the proportion of agents which are riders (resp. drivers) as this indicator. A high value would translate to over-crowding of riders (resp. drivers), which would amplify the negative rate term.

Finally a number of extra parameters exist in the cell population model, and while we do have parallels for them, we choose not to include them in this work. One term that appears is $c_P(t)$ in equation 3.4. This multiplicative term can be understood to represent the economical incentives (or lack-thereof) that influence the positive joining factors of driver agents. The main other one is denominator of $\frac{\mu_I}{1 + \mu_M c_M(t)}$. This serves to control the death-rate of immune cells. For our purposes, μ_M is understood to be the reduction in platform attractiveness for drivers due to driver attrition; and $c_M(t)$ corresponds to the effects of external mitigation to this attrition⁵. While these parameters would bring additional realism and we find them interesting, they are somewhat orthogonal to our research question of interest, namely the study of the limits of network effects in modelling competition.

3.2.4 The limits of this comparison

This inter-domain link is not perfect. The main issue being that in reality T-cells kill cancer cells, removing them completely from the population. In the RHP case, this comparison is obviously non-existent⁶. Whilst some agents might negatively affect others, pushing them away from a certain platform at time t , that agent does theoretically have the capability of returning to this platform at a later time $t_1 > t$. Note that the current model does not account for this.

Another smaller point is that the model made extensive use of the population function $f(\cdot)$ and its density $\rho(\cdot)$ by considering the “area” of the cells’ possible antigenic expressions. In our case, the analogous space would be the different platforms that are being considered. This is a problem because while the original paper considered 400 antigenic expressions, we would only ever consider (at most!) a handful of RHPs, never going past the dozens as most RHP markets are oligopolies [27]⁷. This led to open ended terms in the original model.

⁵e.g. a good healthcare plan for drivers offered by a specific platform.

⁶Hopefully.

⁷Implied by the existence of a limit in number of drivers for any particular ride-hailing market.

Chapter 4

Results

4.1 Reproducing real-world data

4.1.1 The NYC TLC dataset

In order to empirically validate our model, we reproduce the market-share values and growths of major real-world RHPs competing in the same environment. To do this, we use the New York City’s ride-hailing and taxi rides dataset provided by the Taxi and Limousine Commission [28]. This dataset contains more than 780 million completed rides dated from January 2015 to December 2019 and was made available thanks to a freedom of information act request.

From these we extract market-share values for Uber as well as Lyft, Via and Juno (that we classify as competitors) and use this as ground-truth values for the benchmarking of our simulations. Detailed information regarding our data sanitation procedure can be found in section 6.2.

4.1.2 Simulation results

To generate a model that corresponds to the real-world data, we only consider the parameters $\vec{\mu}_{waiting}$ and $\vec{\mu}_{idle}$, setting the price parameter $\vec{\eta}$ to 0 as most ride hailing platforms tend to offer similar prices [29]. Using a constrained grid search on the parameter space, we then find the optimal model, which best replicates the market-share dynamics observed over the past 5 years in NYC. The optimal model is defined as one which minimises the RMSE between the model prediction and observed empirical values. The details of what parameters were tested, and the methods used can be found in section 6.1.4.

Figure 4.1 illustrates the ground-truth data obtained from the TLC dataset as markers (triangles: Uber, cross: competitors). The generated market-shares using our simulation are the solid of corresponding colour (blue: Uber, orange: competitors). Note that the simulation is fitted only on 70% of the available data (before the dotted red line). The dashed line, marked as “Untapped”, corresponds to the fraction of generated agents that chose to not join Uber at the time where it was the only available platform, between January and April 2015.

The “bump” that can be seen at the early stage of the simulation is a consequence of how we chose to model monopolies differently from multi-platform scenarios. In a monopoly, agents join the unique platform w.r.t. the rate equations. This means that if the growth rate of a platform is < 1 , some agents are essentially choosing to join no platform at all. This changes suddenly as a new platform enters the market, and now all generated agents must join a platform. We recognise this as one of the limitations of our model, and will discuss this further in section 5.2. Nonetheless, given that the fit was performed on only 70% of the data, this captures the approximate intuition that was aimed for and is overall a good result.

To show how our model is able to fit long-term data, we also attempted to score each generation with the entire dataset. Upon doing so, the optimal parameters were independently found to be identical to those previously found, suggesting that market dynamics had already converged to

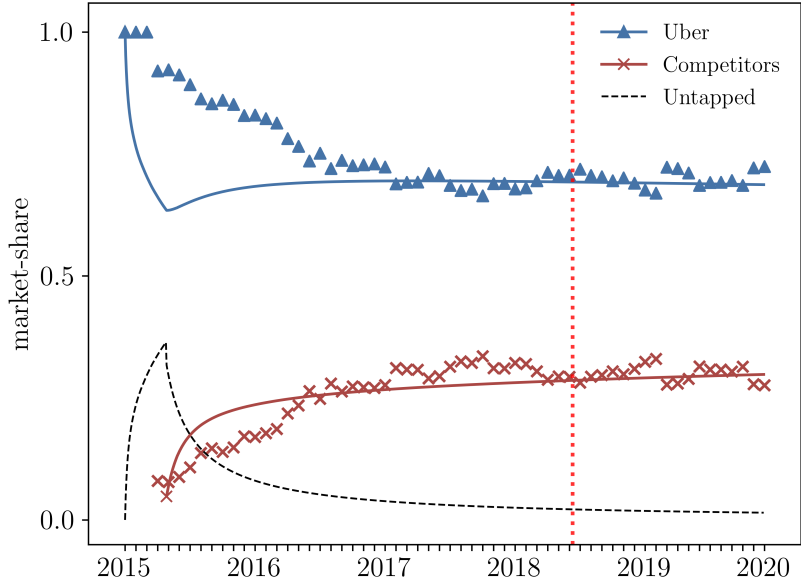


Figure 4.1: Optimal model fit on the first 70% of the NYC TLC dataset. The parameters are $\vec{\mu}_{waiting} = (0.25, 0.05)$ and $\vec{\mu}_{idle} = (0.9, 0.2)$. The model was fit with the RMSE on values to the left of the red dotted line. The black dashed line represents the untapped market, agents which chose to not join Uber whilst the market was in a monopoly (Jan-15 to Apr-15).

Platform	Parameter	70% fit	100% fit
Uber	$\mu_{waiting}$	0.25	0.25
	μ_{idle}	0.9	0.9
competitors	$\mu_{waiting}$	0.05	0.05
	μ_{idle}	0.2	0.2

Table 4.1: Optimal parameters found by the model after having fit on 70% and 100% of the data.

a steady state after 70% of the observation period. This further validates our initial modelling assumption that different platforms can be modelled by considering only average platform level parameter values such as average waiting time sensitivity of riders.

Detailed explanations of the simulation structure can be found in section 6.1.4

RMSE Evaluation

Table 4.1 describes the parameters found after fitting the model on 70% of the data and 100% of the data. In the above we have used the RMSE metric between each generated curve and the corresponding platforms' original data. For these specific fits, Uber had "training" and "testing"¹ scores of 0.1072 and 0.0904, and the competitors had scores of 0.0565 and 0.0498.

4.2 Sensitivity Analysis

From the previous results, it would be natural to conclude that a strong first-mover advantage exists in our simulations as in the real world. In this section, we will investigate the robustness of this phenomenon, and discover under which conditions it breaks / arises.

Throughout we will compare the end of simulation market-share values of two RHPs, u_1 and u_2 . In each simulation, we fix three of the four parameters that make up the platforms ($\vec{\mu}_{waiting}$ and $\vec{\mu}_{idle}$) and analyse the effect of varying the fourth as well as the delay after which the 2nd platform

¹Where "training" refers to the RMSE on the first 70% of the data, and "testing" to the RMSE on the whole.

is introduced to the market.

Note that throughout we will use the $\vec{\mu}$ vectors to represent the sensitivity to waiting and idle times of each platform, where the i^{th} entry corresponds to u_i .

4.2.1 Sensitivity analysis on real-world fitted model

Let us begin by observing the impact that changing agents' sensitivities to both waiting and idle time from a real-world fit has on the competitiveness of the platforms.

In these simulations we will start with a set of parameters:

$$\vec{\mu}_{\text{waiting}} = \begin{pmatrix} \mu_{\text{waiting}}^1 \\ \mu_{\text{waiting}}^2 \end{pmatrix} \quad \vec{\mu}_{\text{idle}} = \begin{pmatrix} \mu_{\text{idle}}^1 \\ \mu_{\text{idle}}^2 \end{pmatrix} \quad \vec{\eta} = \begin{pmatrix} 0 \\ 0 \end{pmatrix} \quad \text{with } \mu_{\text{waiting/idle}}^i \in [0, 1]$$

From these, we will choose one to be variable, and will also vary the delay after which platform 2 (u_2) enters the market (w.r.t. platform 1, u_1). This will give us a heat-map of values where the heat represents the market-share advantage (or disadvantage!) of u_1 . For this real-world application, we will let u_1 be Uber and u_2 be its collective competitors as in figure 4.1.

In this section we will take the parameters that mirror the real-world situation in New York City (as per section 4.1.2). That is, we will set the values from table 4.1. From the data, we also know that Uber's competitor entered the market at the equivalent of the 65th time-step in our simulation. To investigate on the sensitivity of each of these variables, we will generate four heat-maps. The X will represent one of the four above parameters, and the Y will always be the competitor's market-entry time.

Figure 4.2 shows this analysis. The dotted lines in each plot correspond to the real-world values of the corresponding variables. As an example, in figure 4.2 **A**, $Y = 65$ corresponds to the real time at which Uber's competitors come into market, and $X = 0.25$ corresponds to Uber's real μ_{waiting} (as found by our model). The heat in red shows areas where Uber comes out ahead in terms of market-share, and those in blue correspond to situation where its competitors come out ahead.

The first thing to notice here is how each of these figures contain a boundary around which healthy competition, defined as low differences in market shares, occurs. Furthermore, each intersection of the dashed lines (which correspond to the situation that reproduces the NYC market) is located almost exactly on this boundary. There are likely a number of basic economic reasons for this, such as supply and demand pricing that are beyond the remit of this research. However, this feature is more visible in figures 4.2 **A** and **C** due to the abundance of rider agents v.s. driver agents. It also tells us that if the riders of Uber had a slightly higher sensitivity to waiting time, μ_{waiting} , its competitors would rapidly dominate the market.

Figure 4.2 **C** tells the story of Uber's competitors. As before we can also see a boundary on which competition is possible, although more difficult. Where previously we could see the market being split evenly, here Uber is always at an advantage. All we can say is that if the competitors had joined the market earlier, they would have an increasing foothold in the NYC market.

Finally, in figures 4.2 **B** and **D** we can most clearly see the effect of the first-mover advantage. While most of the plot sets Uber as an inevitable winner (regardless of its competitors sensitivity to idle time), it is clear how punitive a late market entry is. Depending on drivers alone, the only way to reach a non-monopoly is for all platforms to start almost at the same point in time.

4.2.2 Sensitivity to waiting and idle times

Now that we have analysed a real-world case, let us observe what happens in some more radically different versions of this market: considering two nameless platforms with arbitrarily low valued parameters. Instead of fixing values based on an optimal fit as previously, we will now fix three parameters to a value $k \in \{0.1, 0.2\bar{3}\}$ and vary the fourth. Again the delay at which our second platform joins the market will always be variable. As such, our first intuition might hint towards

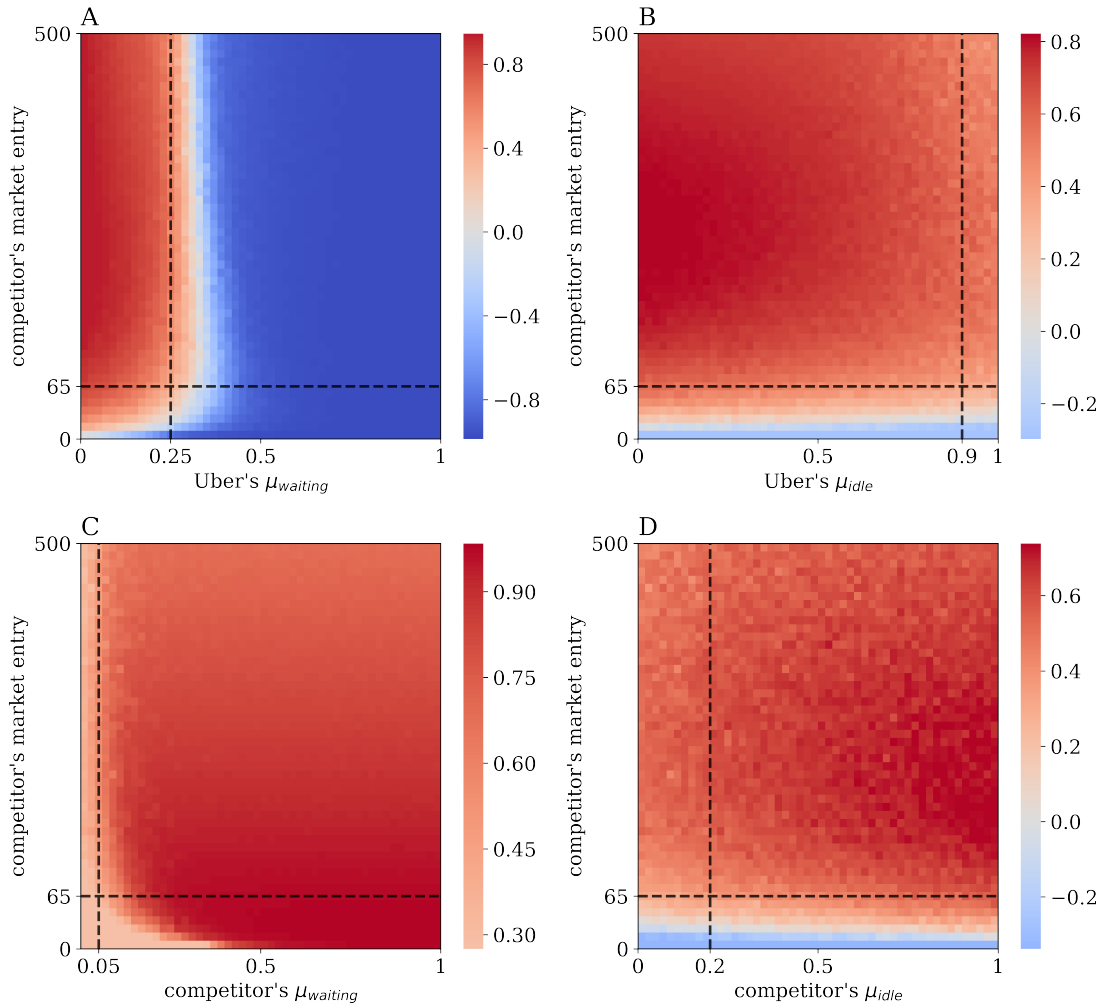


Figure 4.2: Difference in market-share $\kappa(\text{Uber}) - \kappa(\text{competitor})$ where three of the four μ parameters are fixed according to the best optimal fit on empirical data. This figure demonstrates the sensitivity of the final market shares to Uber's μ_{waiting} (**A**), Uber's μ_{idle} (**B**), the competitor's μ_{waiting} (**C**), the competitor's μ_{idle} (**D**). All remaining values are fixed according to their optimal values by the model (fig. 4.1), and the dashed black line represents the variable's optimal value.

the fact that the longer this delay, the lower chances for u_2 to gain any users at all.

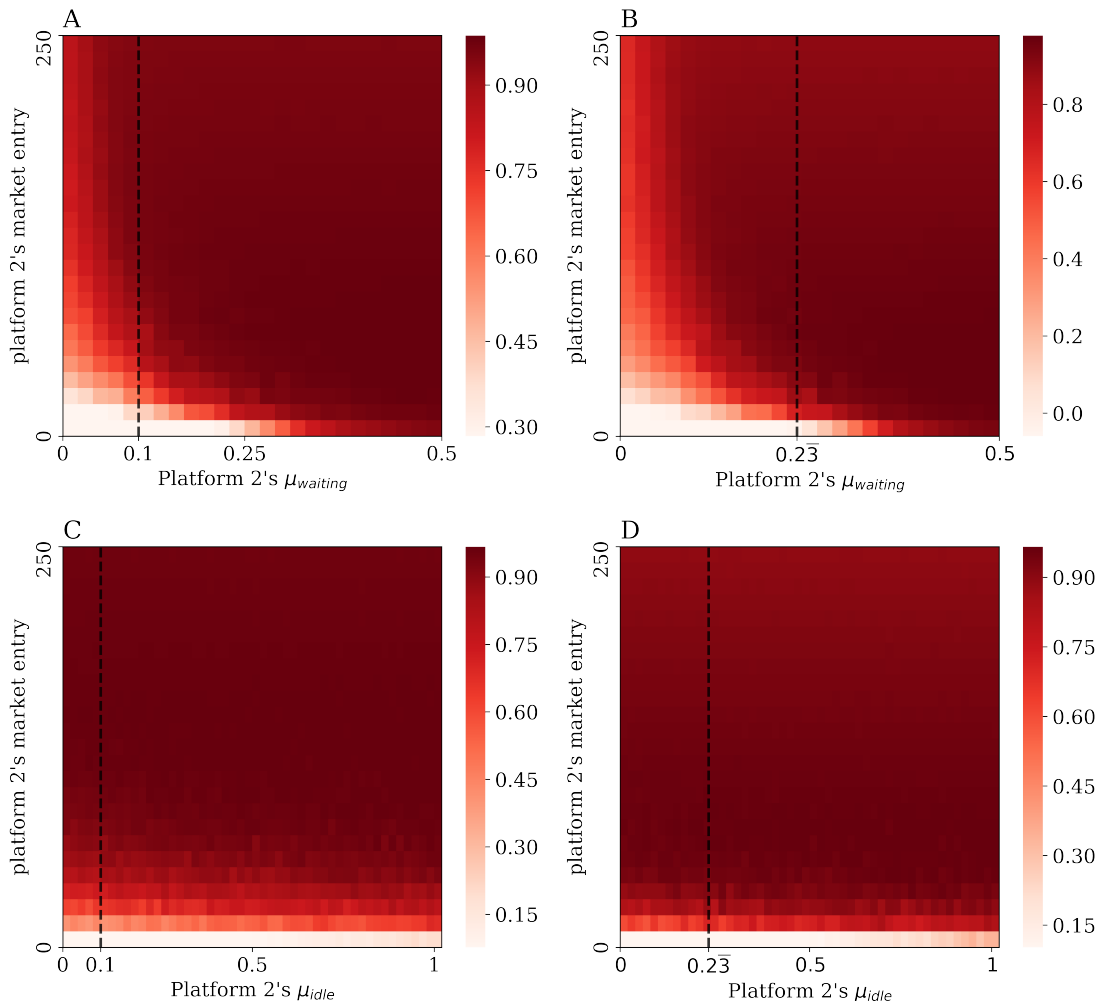


Figure 4.3: Difference in market-share $\kappa(u_1) - \kappa(u_2)$ where three of the four μ parameters are fixed to an arbitrary low value (k) to represent an imaginary world. This figure demonstrates the sensitivity of the final market shares to u_2 's $\mu_{waiting}$ (**A** and **B**), u_2 's μ_{idle} (**C** and **D**). In figures **A** and **C**, we fix $k = 0.1$. In figures **B** and **D**, we fix $k = 0.23$. The dashed black line indicates the situation where all four parameters have the same value (k).

Figure 4.3 shows in red how much of an advantage platform 1 has compared to platform 2 in terms of market-share. The black-dashed lines here represent the values that the three other (non-varying) parameters are fixed at. In Figures 4.3 **A** and **B** a curve can again clearly be seen that marks a boundary on which platform 2 must aim to be within. Joining the market late, if it does not have an exceptionally good waiting times, means agents will certainly favour platform 1. Its only chance is to minimise both delay to market entry, and this $\mu_{waiting}$. This is also the case, although with less importance, for the idle time as shown in figures 4.3 **C** and **D**. Here the parameter doesn't have much of an effect on the overall outcome (due to the low population of drivers). The key factor is to arrive into market as soon as possible in order to mitigate the first-mover-advantage penalty, as was somewhat expected.

4.2.3 Model limitations

In this section we will observe the behaviour that arises from the rate equations when we fix relatively high values for the $\mu_{waiting}$ and μ_{idle} times. This is not expected to reproduce intuitive, real-world applicable data, but is nonetheless interesting.

As previously, in each simulation we fix three of the four parameters appearing in $\vec{\mu}_{waiting}$ and $\vec{\mu}_{idle}$. We will first vary μ_{idle} for four different fixed values $k \in \{0.5, 0.6\bar{3}, 0.7\bar{6}, 0.9\}$, and then do the same operation with $\mu_{waiting}$.

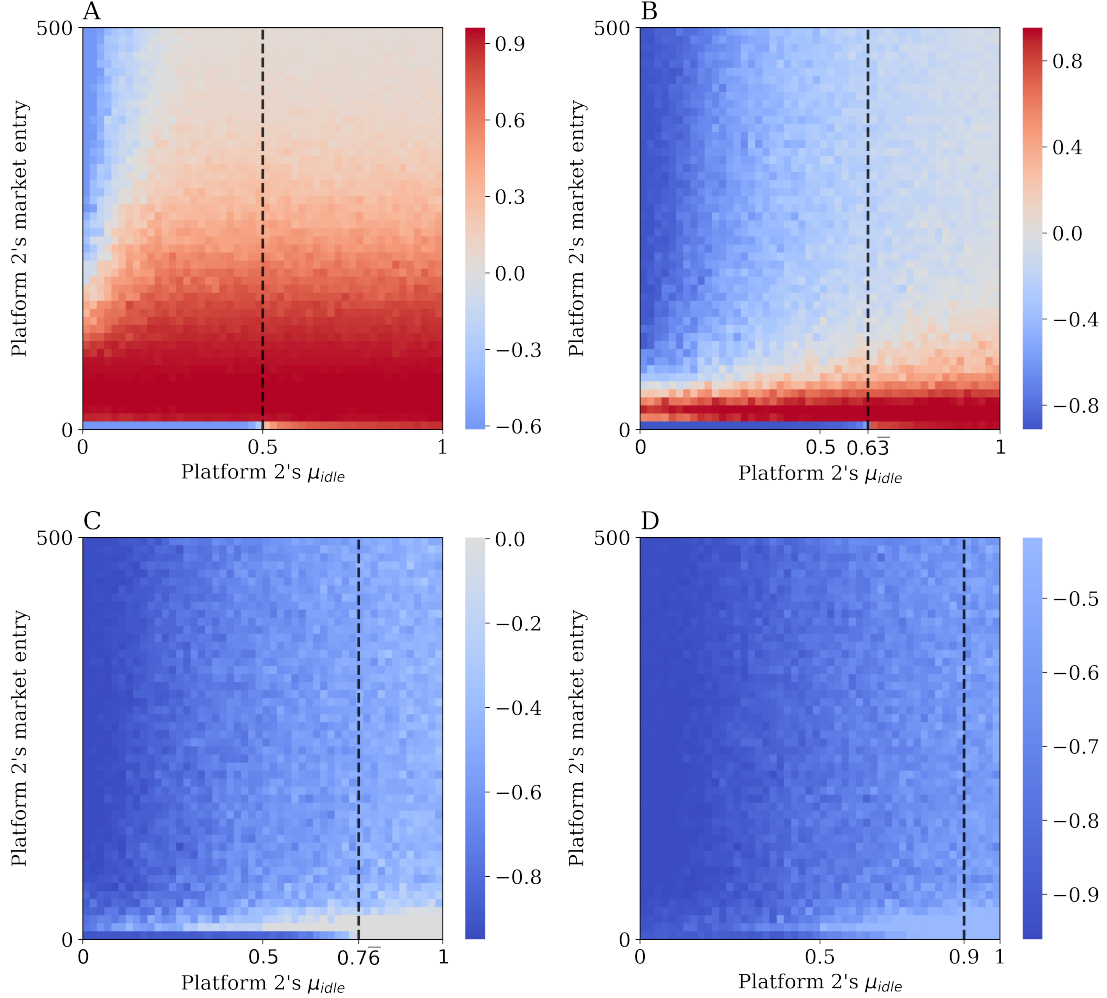


Figure 4.4: Difference in market-share $\kappa(u_1) - \kappa(u_2)$ where $\mu_{waiting}$ and u_1 's μ_{idle} are fixed to an arbitrary high value (k) to represent another imaginary world. This figure demonstrates the sensitivity of the final market shares to u_2 's μ_{idle} for different such k . **A**: $k = 0.5$. **B**: $k = 0.6\bar{3}$. **C**: $k = 0.7\bar{6}$. **D**: $k = 0.9$. The dashed black line indicates the situation where all four parameters have the same value (k).

In figure 4.4 we can start seeing a trend. As we increase the base value (k), the boundary at which these platforms can coexist in a duopoly moves somewhat from left to right. In Figure 4.4 **A**, when all parameters are about average we see something interesting happening. We begin to clearly see somewhat of a border between the red and new blue regions. This area corresponds to the parameter space in which these platforms are able to coexist by splitting the market 50-50 in a relatively stable manner. We are also able to clearly see situations where platform two not only is able to achieve competition, but also dominate the market. The reason the boundary is so volatile in figures 4.4 **B**, **C** and **D** is that μ_{idle} has a notoriously low impact on the final market-shares of the platforms, due to their relatively low population size compared to riders. The boundary movement here is due to the base values of the $\mu_{waiting}$ more than the variation of the μ_{idle}

Going into detail, it seems always better for platform 2 to enter the market as late as possible in figures 4.4 **A** and **B**. What is going on here? It turns out that if platform 1 isn't attractive

enough in terms of waiting/idle time, in a monopoly, agents would rather not join a platform at all. This leaves $\kappa(u_1)$ to be strictly decreasing throughout the simulation, and the longer this goes on, the easier it would be for platform 2 to come out ahead thanks to its more favourable parameters. Furthermore, even when platform 2's parameters are not much better than u_1 's, the market converges to a duopoly where both platforms share about 50% of the market each.

Overall these figures seem to suggest that the first-mover advantage is quite weak in these scenarios. Even though as seen previously μ_{idle} has a relatively low impact on the overall platforms' market-share, we can see that the first-mover advantage can still be reversed with low values of μ_{idle} for an appropriately "bad" base values.

Next we will perform the same analysis using $\mu_{waiting}$, and will identify similar results, in a much stronger fashion.

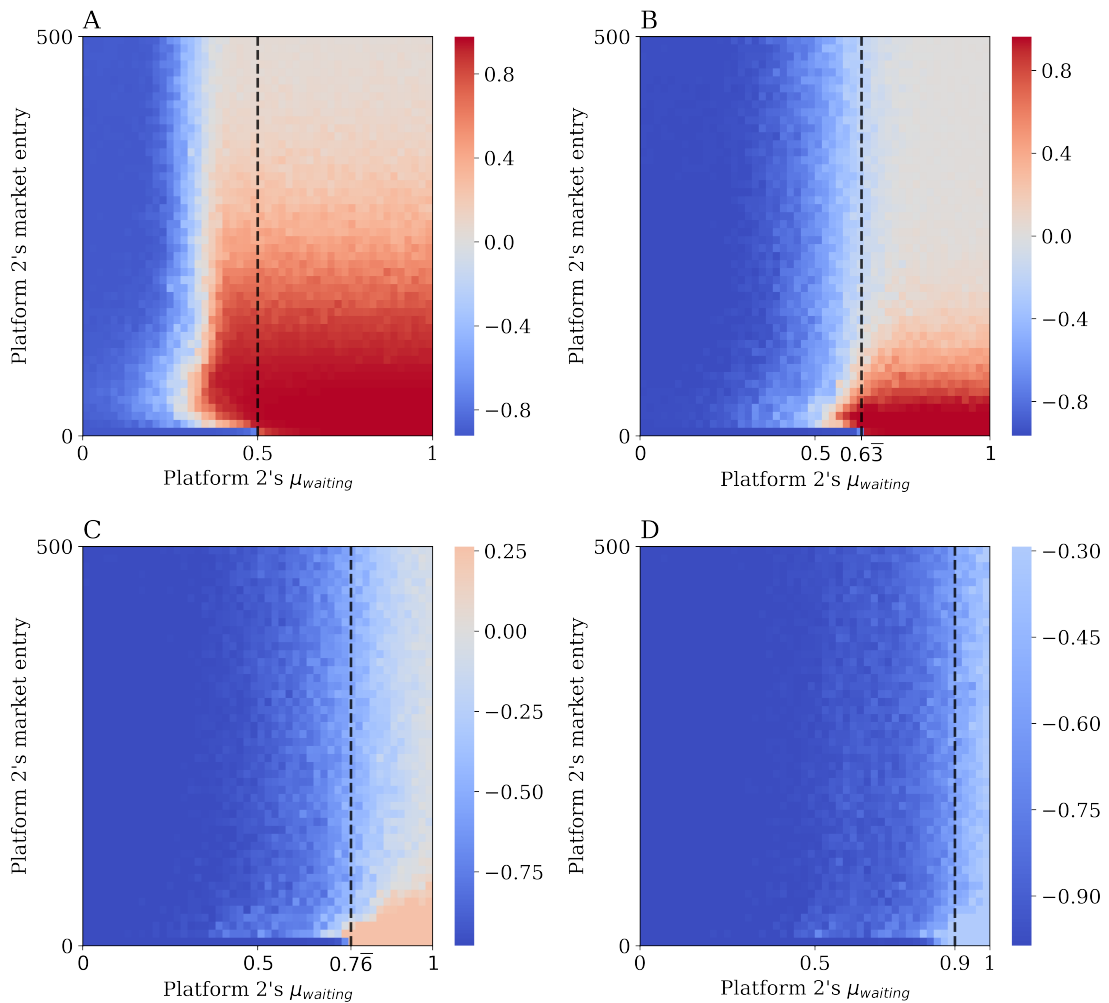


Figure 4.5: Difference in market-share $\kappa(u_1) - \kappa(u_2)$ where the μ_{idle} and u_1 's $\mu_{waiting}$ are fixed to an arbitrary high value (k) to represent an imaginary world. This figure demonstrates the sensitivity of the final market shares to u_2 's $\mu_{waiting}$ for different such k . **A**: $k = 0.5$. **B**: $k = 0.6\bar{3}$. **C**: $k = 0.7\bar{6}$. **D**: $k = 0.9$. The dashed black line indicates the situation where all four parameters have the same value (k).

Figure 4.5 **A** is extremely intriguing. We can again clearly identify a curve flowing between the regions where platforms 1 and 2 respectively dominate. This boundary corresponds to an equilibrium where in those conditions both RHPs are able to exist in a duopoly, splitting the ride-hailing market 50-50.

In addition to this, almost irrespective of the delay to market entry, for values of $X < 0.3$, u_2 systematically comes out ahead in terms of market share. For the other values, we see a completely different version of the story: u_1 comes out well ahead, but increasing the delay to market entry is actually detrimental to u_1 ! Again in all scenarios, it is in platform 2's best interest to join the market as late as possible.

Now from Figure 4.5 we can see how this boundary which we discussed earlier washes through the plot and disappears almost completely in Figure 4.5 C. Once the default sensitivities to waiting and idle times are high for platform 1, it continuously bleeds users by offering a poor service. This effect is so strong that regardless of when platform 2 comes in, it wins by a landslide. Note also that although u_2 wins systematically, as soon as its own sensitivity to waiting time (X) goes above 0.7 (and even more-so after that), the win isn't so monopolistic, with the far right sides of the plots being lighter coloured, indicating that platform 1 is able to retain some of its market-share, coexisting with platform 2.

Overall, these plots seem to suggest that $\mu_{waiting}$ in particular is extremely sensitive and powerful in this model. Keeping it to a low value seems to best reproduce real-world scenarios, where exponential growth still exists although in a controlled fashion. Increasing its value leads to situation where agents would rather not join a platform, even if it is the only one offering its service. Naturally this allows any new platform that enters the market with slightly better service to quickly and immediately dominate the market.

Chapter 5

Discussion

Using an agent based model, starting from basic intuitive ideas about network effects, waiting and idle time, we are able to generate a graph based model that replicates a number of intuitive and empirical features in RHP markets. In the case where $\mu_{waiting} = 0$ we saw that this allows for the reproduction of exponential growth due to the usual network effects. Then, as we increase this value slightly, we start to be able to control this growth, lowering it below the heavy monopoly. This area is extremely sensitive and increasing $\mu_{waiting}$ too far tips it into a third phase, where the exponential growth is completely cancelled out. From this point forward, larger values lead to a larger and larger bleed in users from the platform, even in the absence of a second competing platform, and even goes to hindering the platform from future growth as a new platform enters the market.

We have also shown that our model is able to accurately reproduce the market-share evolution of the two biggest ride-hailing platforms in arguably the most important competitive environment of the United States (New York City). In addition, given partial data, our model is able to generalise quite well into the future.

Through a sensitivity analysis we have also shown that the first mover advantage, whilst strong in some settings, is not indefinite and can be easily counteracted by the agents' sensitivities to waiting/idle times.

Finally, in a slightly altered form, this model was originally designed to simulate the population dynamics of cancer and T-cells inside a human body. Given the somewhat successful application of this model to a completely unrelated domain concerning human behaviour, it begs the question, how much of this shared dynamic is due to some underlying universal property of two part feedback networks, irrespective of what the networks describe. However interesting, this particular question is outside of the scope of our work here, but should be investigated further.

Limits of the first mover advantage

After our initial simulations, it seemed as though being late to join the RHP market would condemn the platform to a low market-share. With this in depth analysis for the 2-platform scenario, this seems increasingly unlikely.

It has been clear throughout this work that the sensitivity of riders to the waiting times of their platforms was one of the main driving factors to achieve high attractiveness. We have now empirically shown that it is also stronger than the first-mover advantage. Platforms that join the market late, are still able to take a substantial share of the market. They merely have to find a large enough, and not very time-sensitive, customer base. Whether that is a possibility is outside the scope of this research but warrants further study.

The results we obtained from figure 4.2 are quite strong. After grounding the model parameters on real-world long term data, we are able to effortlessly simulate what could have happened in an alternate world. This type of analysis has immense potential for competition authorities. It could give them key insights about how the market might evolve depending on their choices to allow

platforms X or Y into their jurisdictions. We have seen that, had their competitors joined earlier and with drivers that had a higher tolerance for idle time, Uber would not be the ride-hailing ruler of New York City.

This also means that if the first platform’s agents are not sensitive to waiting/idle time, the first-mover advantage is indeed strong, and allows it to dominate the market with little resistance from the entering platform.

5.1 Limitations of current study

We recognise here that one major flaw of the simulation is how it behaves differently in a monopoly from an oligopoly. Given that agents have a positive chance to join no platform, with the correct parameters, the way the market-share represents the platforms growth has its limits. Platforms in a monopoly, with the right set of parameters, can essentially bleed users. This need not be a limitation as it could be interpreted as bad service, reducing their effective market-shares greatly as time goes on, yet in reality, it is difficult to imagine the growth of these platforms from the start.

Another limitation from this study is the fact that unlike many previous models on ride-hailing platforms, we do not model the number of rides directly. By modelling the growth of each agent type, we forego the details of ride-matching, a key component of RHPs. This effectively limits our options as far as empirical validation goes as more data is available on number of rides, rather than number of riders/drivers (which are often bundled as “users”). However, it could be argued that the total number of riders and drivers, combined with average usage statistics would result in rider/driver data that can be fed into our model. However, at this early stage, we did not explore such data validation techniques.

Lastly, we acknowledge that the simplicity of some parts of the model might come as a shortcoming. Firstly, both $\mu_{waiting}$ and μ_{idle} could be modelled differently, in a way that makes them both related (as they could be in the real-world). Secondly, the price coefficient η is quite simplistic and hasn’t been expanded much upon in this research. In the real world, this price is not-only variable, but is modelled very specifically and varies quite a lot from platform to platform and even agent to agent. These three improvements would drastically increase complexity but would lead to an even more realistic simulation. Here we have omitted these largely to favour the simplicity of this model.

5.2 Future research directions

As hinted towards in the limitations of this study, there are multiple avenues one could go down in terms of extending this work.

Firstly, increasing the complexity of $\mu_{waiting}$, μ_{idle} and η would greatly improve the performance of this model. What’s more, perhaps unifying the definitions for the μ might drastically reduce the parameter space which currently grows exponentially with the number of additional platforms.

Another way this model can be improved is by considering the geography of a particular city in order to better refine the over-population metrics (the $\rho_A(t, u)$ in equations 3.1 and 3.3) that are already used. One way of achieving this is to model the platforms’ market-share in an ensemble graph-based model where each section of a city map¹ acts as a mini ride-hailing platform. Having this geography introduced to each platform would allow for a global simulation. Simulating the entire Uber company, and observing the growth of different clusters in response to other platforms would be an extremely interesting extension of this work.

Finally, correcting the “bump” that appears in our market-share simulations (e.g. figure 4.1) would be a welcome improvement, however, we don’t believe it would change the message of the results presented here. In its current version, the simulation changes behaviour as the total number of platforms in the market goes from 1 to any more than that. This leads to a situation where a

¹Potentially represented by a Voronoi tessellation

platform can be bleeding users, and then suddenly go to growing again in face of competition. This aspect of the model could be addressed and would improve its real-world performance.

5.2.1 Wider world implications

This work brings an interesting new light to the limits of network effects. Furthermore, it could be a first step to the usage of more complete simulation tool-kits by regulators across different metropolitan areas. They could complement their decision making process with empirically validated models similar to this one in order to simulate a number of scenarios, and analysing the impact on competition throughout.

Chapter 6

Methods

6.1 The Simulation

Here we will go into the details of how the simulation works exactly, and how we are able to extract results from it.

The code is entirely written using Python 3.7 and the only dependencies are Numpy [30] for data-structure manipulation and Matplotlib [31] for the generation of plots. This project is entirely open-source and can be found on GitHub [32].

6.1.1 Agents

At the heart of our simulations are our agents. These are intentionally kept as very simple classes that are created only when a platform is set to grow. On their creation (as part of a variable cluster size), they are assigned to be either riders (with 95% probability) or drivers (with 5% probability). This large difference in population is parametric, but is fixed to these values in order to match virtually all empirical data on ride-hailing platforms. Once they are created, the simulation supplies them with a set of information regarding each platform that is currently on the ride-hailing market. This includes the number of riders and drivers within each platform at the given time, as well as the proportion of riders/drivers that those correspond to within the market. Using this information, the agents apply the respective rate equations (equation (3.1) or (3.3)) in order to generate a joining rate corresponding to each platform. If there is a single platform, then this rate corresponds to the direct growth for the platform, otherwise these rates are first normalised (making them sum to 1) before being sent as growths.

6.1.2 Ride-Hailing Platforms

Around each of these agents and at a higher level we can find ride-hailing platforms (RHPs). These hold most of the actual data for the simulation. Each platform keeps track of its own number of agents (both drivers and riders separately) as well as the corresponding market-share. These are all stored indefinitely, meaning that platforms store their entire growth history and makes it easy to extract at the end of the simulation. Upon their creation, each platform immediately starts with both 1 rider and 1 driver. Platforms are also given information about the current market. As part of their constructors, they receive the current total number of riders and drivers throughout all other platforms. This means that each platform always starts with a market-share of $\frac{2}{N}$, where N is the total number of agents currently in the simulation. As just hinted at, the market-share of a platform is defined to be the number of users it has, over the total number of users in the market. Although this isn't typically how market-share is calculated, this metric should be equivalent to the real-world market-share for our purposes (and would only be off by a constant factor regardless).

6.1.3 The Simulator

Finally comes the simulator class. This object has the responsibility of creating and running a single iteration of a simulation, from end to end. It is created directly from the main program loop

and is given all the appropriate parameters. These include:

- N : the simulation length (in number of new agent generation waves),
- U : the number of RHPs to generate in the simulation,
- $\mu_{waiting}$: as a list it corresponds to the sensitivity to waiting time for each of the platforms in the simulation,
- μ_{idle} : similarly, the sensitivity to idle time of each platform,
- η : this price parameter for each platform, this is an indication of how expensive each ride will be,
- $delays$: as a list, the time at which (during the simulation) each individual platform is to enter the market. At least one platform must be active at time 0,
- n_joins : the number of agents to release onto the market at each time-step.

From these parameters, the simulator’s first task is to generate all the platforms that need to start at time 0, as well as to schedule all the next platform creations / entries to market. Then a simple global clock counts through the N steps, generating n_joins new agents and making them decide which platform to attribute growth to.

This entire process is then repeated it number of times in the main program loop. This allows us to extract a 95% confidence interval for all the interesting metrics, namely: number of riders, number of drivers and market-shares throughout the simulation.

6.1.4 Constraint optimisation based grid-search

In order to find the optimal set of parameters which describe real data as accurately as possible, we perform a grid-search on the parameter space.

In a scenario with P platforms, each simply having a pair of $\mu_{waiting}$ and μ_{idle} parameters, leads to $N^P \times M^P$ possible combinations (where N and M are the granularities of the μ). Running each combination at least 10 times in order to get an average RMSE score is obviously not tractable if we wish to consider a granularity of less than 10^{-1} . In order to circle this problem, let us consider four possible scenarios. An individual platform can have a combination of:

- Many drivers, for few riders: in which case $\mu_{waiting}$ would be low and μ_{idle} should be high,
- Few drivers, for many riders: in which case $\mu_{waiting}$ would be high and μ_{idle} should be low,
- Many drivers, for many riders: in which case both $\mu_{waiting}$ and μ_{idle} would be low,
- Few drivers, for few riders: again in which case both $\mu_{waiting}$ and μ_{idle} would be low.

As we can see, it is never possible for a real RHP to have both a high $\mu_{waiting}$ and a high μ_{idle} . This means we can apply constraint optimisation to our parameter space. Hence whilst generating it, we can simply apply this rule (limiting the average value of the μ) to greatly reduce the number of parameters. In order to generate our main results, we used this technique with $N = 19, M = 9, P = 2$ and $L = 0.6$. Limiting $\frac{\mu_{waiting} + \mu_{idle}}{2} \leq L$ lead to a reduction of the search-space by nearly 60%.

6.2 New York City’s Taxi and Limousine Commission (TLC) dataset

The New York City Taxi and Limousine Commission (TLC) is a local government agency that licenses and regulates the medallion taxis and for-hire vehicle industries. They have been publishing (and somewhat updating) a tremendous amount of data regarding all of their recorded rides within the city: a total of 2.63 billion trips are recorded. Importantly for our purposes, this data is not limited to just cab rides. It is initially split into three parts: data about yellow cabs, green

cabs, and for-hire-vehicles. The latter is of interest to us as this represents rides offered by our ride-hailing platforms.

While the dataset also includes records for cabs, we choose to exclude them from our market-share analysis. In this work, we look at the effects of competition between ride-hailing platforms. We cannot account for the taxi market because they do not share the same two-sided dynamics that RHPs do. This comes from the fact that there are a fixed number of drivers in each metropolitan area¹, although it would be interesting to extend this work to include them in the future.

This data on RHPs is available monthly from January 2015, and monthly thereafter up-to December 2019. These records are extremely detailed:

- `dispatching_base_number`: A unique identifier attributed to each RHP. These identifiers are also tied to a geographic area,
- `PUdatetime` and `DOdatetime`: The pick-up and drop-off time and dates (accurate to the second),
- `PUlocationID` and `DOlocationID`: The pick-up and drop-off location IDs which correspond to various metropolitan areas. These are broken up into “Borough” and “Zone” (e.g. Manhattan / Lincoln Square East),
- `SR_flag`: Binary value (0 or 1), determines whether or not the ride was shared (e.g. Uber Pool).

Note that for years 2015 and 2016, the only information is the `dispatching_base_number` as well as `datetime` and `locationID` of either pick-up or drop-off (not specified).

Readers who are interested in seeing ways in which this entire dataset can be analysed are invited to read Todd Schneider’s article “Analyzing 1.1 Billion NYC Taxi and Uber Trips, with a Vengeance” [33].

For our purposes, we only need a single piece of information for each individual ride: which RHP offered it. This can directly be cross-referenced with a mapping from base number to RHP, which is provided by the TLC. Unfortunately, there are approximately 126 million rows that either contain no base number, or one that isn’t documented. These rides will thus be ignored. This leaves us with a total of 782 million rides that have been offered by one of: Uber, Lyft, Juno or Via between 2015 and 2019.

We will use this data in two ways, one of which was particularly experimental. First, we grouped the total number of rides that each platform offered by date, and extracted monthly market-share data on these platforms. In order to simplify the analysis (and to focus on the two main platforms), we have aggregated all data corresponding to Via and Juno and labelled it as “other” for all of our simulations. Secondly we also regroup and count the number of rides offered by each platform in order to generate an accumulated number of rides offered by them.

Lastly, in order to use RMSE as a metric to compare the market-share points generated by our simulations and the this real-world data, it was necessary to either down-sample the N -dim market-share vectors generated (1 entry per time-step), or to up-sample the real data. For no particular reason, we chose to up-sample the real market share values, by extrapolating the values between each month. Starting with 60 data points, this increase the resolution to 1889 points. Therefore we simply increased the length of the simulations to match the length of the data.

¹Due to the fixed number of annually distributed licenses.

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