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Regulating the ride-hailing market in the age of uberization

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ABSTRACT

The entry of transportation network companies like Uber and Lyft in the ride-hailing market has generated concerns that they unfairly compete against traditional street-hail services. However, regulatory action seeking to address this issue has either been lacking or has resulted in the suspension or restriction of e-hail services. In this paper, we propose a model of competition between these two services and investigate the design of optimal and parsimonious regulation to achieve social efficiency. When the e-hailing platform adopts instantaneous matching with a relatively large matching radius, we analytically show that, absent restrictions, the street-hailing firm has a pricing advantage and can thrive when competing against the e-hailing platform in dense markets or when trip distances are relatively short. Moreover, while a monopolist controlling both firms will tend to internalize some of its congestion externality, we show that congestion can become quite severe in a duopoly setting. However, we show that even when accounting for competition and congestion, regulators only need to regulate the per trip commission that each company earns to maximize social surplus. This provides a potential avenue to simplify the host of regulations, which have historically been a feature of the ride-hailing market and are currently hampering the street-hailing industry.

1. Introduction

Traditionally, the ride-hailing industry has been dominated by street-hailing services. In metropolitan cities like New York City (NYC), these services have usually been subject to major regulations: limits on the number of cabs operating, licensing requirements, fare controls. However, over the past decade, e-hailing transportation network companies such as Uber and Lyft have entered the ride-hailing industry and quickly grown in popularity while operating largely unregulated. For example, Uber's quarterly earning reports show that between 2016 and 2018 the number of trips served by the platform increased tenfold (Chai, 2019). Naturally, this surge in popularity has resulted in the decline of street-hailing services. For example, in NYC, between April 2016 and April 2020, the market share of street-hail fell from 86% to 14% (Schneider, 2022). Faced with dwindling revenues, traditional taxi drivers have been calling for regulatory action, accusing e-hailing companies of unfair competition due to their unregulated status (Rana, 2022).

While one might argue that the imminent death of the street-hailing industry is the natural result of technological advancement and of e-hailing's superior efficiency, empirical evidence suggests that the picture is more complicated. Indeed, using data from Shenzhen, China, Nie (2017) and Zhang et al. (2019) show that, in very dense settings, using street-hailing will tend to result in lower waiting times than using e-hailing. This seems to indicate that, at least in major urban centers like NYC, society might benefit from sustained operation of street-hailing, even if we ignored the mobility needs from those who do not have access to

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a smartphone. This is, however, less likely to occur unless policymakers provide for an appropriate regulatory environment that allows for street-hailing's competitiveness.

However, to date, in major US cities, no regulatory action has sought to address the legal discrepancy between e-hailing companies and the street-hailing industry. Moreover, in other parts of the world, regulatory action has often sought to assuage street-hailing drivers by curtailing or outlawing the use of e-hailing (Rana, 2022). However, the fact that e-hailing companies have a user-base more expansive than street-hailing (Contreras and Paz, 2018; Rayle et al., 2016; Clewlow and Mishra, 2017) suggests that there may be a better regulatory approach to the question. Moreover, in other parts of the world and, recently, in NYC, partnerships between e-hailing companies and taxi drivers seem to indicate that synergistic operation between these two services is possible (Rana, 2022). In this context, one might wonder the potential welfare implications of greater synergy and even consolidation between street-hailing and e-hailing.

To help inform the development of such a regulatory framework, we propose a model of competition in the ride-hailing market. After investigating the socially optimal configuration in such a context, we investigate the outcome of e-hailing and street-hailing competition. We also investigate the integration of these two services into a single platform in which fares are jointly determined but e-hailing customers cannot match with street-hailing drivers through an app. Lastly, we are also able to assess the impact of current policies and to propose policies more suited for the age of e-hailing.

The rest of the paper is organized as follows. We present literature relevant to ride-hailing market regulation in Section 2. Section 3 presents our main assumptions and our model. Then, in Section 4 we analyze the first-best while in Section 5 we analyze the Nash equilibrium and an integrated monopoly. In Section 6, we propose and determine sufficient conditions for the market to be regulated parsimoniously. Additionally, in Section 7, we extend our model to consider the policy implications of accounting for the effect of ride-hailing on congestion. We conclude in Section 10.

2. Literature review

Historically, ride-hailing regulations have been catered to street-hailing services and have spanned three areas: price regulation, entry regulation and quality requirements. Naturally, these regulations have generated a lot of academic and political discussions which are worth exploring when considering how they should evolve with the rise of e-hailing.

Proponents of regulation argue that, in the absence of fare regulations, an equilibrium to the street-hailing market may not exist or may be undesirable due to imperfect information for both customers and drivers (Shreiber, 1975, 1981; Coffman and Shreiber, 1977; Gallick and Sisk, 1987; Cairns and Liston-Heyes, 1996). Indeed, given the spatial nature of the market, the inability of customers to easily collect pricing information and the inability of drivers to easily signal their lower price compared to other drivers, absent regulations, fares might be unnecessarily high or might never stabilize. Evidence also suggests that, at taxi stands with first-in–first-out rules for customers and drivers, bargaining is next to impossible, which results in even higher fares than in the cruising market (Frankena, 1984). Additionally, some advocate that entry restrictions are needed to allow positive profits for the industry and address congestion and pollution externalities (Shreiber, 1975; Arnott, 1996). Absent regulations, the industry's low entry cost would lead to an oversupply of cabs which, absent coordination among drivers, would reduce utilization rates and make taxi operation unsustainable. This oversupply of cabs would also adversely affect traffic and generate more pollution, without either customers or drivers bearing the cost they impose on others. Lastly, there is also an argument that quality requirements in the form of knowledge test, background checks, insurance and vehicle condition and size are needed. Indeed, because of the temporary nature of their interactions with drivers, customers are unable to properly assess the safety and risks associated with their ride before experiencing it.

In general, opponents to regulations argue that price and supply limits lead to higher waiting times and fares than are efficient (Frankena, 1984; Beesley, 1973; Barrett, 2003). This arises in part because these restrictions are set for industry benefits rather than for customers' welfare. These restrictions – coupled with other restrictions such as the inability to provide shared rides – also inhibit the ability of drivers and fleet operators to differentiate their service and thus serve a larger market (Beesley, 1979). Moreover, these price and entry restrictions fail to account for the spatial and temporal nature of the market (Fréchette et al., 2019; Buchholz, 2019). Thus, fares might not reflect the fact that the opportunity cost of a ride depends on its destination, and supply restriction might lead to demand/supply imbalances at different times of day in different geographic locations. Moreover, to address the high prices that arise at taxi stands or in isolated locations where finding a taxi is difficult, the matching process could be tweaked and price caps could be set at these locations instead of widespread industry restrictions (Frankena, 1984). Lastly, externalities could be addressed through tolls and taxes, thus making taxis, their customers and other vehicle users bear the full social cost of their activities.

Evidence from the US and other places are available for either side of the debate, and careful analysis seems to suggest that some regulation might be needed to ensure competitiveness and limit entries in already saturated corners of the industry (Teal and Berglund, 1987; Gaunt, 1995; Dempsey, 1996; Schaller, 2007). With the introduction of e-hailing services, new evidence seems to validate some of the claims for either side. On the one hand, waiting times on the e-hailing services tend to be lower than for street-hailing services. There has also been an increase in the number of rides with e-hailing compared to street-hailing services in some cities, and new services such as pooled rides have been made available. However, there is evidence that both e-hailing (Erhardt et al., 2019; Tarduno, 2021) and street-hailing (Mangrum and Molnar, 2020) contribute to increased congestion levels in cities like NYC and San Francisco. Moreover, the dynamic pricing mechanism used by the platforms to deal with unforeseen surges in demand has occasionally resulted in very high prices, to the dismay of customers.

A number of studies have also investigated the issue of competition in markets with search friction, especially ride-hailing (Zha et al., 2016; Nikzad, 2017; Fréchette et al., 2019; Benjaafar et al., 2020; Zhang and Nie, 2021a). A consensus seems to emerge that extreme competition between these two ride-hailing firms might not necessarily be socially efficient because it may reduce market thickness for each service, thus leading to lower service quality and higher fares than with a single service. While these studies provide insights as to the interplay between search friction and competition, our work focuses instead on how to regulate competition between e-hailing and street-hailing by taking into account differences in both their matching technology and, to a certain extent, their operating structure.

More recently, a number of papers have focused on the specific issue of competition between e-hailing and street-hailing (Yu et al., 2019; Daniels and Turcic, 2021; Noh et al., 2021). Yu et al. (2019) considers the effect of regulatory intervention in a market in which e-hailing and street-hailing compete. While their findings seem to validate our premise – better regulations can improve street-hailing's competitiveness against e-hailing – their model does not incorporate one of the crucial differences between the two services: their matching technology and the resulting waiting times. On the other hand, Noh et al. (2021) focuses on the impact of each service's managerial structure (i.e. street-hailing exercises more control on its supply compared to e-hailing) on service quality, prices and welfare. Similarly to Yu et al. (2019), their model does not incorporate the effect of matching technology on the outcome of competition in the industry. Additionally, in the long run, e-hailing drivers' greater flexibility compared to street-hailing drivers should be a minor factor in determining the outcome of competition.[1] Daniels and Turcic (2021) investigates the role of matching technology in determining the outcome of competition between e-hailing and street-hailing. By modeling the matching process, they are able to derive waiting time functions for each service as a function of demand and supply levels. Then, they proceed to show that restricting the service area – as opposed to adopting e-hailing style centralized dispatch – would be a better option for street-hailing to compete against e-hailing.

Our work is closest in spirit to that of Daniels and Turcic (2021). We incorporate the differences in matching technology between e-hailing and street-hailing and use the resulting model to derive insights as to the operational settings that favor one service over the other. While Daniels and Turcic (2021) focuses on waiting times, our analyses account for both waiting times and pricing behavior. Additionally, going further than Daniels and Turcic (2021), we evaluate potential regulatory strategies for the ride-hailing industry as a whole and their implications for welfare and congestion.

3. Model

We consider a market with a street-hailing and an e-hailing service. It is assumed that customers have access to the prices and waiting times on both services and can choose which one to use by comparing features across both platforms. Drivers also have access to earning information on both services and can choose whether and for which company to provide service. However, no multi-homing is considered in this setting. The e-hailing platform decides the fares and driver earning per ride and earns the difference, i.e., a per-trip commission. The street-hailing company decides its fleet size as well as the leasing fee for its vehicles.

Additionally, we consider the following:

1. The e-hailing platform implements instantaneous matching upon a customer's request with an infinite matching radius. Thus, e-hailing customers experience no (online) matching time (Castillo, 2018; Xu et al., 2019). This tends to be a common practice among e-hailing companies in the US market. Alternatively, some companies (e.g.: DiDi Chuxing in China) implement batch matching that would yield online matching time for customers in addition to the pickup time. We do not consider such a strategy here.
2. Street-hailing customers experience no pickup time. Rather, (physical) matching between customers and drivers occurs as described in Arnott (1996), Chen et al. (2019) and Zhang et al. (2019).
3. Each firm only provides a solo service: no pooling is considered.

A description of the main variables used in our model is given in Table A.1 and a description of relevant parameters is given in Table D.1.

3.1. Matching, pickup, and delivery

Let w_i^m denote the expected waiting time experienced by customers using service $i \in \{e, s\}$.[2] If service i is an e-hailing company, then w_i^m corresponds to the pickup time experienced by the requesting customer. If, instead, i is a street-hailing company, then w_i^m corresponds to the "matching" time (search frictions) experienced by the requesting customer. Then, we have:

$$w_i^m = \frac{d_i^m}{v}$$

where d_i^m represents the average distance between a customer and her closest available driver on service i; and v represents the traffic speed. The average distance d_i^m is a decreasing function of the number of idle drivers n_i^I and is such that:

$$d_i^m = D_i^m(n_i^I) \tag{1}$$

[1] Since, in the long run, drivers can decide on which of these two platforms to provide services and, from a managerial perspective, compensation costs can be adjusted accordingly.

[2] e stands for e-hailing.

where $D_i^m(\cdot)$ is a decreasing and convex function that reflects the matching technology for service i. Then, if we let d^r be the average trip distance, the trip time w^r experienced by customers of either service once they are picked up is given by:

$$w^r = \frac{d^r}{v}$$

3.2. Demand

We assume that customers are homogeneous in their value of time β but differ in other aspects that influence choice (e.g., preference for a particular service, inertia and diligence in comparing features across services).[3] Given the distribution of these customer specific attributes, the demand rate λ_i for each service i is given by:

$$\lambda_i = \Lambda_i(\mu_i, \mu_{-i})$$

where $\Lambda_{i,1} < 0$ and $\Lambda_{i,2} > 0$[4]; and μ_i is the average cost of using service i[5] and is such that:

$$\mu_i = f_i + \beta \cdot (w_i^m + w^r)$$

where f_i is the fare on service i.

3.3. Supply

When multi-homing is not permitted, drivers must decide which platform to join before beginning service. As such, given the distribution of drivers' reservation costs and their idiosyncratic preferences, the supply n_i of drivers is given by:

$$n_i = S_i(\omega_i, \omega_{-i})$$

where $S_{i,1} > 0$ and $S_{i,2} < 0$; and ω_i is the expected hourly earning on service i.

3.4. Equilibrium

At equilibrium, we consider a steady state in the system where the following conservation equation holds as per Little's law:

$$n_i = n_i^I + \lambda_i \cdot (w_i^d + w^r)$$

where w_i^d represents the pickup time experienced by drivers on service i. For e-hailing drivers, $w_i^d = w_i^m$ and, for street-hailing drivers, $w_i^d = 0$.

We then obtain the system of Eqs. (2a) and (2g):

$$\lambda_i = \Lambda_i(\mu_i, \mu_{-i}) \quad \forall i \in \{s, e\} \tag{2a}$$

$$\mu_i = f_i + \beta \cdot (w_i^m + w^r) \quad \forall i \in \{s, e\} \tag{2b}$$

$$w_i^m = \frac{d_i^m}{v} \quad \forall i \in \{s, e\} \tag{2c}$$

$$w^r = \frac{d^r}{v} \tag{2d}$$

$$d_i^m = D_i^m(n_i^I) \quad \forall i \in \{s, e\} \tag{2e}$$

$$n_i = S_i(\omega_i, \omega_{-i}) \quad \forall i \in \{s, e\} \tag{2f}$$

$$n_i = n_i^I + \lambda_i \cdot (w_i^d + w^r) \quad \forall i \in \{s, e\} \tag{2g}$$

The above system of equations contains 14 equations and 18 unknowns. By specifying a set of 4 exogenous variables and 14 endogenous variables, we can assume that this system defines a continuously differentiable function $G : \mathbb{X} \to \mathbb{E}$ where $\mathbb{X} \subseteq \mathbb{R}_+^4$ is a set of exogenous variables and $\mathbb{E} \subseteq \mathbb{R}_+^{14}$ is a set of endogenous variables. That the existence of such a function can be assumed relies on the existence and uniqueness of a solution to Eq. (2) once the exogenous variables are specified.

We first discuss the issue of existence. Suppose we specify $\mathbf{f}$ and $\boldsymbol{n}$ as exogenous variables.[6] Then, Eq. (2) can eventually be reduced to a fixed-point problem $\mathbf{x} = F(\mathbf{x})$ where $\mathbf{x} = (\lambda, \boldsymbol{w}^m, \boldsymbol{n}^I, \boldsymbol{\omega})$. Following Zhang and Nie (2021c), it is possible to show that there exists an equilibrium solution for our market. Two conditions must hold: the mapping $F(\cdot)$ should be continuous and $\mathbf{x}$ should be bounded. The former condition easily follows from the continuity of the functions involved.[7] The latter condition is easily met when we note that demand λ and supply $\boldsymbol{n}$ are limited by the size of our market. Thus, the waiting times $\boldsymbol{w}^m$ and wages $\boldsymbol{\omega}$ can be

[3] A discussion of the heterogeneous value of time case is provided in Appendix E.

[4] Subscripts 1 and 2 refer to the first derivative of $\Lambda(\cdot,\cdot)$ with respect to the first and the second argument, respectively.

[5] As is standard, $-i$ will refer to variables for the service that is not i.

[6] We use boldface notation to represent a vector. For example, $\mathbf{f} = (f_i)_i$.

[7] The demand, supply, and distance functions are all differentiable.

made neither infinitely large nor infinitely small. Moreover, the number of idle drivers $\boldsymbol{n}^I$ is naturally bounded by the supply of drivers.

As for uniqueness, there could exist two solutions due to the well-known issue of the "wild-goose chase": an efficient one and an inefficient one (Castillo, 2018). However, the outcome from the three problems we study (first-best, monopoly, and duopoly) will always lie in the efficient regime (Vignon et al., 2021) so that uniqueness naturally holds.

4. First-best analysis

In this section, we analyze the first-best to understand when and how regulatory actions can be taken in the ride-hailing market.

4.1. Problem equivalence

Before proceeding to analyze the first-best, a simple analysis of firms' independent decisions can help us further simplify the problem by treating e-hailing and street-hailing in a similar fashion. An e-hailing company maximizes its profits as follows:

$$\begin{aligned} \pi_e = \max_{\substack{f_e \geq 0,\\ n_e \geq 0,\\ r_e \geq 0}} \quad & (f_e - r_e) \cdot \lambda_e \\ \text{s.t} \quad & (\omega_e + c_e) \cdot n_e = r_e \cdot \lambda_e \end{aligned} \tag{3}$$

where c_e is the (given) per unit time operation cost for drivers who decide to serve on platform e; and r_e is the compensation per ride that drivers earn. The constraint in the above problem indicates that, under free-entry condition and sufficient supply, drivers enter the market until economic profits reach zero. The problem can be rewritten as:

$$\pi_e = \max_{\substack{f_e \geq 0,\\ n_e \geq 0}} \quad f_e \cdot \lambda_e - (\omega_e + c_e) \cdot n_e \tag{4}$$

Meanwhile, a street-hailing company solves the following problem:

$$\begin{aligned} \pi_s = \max_{\substack{f_s \geq 0,\\ n_s \geq 0,\\ l_s \geq 0}} \quad & (l_s - c_s^c) \cdot n_s \\ \text{s.t} \quad & (\omega_s + c_s^d + l_s) \cdot n_s = f_s \cdot \lambda_s \end{aligned} \tag{5}$$

where c_s^c is the (given) per unit time cost of vehicle ownership for the company; c_s^d is the (given) cost of operation incurred by drivers; and l_s is the leasing fee that the company charges drivers. By posing $c_s = c_s^c + c_s^d$, it is now possible to rewrite the problem for the street-hailing company as:

$$\pi_s = \max_{\substack{f_s \geq 0,\\ n_s \geq 0}} \quad f_s \cdot \lambda_s - (\omega_s + c_s) \cdot n_s \tag{6}$$

Thus, provided that c_s and c_e are properly specified, both street-hailing and e-hailing companies solve mathematically equivalent problems. This greatly simplify the rest of our work.

In our following analyses, both in this and subsequent sections, we assume that the exogenous variables for this system will be the fares f_i and the number of drivers n_i for each company.

4.2. Comparison between e-hailing and street-hailing

Using empirical data and a model of the matching technology for both e-hailing and street-hailing, Zhang et al. (2019) show that, in high density settings, waiting times for street-hailing could be lower than those for e-hailing. This is largely attributed to stronger returns to scale for street-hailing. These stronger returns to scale stem from the fact that, by expanding customers' hailing radius, e-hailing also increases inter-customer competition for drivers. Thus, while the radius expansion can lead to lower waiting times for customers in low density areas, it can result in longer waiting times in denser settings. This waiting time advantage of street-hailing in denser settings is corroborated by other researchers, both analytically and empirically (Nie, 2017; Daniels and Turcic, 2021).

In this section, we are interested in examining whether, when considering the generalized cost of service, street-hailing could still possess an advantage over e-hailing. Indeed, lower waiting times could be associated with higher fares and, subsequently, make a service less desirable. Naturally, to capture these trade-offs between higher fares and lower waiting times, we must be able to capture the impact of waiting times on fares. A potential approach to establish that connection would be to consider fares under marginal cost pricing. Indeed, under marginal cost pricing, the fares would capture the waiting time externality that a given customer imposes on others. Moreover, an appropriate comparison between the two services would compare their generalized costs when they operate at their most efficient level. These considerations motivate studying the optimality condition of the first-best problem:

$$W = \max_{\substack{f_i \geq 0,\\ n_i \geq 0}} \quad CS(\mu_s, \mu_e) + \sum_i f_i \cdot \lambda_i - (c_i + \omega_i) \cdot n_i + DS(\omega_1, \omega_2) \tag{FB}$$

where $CS(\cdot,\cdot)$ represents the consumer surplus with $CS_i = -\lambda_i$; and $DS(\cdot,\cdot)$ represents driver surplus with $DS_i = n_i$. We note that, at the first-best, the planner maximizes the joint profit of both companies, not favoring one over the other beyond what efficiency would require. Then, we have:

$$f_i = \overline{mc}_i = mc_i \cdot (w_i^d + w^r) \tag{7a}$$

$$mc_i = c_i + \omega_i \tag{7b}$$

with:

$$mc_s = -\beta \cdot \lambda_s \cdot w_s^{m'} \tag{8a}$$

$$mc_e = -\beta \cdot \lambda_e \cdot w_e^{m'} \cdot \frac{1}{1 + \lambda_e \cdot w_e^{m'}} \tag{8b}$$

$$w_i^{m'} = \frac{D_i^{m'}(n_i^I)}{v} \tag{8c}$$

In the above, $\overline{mc}_i$ represents the marginal service cost for service i i.e. the cost that serving the marginal customer imposes on other users of the service; and mc_i represents the marginal service cost per unit time for service i. Simply, Eq. (7a) refers to marginal cost pricing while Eq. (7b) indicates that drivers' costs and their marginal benefit to the system should be equalized. Now, let us compare the relative socially optimal costs of using e-hailing and street-hailing. To do this, let us consider a widely adopted form in the literature for the pickup distance (Arnott, 1996; Zhang et al., 2019):

$$D_i^m(n_i^I) = \frac{1}{a_i} \cdot (n_i^I)^{\alpha_i}$$

where a_i is a parameter that captures the efficiency of the meeting process; and α_i is the elasticity parameter with $\alpha_s = -1$ and $\alpha_e = -0.5$.

Thus, using Eqs. (2b) and (8b), the socially efficient cost of serving a trip can be written as:

$$\mu_s = \beta \cdot w_s^m \cdot \left[\lambda_s \cdot \left(n_s^I\right)^{-1} \cdot w^r + 1 \right]$$

$$\mu_e = \beta \cdot w_e^m \cdot \left[\frac{1}{2} \cdot \lambda_e \cdot \left(n_e^I\right)^{-1} \cdot \left(\frac{w_e^m + w^r}{1 - \frac{1}{a_e \cdot 2 \cdot v} \cdot \lambda_e \cdot \left(n_e^I\right)^{-1.5}} \right) + 1 \right]$$

Then, we obtain Proposition 1:

Proposition 1. *Given a_i, d^r and v, and assuming identical labor costs for both services, there exists supply and demand levels such that street-hailing is more efficient[8] than e-hailing.*

Proof. Street-hailing is more efficient than e-hailing when $\frac{\mu_e}{\mu_s} \leq 1$, assuming identical levels of demand served and identical number of vehicles (i.e $\lambda_e = \lambda_s = \lambda$ and $n_s = n_e = n$). However, it is sufficient to show that $\frac{\mu_s}{\mu_e} \leq 1$ holds when considering identical levels of demand served and identical number of idle drivers ($n_s^I = n_e^I = n^I$). Indeed, when $\lambda_i = \lambda$ and $n_i^I = n^I$ $\forall i$, it follows that $n_s < n_e$. If $\frac{\mu_s}{\mu_e} \leq 1$, it implies that it is possible to serve λ with a lower driver cost using street-hailing. Reducing n_e to n_s would not alter that result but would increase the customer cost by increasing waiting time for e-hailing customers.

Then, considering $\lambda_i = \lambda$ and $n_i^I = n^I$ $\forall i$, it is a matter of algebraic transformations to rewrite $\frac{\mu_s}{\mu_e} \leq 1$ as:

$$-\frac{1}{2 \cdot a_s \cdot v} \cdot (n^I)^{-1} \cdot w^r \cdot \phi^2 - \left[\frac{1}{2 \cdot a_s \cdot v} \cdot (n^I)^{-1} + w^r \cdot \left(\frac{1}{2} - \frac{a_e}{a_s} \cdot (n^I)^{-0.5} \right) \right] \cdot \phi + \left(\frac{a_e}{a_s} \cdot (n^I)^{-0.5} - 1 \right) \leq 0 \tag{9}$$

where $\phi = \frac{\lambda}{n^I}$. Now, we have:

- if $n^I \geq \frac{a_e^2}{a_s^2}$, then regardless of the value of ϕ (which is uniquely determined by the level of demand once n^I is set), the above condition is met.
- if $n^I < \frac{a_e^2}{a_s^2}$, the left hand-side of Eq. (9) is a concave parabola whose value at $\phi = 0$ is positive and whose smallest root is negative. Thus, if ϕ is greater than the positive root of Eq. (9), the condition is met. □

Proposition 1 indicates that if there is a large supply of drivers, or if demand is sufficiently large, then street-hailing will tend to be preferable to e-hailing. This could potentially be explained by stronger increasing returns to scale for street-hailing. A closer examination reveals the underlying mechanism that gives rise to those increasing returns to scale. First, note that even if both services had the same waiting time functions ($\alpha_s = \alpha_e$ and $a_s = a_e$), street-hailing would still be more efficient under certain

[8] Efficiency here refers to cost advantage. That one service is more efficient than another implies that serving a ride on that service is cheaper than on the other service.

conditions. This is simply due to the nature of the marginal cost of both services. While the marginal cost of street-hailing is only a function of delivery time, that of e-hailing is a function of both delivery time and pickup time. Indeed, a marginal street-hailing user only monopolizes driving resources for the duration of her trip. In e-hailing, unless reassignments are made, a marginal user also monopolizes a driver for the duration of her pickup time. High density of drivers and customers then has two effects on e-hailing. First, a marginal e-hailing user imposes a pickup time cost on a larger number of users. Second, relative to street-hailing, an increase in both e-hailing supply and demand does not fully translate into an increase in available drivers, since the time dedicated to pickup by the fleet also increases (due to the larger number of people to pickup). Thus, when supply and/or demand are high, street-hailing will have higher market shares than e-hailing if demand is served optimally. It is possible to gain further insights into the relative performance of both services by considering the following:

Corollary 1.1. *Given a demand level λ and supply n, there exists $(a_s, a_e, d^r, v) \in \mathbb{R}^4_+$ such that street-hailing is more efficient than e-hailing. In particular:*

- *If $a_e \leq \frac{\sqrt{n^I}}{2} \cdot a_s$, then street-hailing is more efficient regardless of demand level.*
- *If $\frac{\sqrt{n^I}}{2} \cdot a_s < a_e$ and $v \leq \tilde{v}$, then street-hailing is more efficient.*
- *If $\frac{\sqrt{n^I}}{2} \cdot a_s < a_e < \sqrt{n^I} \cdot a_s$, $v > \tilde{v}$ and $d^r \leq \tilde{d}^r$, then street-hailing is more efficient.*
- *If $a_e > \sqrt{n^I} \cdot a_s$, $\tilde{v} < v < \tilde{\tilde{v}}$, and $d^r \leq \tilde{d}^r$, then street-hailing is more efficient.*

In the above:

$$\tilde{v} = \lambda \cdot (n^I)^{-\frac{3}{2}} \cdot \frac{1}{2 \cdot a_e - a_s \cdot \sqrt{n^I}}$$

$$\tilde{\tilde{v}} = \frac{1}{2} \cdot \lambda \cdot (n^I)^{-\frac{3}{2}} \cdot \frac{1}{a_e - a_s \cdot \sqrt{n^I}}$$

$$\tilde{d}^r = v \cdot \frac{n^I}{\lambda} \cdot \frac{1 - \frac{v}{\tilde{\tilde{v}}}}{\frac{v}{\tilde{v}} - 1}$$

Proof. Applying the same principles as in Proposition 1 and rewriting Eq. (9) as a quadratic in v, we obtain the following condition for street-hailing dominance:

$$\left(\frac{a_e}{a_s} \cdot (n^I)^{-0.5} - 1\right) \cdot v^2 - \left[\frac{1}{2 \cdot a_s} \cdot (n^I)^{-1} + d^r \cdot \left(\frac{1}{2} - \frac{a_e}{a_s} \cdot (n^I)^{-0.5}\right)\right] \cdot \phi \cdot v - \frac{1}{2 \cdot a_s} \cdot (n^I)^{-1} \cdot d^r \cdot \phi^2 \leq 0 \tag{10}$$

In other words, Eq. (10) describes a parabola whose concavity is governed by the relative efficiency $\frac{a_e}{a_s}$ and for which the negative region is determined by the relative efficiency as well as the travel distance d^r. It is then easy to verify that the statements in Corollary 1.1 hold. □

Corollary 1.1 indicates that, when traffic speed is low, street-hailing is more efficient. Indeed, low traffic speed implies that e-hailing drivers spend a larger fraction of their time in pickup mode, thus serving less rides.[9] Additionally, settings with low travel distances will also favor street-hailing. Indeed, as trip distance increases, the reduction in available supply depresses the number of available drivers on the street-hailing service to a stronger extent than the number of drivers for e-hailing. For the latter, an increase in travel distance actually reduces the fraction of time drivers spend on pickup, thus reducing the pickup inefficiency. This latter result is consistent with findings from Daniels and Turcic (2021) whose counterfactual show that limiting the service area of street-hailing could help them better compete against e-hailing.

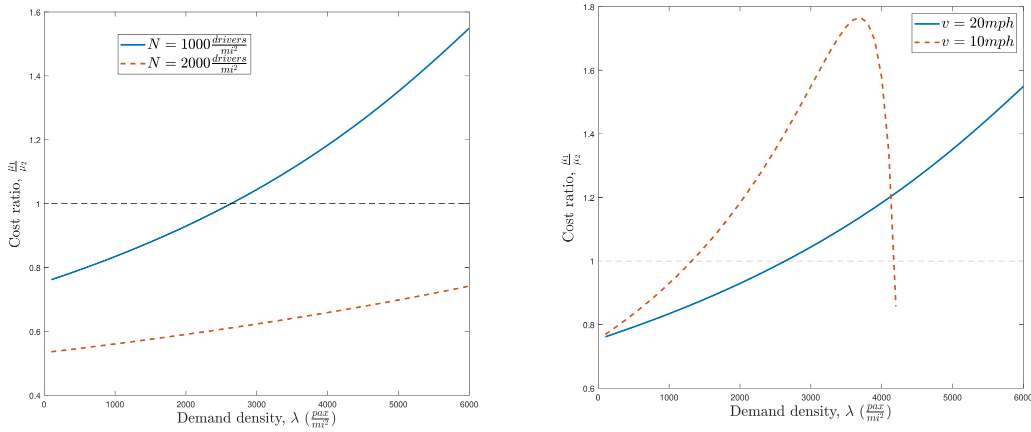
The insights from Proposition 1 and Corollary 1.1 are illustrated in Fig. 1 which presents the cost ratio between e-hailing and street-hailing, $\frac{\mu_s}{\mu_e}$ as a function of demand density.

These results illustrate that, depending on market characteristics, one alternative may be preferable to the other. We might wonder under which circumstances it will be optimal to use both services. Indeed, following the literature on ride-hailing, when two companies operate, increased market frictions due to demand/supply splitting could actually reduce welfare (Zha et al., 2016; Zhang and Nie, 2021a). Thus, it would seem that in dense urban settings with large available supply, two services could be supported. In settings with low driver supply or low demand, operating an e-hailing service might be preferable to operating both. When both services operate, Proposition 1 and Corollary 1.1 simply indicate the circumstances under which street-hailing would dominate the market.

Additionally, as noted by Arnott (1996), Yang et al. (2014) and Zha et al. (2016), at the first-best in a single firm environment, ride-hailing services must be subsidized. When two firms operate, the same finding holds. Indeed, using Eqs. (2g) and (7), it is possible to show that first-best profits are as follows:

$$\pi_i = -(c_i + \omega_i) \cdot n_i^I < 0 \tag{11}$$

[9] Note that this result has nothing to do with different congestion externality from both services, since we have not yet included the effect of vehicles on congestion.



(a) $v = 20$ *mph*

(b) $n = 1000 \frac{drivers}{mi^2}$

Fig. 1. Equilibrium variables under the first-best and the Nash equilibrium. In 1(a), we see that when supply increases, the cost of using street-hailing significantly drops. Moreover, economies of scale are stronger for street-hailing, resulting in a better cost advantage for street-hailing as demand and supply increase. However, when supply is constant, increased demand can eventually cause street-hailing to become more expensive than e-hailing unless demand exceeds a certain threshold and traffic speed is low. Past that threshold, e-hailing drivers' utilization becomes more inefficient 1(b). For all demand levels below that threshold, the cost curves in 1(b) also capture the effect of increased travel distance d^r (as opposed to reduced travel speed) on the relative cost of each service. Due to effects of scale, longer trips have a stronger negative impact on the quality of service of the street-hailing service.

In essence, the fare only covers the time a driver is assigned to serving a customer but not their idle time, resulting in a loss for both ride-hailing companies. Thus, we now take a look at the second-best.

4.3. Second-best

Here, the social planner maximizes welfare subject to profit constraints for both e-hailing and street-hailing. The problem is as follows:

$$\begin{aligned} W = &\max_{\substack{f_i \geq 0,\\ n_i \geq 0}} \quad CS(\mu_s, \mu_e) + \sum_i f_i \cdot \lambda_i - (c_i + \omega_i) \cdot n_i + DS(\omega_s, \omega_e) \\ &\text{s.t} \quad \pi_i \geq \bar{p}_i \cdot \lambda_i \end{aligned} \tag{SB}$$

where $\bar{p}_i$ is the reservation profit per ride served (or commission) for company i. The FONC for this problem is given by:

$$f_i = mc_i \cdot (w_i^d + w^r) - \frac{\delta_i}{1+\delta_i} \cdot \frac{f_i}{\epsilon_i^{dm}} + \frac{\delta_{-i}}{1+\delta_i} \cdot \frac{f_{-i}}{\epsilon_i^{dm}} \cdot \frac{\lambda_{-i}}{\lambda_i} \cdot \frac{\epsilon_{-ii}}{\epsilon_{-i-i}} + \bar{p}_i \cdot \frac{\delta_i}{1+\delta_i} \tag{12a}$$

$$c_i + \omega_i = mc_i - \frac{\delta_i}{1+\delta_i} \cdot \frac{\omega_i}{\eta_i^{dm}} + \frac{\delta_{-i}}{1+\delta_i} \cdot \frac{\omega_{-i}}{\eta_i^{dm}} \cdot \frac{n_{-i}}{n_i} \cdot \frac{\eta_{-ii}}{\eta_{-i-i}} \tag{12b}$$

where $\delta_i \geq 0$ is the Lagrangian multiplier associated with the profit constraint for firm i. Essentially, the profit constraint introduces a wedge between the fare and the marginal cost of service (on the customer side) and a wedge between drivers' earnings and the marginal cost. In essence, the second-best realizes a transfer from customers to companies and drivers. We also note that additional earnings beyond marginal costs on service i are tied to the level of service on the other platform. Thus, in essence, the consolidated firm[10] endogenizes competitive externalities that arise under the Nash game (see Section 5 below).

It is also worth noting that Eq. (12) defines, given the δ_i, a solution on the Pareto frontier that joins the joint monopoly between e-hailing and street-hailing to the first-best.

Further, it is interesting to consider the case when $\delta_e = 0$, i.e., the e-hailing industry is not subject to a profit constraint but operates close to marginal cost. This scenario is somewhat close to the current status quo in the industry. Indeed, because of the vast amount of their financial resources, e-hailing companies have been operating at a loss, subsidizing customers while offering multiple incentives to drivers. Thus, in reality, fares might be below marginal costs while driver incentives bring their earning in line with their marginal benefit. In this context, it is easy to see that street-hailing vehicles are at a natural disadvantage: at most levels of demand, the fare required to use taxi services would be higher than marginal costs (to guarantee profitability of the industry). Thus, the higher market shares for e-hailing that we observe might not necessarily be the result of their efficiency, but rather the outcome of inefficient pricing at two levels: higher than efficient prices for street-hailing and lower than efficient prices for e-hailing.

[10] Recall that joint profits are maximized.

In light of the above, we might ask whether removing restrictions on street-hailing could provide a better outcome for the street-hailing industry as well as the overall impacts of such a move on welfare.

5. Unregulated market

In this section, we focus on an unregulated market featuring both street-hailing and e-hailing. On the one hand, we consider the case when the two industries compete for customers and drivers and try to understand the implications for the profitability of street-hailing. Then, we consider the case of a more integrated operation between the two services and whether and when it is preferable to competition.

5.1. Nash equilibrium

We define the Nash equilibrium as a set of fares $\{f_s^*, f_e^*\}$ and fleet sizes $\{n_s^*, n_e^*\}$ such that, $\forall i \in \{s, e\}$:

$$(f_i^*, n_i^*) = \max_{\substack{f_i \geq 0,\\ n_i \geq 0}} \quad f_i \cdot \lambda_i(f_i, f_{-i}^*, n_i, n_{-i}^*) - [\omega_i(f_i, f_{-i}^*, n_i, n_{-i}^*) + c_i] \cdot n_i \tag{NE}$$

The FONC resulting from (NE) is as follows:

$$f_i = mc_i \cdot (w_i^d + w^r) - \frac{f_i}{\epsilon_i^{ne}} \tag{13a}$$

$$mc_i = c_i + \omega_i \cdot \left[1 + \frac{\eta_{-i-i}}{\eta_{ii} \cdot \eta_{-i-i} - \eta_{-ii} \cdot \eta_{i-i}} \right] \tag{13b}$$

with:

$$\epsilon_s^{ne} = \epsilon_{ss} - \frac{\lambda_e}{f_e} \cdot \frac{\beta \cdot (w_e^m + w^r) \cdot w_e^{m'}}{1 + w_e^{m'} \cdot \left[1 + \beta \cdot (w_e^m + w^r) \cdot \Lambda_{ee} \right]} \cdot \epsilon_{se} \cdot \epsilon_{es} < 0 \tag{14a}$$

$$\epsilon_e^{ne} = \epsilon_{ee} - \frac{\lambda_s}{f_s} \cdot \frac{\beta \cdot w^r \cdot w_s^{m'}}{1 + \beta \cdot w_s^{m'} \cdot w^r \cdot \Lambda_{ss}} \cdot \epsilon_{se} \cdot \epsilon_{es} < 0 \tag{14b}$$

In the above, ϵ_{ij} represents the elasticity of demand on service i with respect to the cost of service j; and η_{ij} is the elasticity of supply on service i with respect to the hourly wage on service j. Comparing Eqs. (7) and (13), it is expedient to note that the action of the planner contributes to increasing both the demand and supply for each service compared to their levels in the unregulated case.

By examining Eqs. (14a) and (14b), we note that the markup on one service is a function of friction imposed by a marginal customer on the other service: the higher the marginal friction on the other service, the higher the markup charged by a given firm, $\frac{1}{|\epsilon_i^{ne}|}$. In particular, because of deadheading trips on the e-hailing platform, marginal frictions are higher for e-hailing when demand is high: the street-hailing platform will be able to command higher prices relative to its marginal cost than e-hailing ($|\epsilon_s^{ne}| < |\epsilon_e^{ne}|$). This insight could also be gotten at by considering that, when demand is high, the marginal cost for e-hailing will be higher than that for street-hailing (again, due to increased friction). Thus, the ability of e-hailing to raise fares above marginal cost is lower compared to that of street-hailing. *Thus, in the absence of supply and price constraints and in high density areas, street-hailing stands to benefit more than e-hailing, from a pricing perspective.*

It is also useful to compare the above results to those under a monopoly (which operates a single e-hailing or street-hailing platform with the same market size), which we recall below from Zha et al. (2016):

$$f^{sm} = mc \cdot (w^d + w^r) - \frac{f^{sm}}{\epsilon^{sm}} \tag{15a}$$

$$mc = c^{sm} + \omega^{sm} \cdot \left[1 + \frac{1}{\eta^{sm}} \right] \tag{15b}$$

where the superscript sm indicates that the relevant functions and quantity are that faced by a single service monopoly.

In principle, we expect $|\epsilon_{ii}| \geq |\epsilon^{sm}|$ since, given other options, users become more sensitive to price increases. However, as indicated earlier, the market power term, $\frac{f_i}{\epsilon_i^c}$ under the Nash equilibrium also depends on friction on the competing platform: the larger the friction (low n_{-i}^I or high w^r), the lower, in absolute term, ϵ_i^c. If friction is sufficiently high, higher prices may result under the NE compared to the single firm, single service case: $|\epsilon_i^c| \leq |\epsilon^{sm}|$. This is consistent with numerical experiments from Zha et al. (2016) and Zhang and Nie (2021a) and we show in Appendix B that frictions are the main drivers of this phenomenon.

Comparing Eqs. (13b) and (15b), we note that competition on the driver side can lead to a substantial reduction of supply under the duopoly. Indeed, when the cross-elasticities of substitution are high (high η_{i-i} and η_{-ii}), unless demand served is high, the incentive for hiring supply can decrease, leading to lower supply overall. This corroborates numerical examples from Zhang and Nie (2021a) and indicates that, multi-homing on the driver side might actually result in a lower driver pool and lower quality of service.

5.2. Integrated monopoly

In this section, we seek to provide insights into recent developments in cities like NYC where Uber will begin listing street-hail drivers on its platform (Rana, 2022). In the context of this paper, we will assume that a single firm is able to integrate and manage pricing and compensation for both services at the same time. Importantly, we do not incorporate the fact that street-hailing drivers could also be matched to e-hailing customers. Indeed, in our context, we are concerned with efficiency gains/losses that might result from joint pricing and compensation. The case of differentiated supply for e-hailing in the presence of street-hailing will be modeled and discussed in a subsequent work. With this in mind, the profit maximization problem is given by:

$$\pi^{dm} = \max_{\substack{f_i \geq 0, \\ n_i \geq 0}} \quad \sum_i f_i \cdot \lambda_i - (\omega_i + c_i) \cdot n_i \tag{DM}$$

The FONC for (DM) yields:

$$f_i = mc_i \cdot (w_i^d + w^r) - \frac{f_i}{\epsilon_i^{dm}} + \frac{f_{-i}}{\epsilon_i^{dm}} \cdot \frac{\lambda_{-i}}{\lambda_i} \cdot \frac{\epsilon_{-ii}}{\epsilon_{-i-i}} \tag{16a}$$

$$c_i + \omega_i = mc_i - \frac{\omega_i}{\eta_i^{dm}} + \frac{\omega_{-i}}{\eta_i^{dm}} \cdot \frac{n_{-i}}{n_i} \cdot \frac{\eta_{-ii}}{\eta_{-i-i}} \tag{16b}$$

where

$$\epsilon_i^{dm} = \epsilon_{ii} - \frac{\epsilon_{-ii} \cdot \epsilon_{i-i}}{\epsilon_{-i-i}} \tag{17a}$$

$$\eta_i^{dm} = \eta_{ii} - \frac{\eta_{-ii} \cdot \eta_{i-i}}{\eta_{-i-i}} \tag{17b}$$

and dm indicates that quantities correspond to those faced by a dual service monopoly. Comparing Eqs. (13) and (16), we note that integrating the platforms in an unregulated market has two effects. On the one hand, fares for both services increase in tandem since the absence of competition increases the monopolist's market power. On the other hand, the monopolist internalizes the friction-related competitive externality that arises in the Nash equilibrium. For given levels of supply and demands, the direct effect of this internalization can be to either increase or decrease prices for a given service. Indeed, let us compare ϵ_i^{ne} and ϵ_i^{dm}. We have:

$$\epsilon_s^{ne} - \epsilon_s^{dm} = -\frac{\lambda_e}{f_e} \cdot \epsilon_{se} \cdot \epsilon_{es} \cdot \left[\frac{\beta \cdot (w_e^m + w^r) \cdot w_e^{m\prime}}{1 + w_e^{m\prime} \cdot \left[1 + \beta \cdot (w_e^m + w^r) \cdot \Lambda_{ee}\right]} - \frac{1}{\Lambda_{ee}} \right] \tag{18a}$$

$$\epsilon_e^{ne} - \epsilon_e^{dm} = -\frac{\lambda_s}{f_s} \cdot \epsilon_{se} \cdot \epsilon_{es} \cdot \left[\frac{\beta \cdot w^r \cdot w_s^{m\prime}}{1 + \beta \cdot w_s^{m\prime} \cdot w^r \cdot \Lambda_{ss}} - \frac{1}{\Lambda_{ss}} \right] \tag{18b}$$

When frictions are high (low n_i^I and high w^r), the quantities in Eq. (18) are positive: each individual firm's markup is higher than what it would be under the integrated monopoly. If friction is sufficiently high, then, the price under the Nash equilibrium might even exceed that under the integrated monopoly, and this despite the latter's greater market power. Thus, it cannot be ruled out that integration might actually reduce prices and be profitable for both customers and producers.[11]

6. Policy analysis

Following our discussions in Sections 4 and 5 it is indubitable that the regulatory environment must change. This can be done by regulating both fares and entry in both markets. However, such an approach would be rather heavy-handed and would remove an important feature of ride-hailing's performance: its flexibility. In the following section, we will investigate possible alternatives and their outcomes.

6.1. Commission cap on e-hailing, regulation adjustment for street-hailing

Following Zha et al. (2016) and Vignon et al. (2021), it is known that a cap on the commission of an e-hailing monopoly can replicate the second-best when supply is perfectly elastic. In the presence of competition between e-hailing and street-hailing, would such a cap be effective, assuming fares and supply regulations for street-hailing are properly adjusted? Under a commission cap, the problem for the e-hailing platform becomes:

$$\begin{aligned} \pi_e = \max_{\substack{f_e \geq 0, \\ n_e \geq 0, \\ r_e \geq 0}} \quad & (f_e - r_e) \cdot \lambda_e \\ \text{s.t} \quad & (\omega_e + c_e) \cdot n_e = r_e \cdot \lambda_e, \\ & (f_e - r_e) \cdot \lambda_e = r_e \leq \bar{p}_e \cdot \lambda_e \end{aligned}$$

11 Again, we show in Appendix B that such an issue does not arise in a friction-less environment.

where $\bar{p}_e$ is the commission cap. The problem can be recast as:

$$\begin{aligned} \pi_2 = \max_{\substack{f_e \geq 0,\\ n_e \geq 0}} \quad & \bar{p}_e \cdot \lambda_e \\ \text{s.t} \quad & (\omega_e + c_e) \cdot n_e \geq (f_e - \bar{p}_e) \cdot \lambda_e \end{aligned} \tag{EH-REG}$$

Thus, the e-hailing platform must maximize demand served on its platform. Can such as regulation induce the platform to choose the socially optimal f_e and n_e? Suppose not. Clearly, the set of decision variables that would be chosen by the platform must be such that $\lambda_e^{dm} > \lambda_e^{sb}$. Such an increase over the socially-optimal market share would have to come at the expense of either the street-hailing service or the outside option. However, those customers switching from either of these services would see their utility increase relative to the second-best.[12] Therefore we must ask what happens to those customers who remain on the street-hailing service. Since both the fares and the fleet size are set, it follows that they will experience lower waiting times. Thus, their utility also increases. This implies that the second-best is actually not Pareto efficient, a contradiction.

Additionally, the regulator must set n_s and f_s appropriately, since street-hailing's limited supply puts them at a disadvantage.

Thus, the proposed regulation is optimal and provides a simple avenue for policymakers to make the ride-hailing market more efficient. Are there other, potentially simpler regulations able to achieve the same objective?

6.2. Consolidation and commission cap regulation

Since the social planner maximizes the joint producer profit, we might ask whether consolidating the ride-hailing industry and then regulating the resulting monopoly might be a better approach. This approach would lead to a major restructuring of the ride-hailing industry but would also simplify the patchwork of regulation that governs the industry. It would also leave a number of operational features such as pricing and wages into the hands of service operators which could provide for better and more synergistic operation between the two services.

Thus, consider the following problem:

$$\begin{aligned} \pi_M = \max_{\substack{f_i \geq 0,\\ n_i \geq 0,\\ l_s, r_e \geq 0}} & (l_s - c_s^c) \cdot n_s + (f_e - r_e) \cdot \lambda_e \\ \text{s.t} \quad & (\omega_s + c_s^d + l_s) \cdot n_s = f_s \cdot \lambda_s \\ & (\omega_e + c_e) \cdot n_e = r_e \cdot \lambda_e \\ & (l_s - c_s^c) \cdot n_s \leq \bar{p}_s \cdot \lambda_s \\ & (f_e - r_e) \cdot \lambda_e \leq \bar{p}_e \cdot \lambda_e \end{aligned}$$

First, it is easy to note that, unless $\bar{p}_s = \bar{p}_e = \bar{p}$, the regulation might lead to the highest cap service being over-utilized following the monopolist's bid to maximize profits. Thus, for this regulation to be effective, both caps must be identical to ensure that the monopoly favors a service over the other only on efficiency grounds. Then, we can rewrite the above as:

$$\begin{aligned} \pi_M = \max_{\substack{f_i \geq 0,\\ n_i \geq 0}} \quad & \bar{p} \cdot \sum_i \lambda_i \\ \text{s.t} \quad & (\omega_i + c_i) \cdot n_i \geq (f_i - \bar{p}) \cdot \lambda_i \end{aligned} \tag{MONO-REG}$$

Naturally, the monopolist will choose f_i and n_i such that $\lambda_s^{dm} + \lambda_e^{dm} \geq \lambda_s^{sb} + \lambda_e^{sb}$. If $\lambda_s^{dm} + \lambda_e^{dm} > \lambda_s^{sb} + \lambda_e^{sb}$, it could mean that the monopolist is charging lower than second-best prices. Since this behavior must be profit maximizing, it follows that the reduction in fares is also accompanied by a reduction in earnings for either one or both groups of drivers. Thus, essentially, the monopolist would realize a surplus transfer from drivers to consumers in order to increase its profits. When supply is perfectly elastic so that all drivers are identical and drivers have a reservation wage $\underline{\omega}$, such a profitable move from the monopolist does not arise since driver surplus is null and any reduction in that surplus would result in a loss of supply.

On the other hand, a profitable deviation of the monopoly might be to increase driver earnings which would in turn reduce waiting times and result in higher fares for customers but, most importantly, increase the number of customers for the platform.[13] However, if such an approach were preferable to the second-best, it would mean that every agent' surplus increases, which would contradict the Pareto optimality of the second-best. Thus, when supply is homogeneous, consolidating the industry and imposing an identical commission cap is not only welfare improving but can replicate the second-best. *Following Uber's move of opening its app to street-hail drivers, regulating the industry might be simpler and more straightforward than in the case of outright competition.*

When supply is heterogeneous, the distortion created from the second-best may or may not be significant: this becomes an empirical question.

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[12] This is why they switch.

[13] Otherwise, profits would not increase.

6.3. Nash game with commission cap

Would it be possible to keep both industries separate while applying a commission cap? This would avoid the regulatory headache that would arise from trying to determine how stakes in a consolidated ride-hailing company would be allocated among current actors in the ride-hailing industry. Moreover, the consolidated setting is somewhat restrictive since only identical caps can be imposed. Under a commission cap regulation of two competing firms, we would have:

$$\begin{aligned} \pi_i = \max_{\substack{f_i \geq 0,\\ n_i \geq 0}} \quad & f_i \cdot \lambda_i - (c_i + \omega_i) \cdot n_i \\ \text{s.t} \quad & (\omega_i + c_i) \cdot n_i \geq (f_i - \bar{p}_i) \cdot \lambda_i \end{aligned} \tag{NE-REG}$$

Here, it is not straightforward to demonstrate that neither company has an incentive to deviate from the second-best. Indeed, either company could increase its wage rate and/or decrease its prices to increase its market share at the expense of the other company. However, we are able to show that, so long as the company is sustainable under the second-best, the regulation can achieve the desired outcome. This can be shown in the manner of Vignon et al. (2021). Indeed, let θ_i be the Lagrangian multiplier associated with the commission cap constraint in (NE-REG). Then, assuming the regulation replicates the second-best, we must have:

$$\theta_i = \frac{f_i^{ne} - f_i^{sb}}{f_i^{ne} - (c_i + \omega_i) \cdot \frac{n_i}{\lambda_i}} \geq 0 \tag{19}$$

where f_i^{ne} and f_i^{sb} are the fare formulae derived in Eqs. (7a) and (13a) evaluated at the targeted second-best. Now, at the second-best, it must be that $f_i^{ne} \geq f_i^{sb}$. Otherwise, regulatory intervention is not warranted since it increases prices while there are no externalities. If the second-best is sustainable, then it must also be that $f_i^{sb} \geq (c_i + \omega_i) \cdot \frac{n_i}{\lambda_i}$. Thus, necessarily, $\theta_i \geq 0$. Thus, provided both companies make positive profits at the second-best, the commission cap regulation can regulate the duopoly ride-hailing market.

7. Congestion and competition

As mentioned in Section 2, the rise of e-hailing has been associated with an increase in congestion in major urban centers. Thus, regulators have been looking into ways to address the issue by imposing congestion fees, tolls and minimum fleet utilization rate requirements. As pointed out in Vignon et al. (2021) and in Zhang and Nie (2021b), the latter set of regulations are either redundant or detrimental to welfare. Rather, as shown by Zhang and Nie (2021b), the imposition of tolls on either trips or e-hailing drivers present the best opportunity for regulators to address the issue of congestion. Moreover, as pointed out by Vignon et al. (2021) and Xu et al. (2017), in a monopoly setting, when congestion increases, the monopolist and the social planner tend to behave similarly: they both look to mitigate the negative impact of congestion. Thus, regulatory intervention in that context might not be needed. However, we might wonder whether such a reasoning holds in the context of competition within the ride-hailing industry. Lastly, should competition create significant congestion issues, we must determine whether and to which extent tolls should be differentiated between e-hailing and street-hailing companies.

To answer these questions, we must first extend our model in Eq. (2) to incorporate background traffic and congestion.

Assuming that background traffic trips originate at a (given) rate λ^b with an average trip length of d^{rb}, we have:

$$w^{rb} = \frac{d^{rb}}{v} \tag{20a}$$

$$n^b = \lambda^b \cdot w^{rb} \tag{20b}$$

where w^{rb} represents the average travel time of background traffic. Then, following the network macroscopic fundamental diagram approach (Geroliminis and Daganzo, 2008), it is possible to describe the average traffic speed v using the accumulation of vehicles in the network, which is the sum of the number of vehicles for each service n_i and the number of background vehicles n^b:

$$v = V(n^b + \sum_i n_i) \tag{21}$$

with $V'(\cdot) < 0$.

We show in Appendix C that, under the Nash game, unlike the integrated monopolist which internalizes all but the congestion externality it imposes on background travelers, ride-hailing companies competing against each other benefit from the fact that congestion hurts their opponent (Appendix C.1). Thus, they do not fully internalize their congestion externality. This leads to more drivers on the road than in the monopoly case and can have deleterious effects on congestion. Under the first-best, because the planner regulates a consolidated ride-hailing company, the "competitive" externality is internalized (Appendix C.2). More interestingly, from the point of view of the planner, all vehicles impose the same externality on traffic regardless of their status—background vehicle, e-hailing vehicle or street-hailing vehicle. Thus, not only should ride-hailing vehicles be tolled, but so should background traffic vehicles.[14]

[14] This is shown by making background traffic elastic.

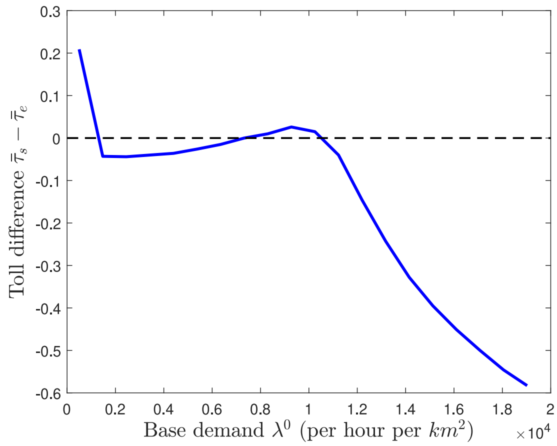


Fig. 2. Toll difference between street-hailing and e-hailing.

When it comes to regulatory actions, imposing appropriate tolls and commission caps can readily achieve the first-best (or the second-best). Indeed, when congestion is present, the social planner essentially maximizes demand served after accounting for the higher (social) cost of operating a vehicle. Thus, once an appropriate toll is set, it is straightforward to verify that, given the commission cap, our insights from Section 6 carry over. Most importantly, however, despite congestion, it is possible to regulate the market, regardless of its structure, using only commission caps (Appendix C.3). If, however, regulatory authorities decide to impose a toll, e-hailing might end up bearing a higher toll per unit time than street-hailing ($\bar{\tau}_e - \bar{\tau}_s \geq 0$), as shown in Fig. 2. This strategy is consistent with, for example, NYC's surcharge structure which charges e-hailing trips \$0.25 higher than street-hailing trips (TLC, 2022).

8. Further considerations

The preceding sections have shown that by regulating both e-hailing and street-hailing companies uniformly with a commission cap (and at times also with a toll), welfare can be maximized. Here, we would like to discuss a few practical considerations.

First, an obvious issue that must be addressed is the current medallion system that regulates the operation of street-hailing. As discussed in Section 6.1, it is possible to address the limited street-hailing supply by increasing the number of available licenses. This measure would be incremental and create the least possible disruptions.

Another strategy would be to do away with the medallion system for street-hailing. While this would be harder to implement, it would simplify regulation of the industry in the long run while allowing for the industry to adjust and respond to changing market conditions more easily. One approach to implementing that strategy would be for the city to buy back medallions from their owners at current market rates (or another agreed upon rate) and then establish a single street-hailing company which would operate subject to the commission cap. This company would, however, be free to set its own fares and to decide how many vehicles to use to provide service and compete with e-hailing companies. Another approach would be to directly consolidate all medallion owners under one company, while providing an avenue for owners uninterested by the venture to sell their share to the consolidated company. Here again, this company would operate under the commission cap.

The second obvious issue is that of competition and congestion. Indeed, several e-hailing companies already compete for dominance of the market in the US. Unshackling the street-hailing industry by reducing its regulatory burden would only make competition more ferocious and could severely affect congestion. In this context, a potential regulatory approach would be to force a merger of these e-hailing companies. In that context, two main companies, one street-hailing company and one e-hailing company, would operate independently while subject to a commission cap.

In the early days of such configuration, either company could over-invest in vehicles and drivers. This would likely be the case for the street-hailing company since its operation requires capital investments in vehicles. Indeed, street-hailing's supply of vehicles is more sticky and less nimble than that of e-hailing (since the former requires capital investment while the latter does not). This could potentially push the street-hailing company, in anticipation of fierce competition from e-hailing, to acquire a fleet larger than is optimal. The commission cap should, however, moderate that impulse since the company would still need to generate enough revenue *per driver* to keep a stable workforce. Additionally, a congestion toll would further inhibit any over-investment impulse from either company. If these moderating effects are deemed insufficient by the regulator, a monthly limit on the increase in the supply of cabs could be set for the street-hailing company. Such a measure would last for a limited period and should further moderate an over-investment impulse.

We must however note that a merger of these e-hailing companies is not an action that can be decided at the city level. Thus, city officials might simply have to tailor the commission cap regulation to a context in which several e-hailing companies operate and compete against one street-hailing company, keeping in mind some of the considerations we have outlined above.

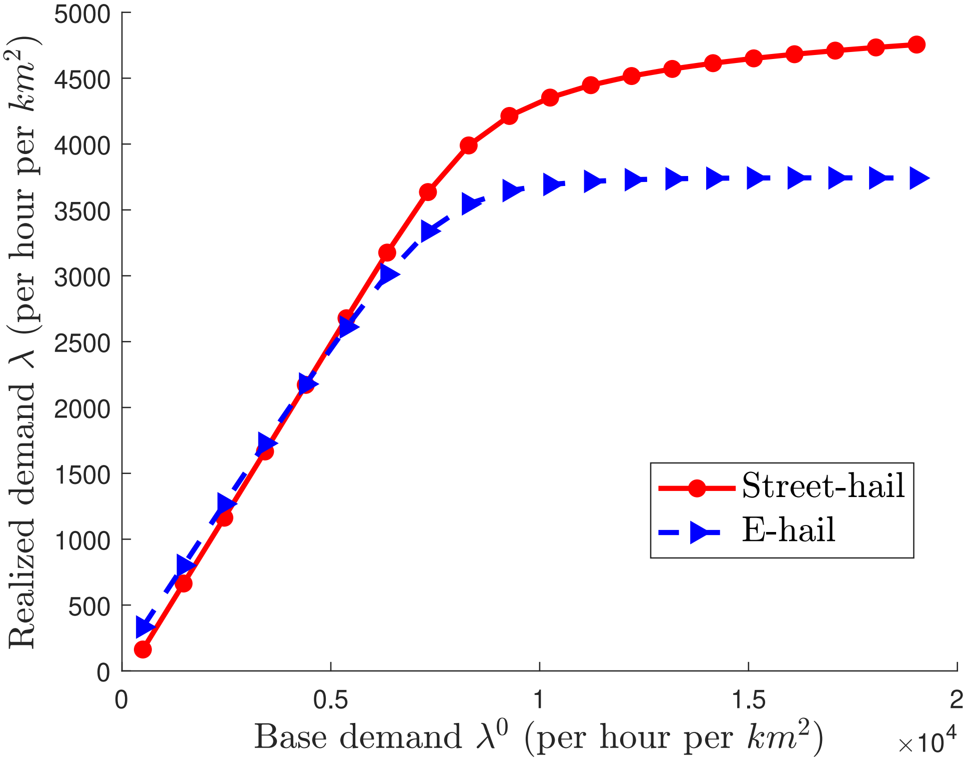


Fig. 3. Demand for e-hailing and street-hailing under the first-best.

9. Numerical examples

In this section, we present different numerical examples to illustrate some of our findings and provide further insights. Details on the numerical examples are given in Appendix D.

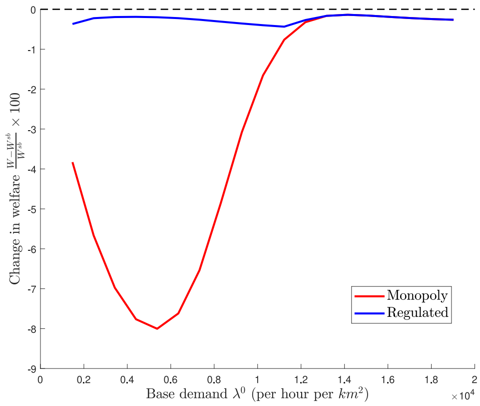
9.1. Socially optimal configuration

Fig. 3 shows demand served by the two services under the first-best. When the market size is low, demand served on the e-hailing platform is slightly larger than that for street-hailing. However, as the system becomes denser, the dominance switches to e-hailing and the divide between the two services widens. Note, however, that this larger divide only occurs at very passenger densities high densities (equivalent to serving, for example, NYC's travel demand solely with ride-hailing). In a context closer to actual observed demand (3000 passengers per unit area), the market shares for both types of services should be close to each other.

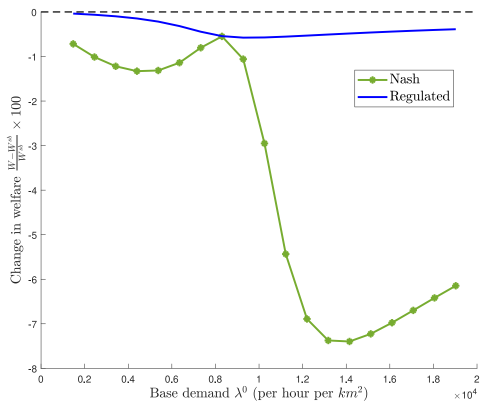
Moreover, we also note that, in most scenarios of interest, it is optimal for the planner to use both services. Further numerical examples show that only when demand is extremely low (e.g.: 250 inhabitants per square mile or less) and travel distances large (e.g.: 25 mi or higher) is it more efficient to operate only the e-hailing service.

9.2. Effects of commission cap regulation

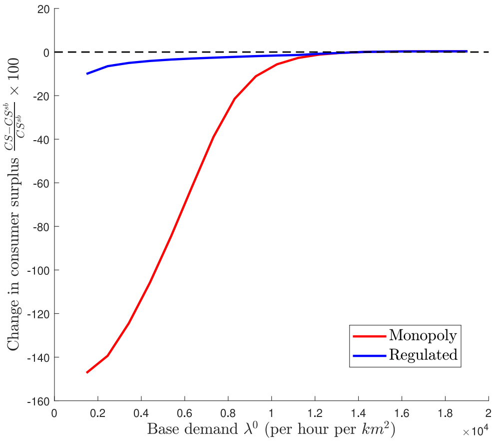
As shown in Figs. 4(a) and 4(b), the commission cap regulation can significantly improve welfare in both the monopoly and duopoly cases. However, the manner in which the cap achieves that objective differs in both settings. In the monopoly case, the effect of the cap is to increase demand in low density markets (Fig. 4(c)). Indeed, in these markets, the monopolist's decisions tend to restrict demand with higher than optimal prices. As density increases, the behavior of the monopolist starts to mirror that of the planner, thus resulting in improved welfare (despite a mild increase in congestion relative to the second-best). Under a duopoly, the same demand and traffic patterns compared to the monopoly occur when density is low (Figs. 4(d) and 4(f)). However, as density increases, competition between the two services leads to a significant reduction in traffic speed. In that context, by forcing each company to improve its efficiency, the commission cap also contributes to improving traffic speed while increasing consumer welfare.



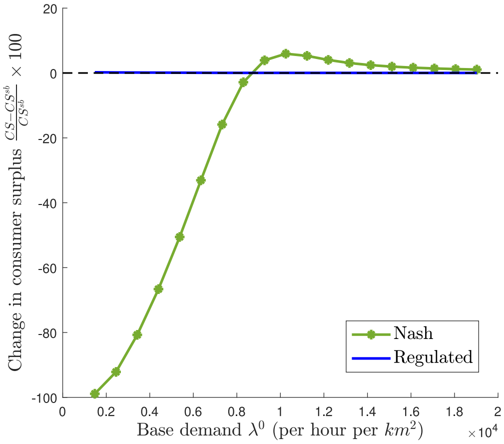
(a) *Welfare under integrated monopoly*



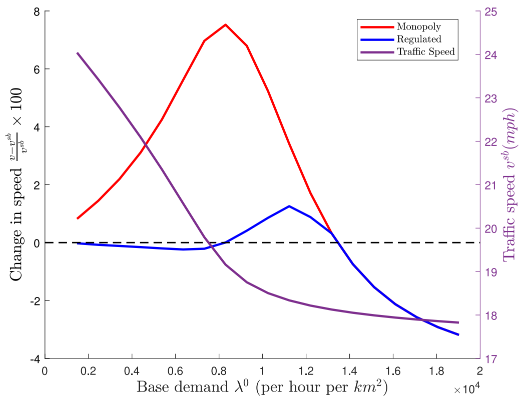
(b) *Welfare under Nash equilibrium*



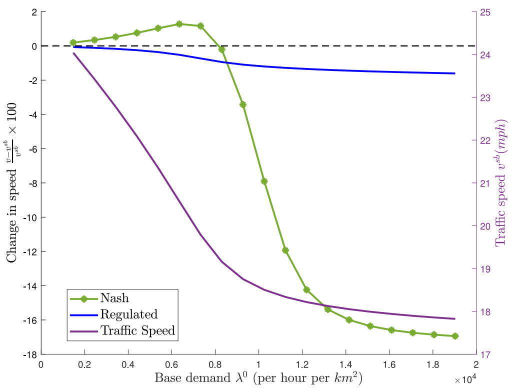
(c) *Consumer surplus under integrated monopoly*



(d) *Consumer surplus under Nash equilibrium*



(e) *Traffic speed under integrated monopoly*



(f) *Traffic speed under Nash equilibrium*

Fig. 4. Effect of commission cap regulation under both an integrated monopoly and a Nash game. The commission cap improves welfare and contributes to reducing congestion in both settings. As demand increases and the system becomes more congested under the second-best, the monopolist's behavior leads to slightly more congestion than under the second-best. Thus, the commission cap regulation mostly serves to increase consumer welfare (Fig. 4(c)). However, in the Nash game, competition can have dramatic effects on congestion. In that context, the commission cap can reduce congestion (Fig. 4(f)) while obtaining socially efficient levels of demand (Fig. 4(d)).

10. Conclusion

In this paper, we have sought to inform the development of policies for the ride-hailing industry in the age of uberization. To this effect, we presented a model of competition in the ride-hailing industry and analyzed the impact of current and alternative policies to regulate that market. Some of our key findings are as follows:

- we analytically show that, in denser settings, or when trip distances are low or traffic speed is low, the socially-efficient cost of street-hailing will be lower than that of e-hailing. Thus, in cities like NYC, there is room for a more expanded role of street-hailing in serving the market;
- additionally, we show that in these settings and barring any supply or fare restrictions, the street-hailing industry can have greater market power and thus, better fend for itself. Thus, the industry should seek to relax their current supply restrictions as opposed to trying to curtail e-hailing;
- we also show that, despite the potential benefits of relaxed regulation on street-hailing for that industry, unchecked competition between e-hailing and street-hailing would still result in higher prices and higher congestion than is socially efficient. This latter effect of deregulation on congestion does not, however, arise when the pricing and compensation for both platforms is managed by a single platform;
- lastly, we show that, by imposing a commission cap on either an integrated company or the two competing services, both consumer welfare and congestion levels will improve. Especially, under certain assumptions, such regulation can readily achieve the socially optimal configuration. This demonstrates the effectiveness of commission cap regulation, as it is effective even in congested and competitive settings.

In our analysis, we have not considered spatially heterogeneous markets. Indeed, we have shown that both services have different efficiency advantages depending on the characteristics of demand (density and distance of trips requested) and of traffic. In a spatially heterogeneous context, we might wonder whether an equilibrium in which the two services do not directly compete with each other but operate in markets in which they have a competitive advantage is socially efficient. We might also wonder whether a commission cap regulation could achieve the socially efficient outcome in a setting of spatial competition. We also have not considered the potential efficiency gains or losses that might come from allowing street-hailing drivers to be matched to street-hailing customers. We will propose a model appropriate for exploring that question. Lastly, our present work will be further enhanced by bringing data to our model to better inform policymakers and help answer practical questions such as the value of an appropriate commission cap in NYC or the distributional effects of such a policy.

CRediT authorship contribution statement

Daniel Vignon: Methodology, Validation, Formal analysis, Investigation, Writing – original draft, Visualization, Writing – review & editing. **Yafeng Yin:** Conceptualization, Methodology, Writing – review & editing, Funding acquisition. **Jintao Ke:** Conceptualization, Writing – review & editing.

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Appendix A. Nomenclature

See Table A.1.

Appendix B. Competition in friction-less environment

In order to show that, in the absence of friction, competition necessarily leads to lower fares, we will consider a perfectly elastic labor supply with reservation wage c. Then, both services are identical and the system of equations that describes the operation of this friction-less hailing service is as follows:

$$\lambda_i = \Lambda_i(\mu_i, \mu_{-i}) \tag{B.1a}$$

$$\mu_i = f_i + \beta \cdot w^r \tag{B.1b}$$

$$w^r = \frac{d^r}{v} \tag{B.1c}$$

$$n_i = \lambda_i \cdot w^r \tag{B.1d}$$

The above system is actually determined by two exogenous variables which we select to be the fares. Then, the Nash equilibrium can be described by the following set of equations:

$$f_i = -\frac{f_i}{\epsilon_{ii}} + c \cdot w^r \quad \forall i \tag{B.2}$$

Table A.1
Variable description.

Variable	Description	Unit
μ_i	Generalized cost of service i	$
λ_i	Demand density rate for service i	/mi²/h
f_i	Trip fare for service i	$
w_i^m	Average customer waiting time on service i	h
w^r	Average trip time	h
d_i^m	Distance between customer and closest available driver on service i	mi
d^r	Average trip distance	mi
v	Traffic speed	mi/h
n_i^I	Density of idle/cruising drivers on service i	/mi²
n_i	Driver density on service i	/mi²
ω_i	Hourly driver earnings on service i	$
w_i^d	Average pickup time experienced by drivers on service i	h
$\overline{mc}_i$	Marginal cost for service i	$
mc_i	Marginal cost per unit time for service i	$/h
$\bar{p}_i$	Commission cap imposed on service i	$
$\bar{\tau}_i$	Toll per unit time imposed on service i vehicles	$/h
λ^b	Trip density rate for background vehicles	/mi²/h
w^{rb}	Average travel time for background vehicles	h
n^b	Density of background vehicles	/mi²

It is trivial to show that the pricing equation for a monopoly operating a single service is identical to Eq. (B.2):

$$f^{sm} = -\frac{f^{sm}}{\epsilon^{sm}} + c \cdot w^r$$

However, at any level of supply and demand combination, the elasticity of demand faced by the monopoly is lower, in absolute terms, than that faced by a duopolist: $|\epsilon^{sm}| < |\epsilon_{ii}|$. It follows that, at equilibrium, the fare is always lower in the duopoly case for this friction-less service. If the monopoly operates both services, the same conclusion holds, since $\epsilon_{ii} - \epsilon_i^{dm} = \frac{\epsilon_{-ii} \cdot \epsilon_{i-i}}{\epsilon_{-i-i}} < 0$.

Appendix C. Derivation under congestion

We apply the same analysis techniques as in Sections 4 and 5.

C.1. Nash game and integrated monopoly

Under congestion, the Nash equilibrium can be described with the following set of equations:

$$f_i = mc_i \cdot (w_i^d + w^r) - \frac{f_i}{\epsilon_i^{ne}} \tag{C.1a}$$

$$mc_i = c_i + \omega_i \cdot \left[1 + \frac{\eta_{-i-i}}{\eta_{ii} \cdot \eta_{-i-i} - \eta_{-ii} \cdot \eta_{i-i}}\right] + \tau_i^o + \tau_i^{ne} \tag{C.1b}$$

where

$$\tau_s^o = -\beta \cdot \lambda_s \cdot [d_s^m - d^r \cdot \lambda_s \cdot w_s^{m'}] \cdot \delta^c > 0 \tag{C.2a}$$

$$\tau_e^o = -\beta \cdot \lambda_e \cdot \frac{d_e^m - d^r \cdot \lambda_e \cdot w_e^{m'}}{1 + \lambda_e \cdot w_e^{m'}} \cdot \delta^c > 0 \tag{C.2b}$$

$$\tau_s^{ne} = -\frac{f_s}{\epsilon_s^{ne}} \cdot [d_e^m - d^r \cdot \lambda_e \cdot w_e^{m'}] \cdot \frac{\Lambda_{se}}{1 + w_e^{m'} \cdot \left[1 + \beta \cdot (w_e^m + w^r) \cdot \Lambda_{ee}\right]} \cdot \delta^c < 0 \tag{C.2c}$$

$$\tau_e^{ne} = -\frac{f_e}{\epsilon_e^{ne}} \cdot [d_s^m - d^r \cdot \lambda_s \cdot w_s^{m'}] \cdot \frac{\Lambda_{es}}{1 + \beta \cdot w^r \cdot d_s^{m'} \cdot \Lambda_{ss}} \cdot \delta^c < 0 \tag{C.2d}$$

$$\delta^c = \frac{V'}{v^2 + \lambda^b \cdot d^{rb} \cdot V'} < 0 \tag{C.2e}$$

From Eq. (C.1a), it is easy to note that a competing ride-hailing platform internalizes the congestion externality that its marginal customer imposes on its other customers (τ_i^o). However, the term τ_i^{ne} and the absence of τ_{-i}^o in firm's i pricing equation also indicate that the platform considers the externality that this marginal customer imposes on customers on the competing platform. Such externality is advantageous from a competitive standpoint and incentivizes the company to price its rides less than it would in the absence of a competitor. Indeed, if we consider an integrated company, the pricing equations become:

$$f_i = mc_i \cdot (w_i^d + w^r) - \frac{f_i}{\epsilon_i^{dm}} + \frac{f_{-i}}{\epsilon_i^{dm}} \cdot \frac{\lambda_{-i}}{\lambda_i} \cdot \frac{\epsilon_{-ii}}{\epsilon_{-i-i}} \tag{C.3a}$$

$$mc_i = c_i + \omega_i \cdot \left[1 + \frac{1}{\eta_i^{dm}}\right] - \frac{\omega_{-i}}{\eta_i^{dm}} \cdot \frac{n_{-i}}{n_i} \cdot \frac{\eta_{-ii}}{\eta_{-i-i}} + \sum_j \tau_j^o \tag{C.3b}$$

Comparing Eqs. (16b) and (C.1b), it is easy to note that τ_i^{ne} disappears from the company's pricing and that τ_{-i}^o is also accounted for. Thus, it appears that competition has the effect of worsening traffic congestion.

C.2. First-best

The solution to the first-best problem:

$$W = CS(\mu_1, \mu_2) + \sum_i \left[f_i \cdot \lambda_i - \omega_i \cdot n_i\right] + DS(\omega_1, \omega_2) - \beta^b \cdot \lambda^b \cdot w^{rb} \quad \underset{f_i \geq 0,\; r_i \geq 0}{} \tag{FBC}$$

can be readily derived as:

$$f_i = mc_i \cdot (w_i^d + w^r) \tag{C.4a}$$

$$mc_i = c_i + \omega_i + \sum_j \tau_j^o + \tau^b \tag{C.4b}$$

where

$$\tau^b = -\beta^b \cdot \lambda^b \cdot d^{rb} \cdot \delta^c > 0 \tag{C.5}$$

As the inclusion of τ^b indicates, ride-hailing customers must now pay for the externality they impose on the background traffic. Moreover, just as in the congested monopoly case of Vignon et al. (2021), the first-best is sustainable when congestion is high enough:

$$\pi_i = -(c_i + \omega_i) \cdot n_i^I + (\tau_i^o + \tau^b) \cdot (w_i^d + w^r) \cdot \lambda_i \tag{C.6}$$

C.3. Regulation

We focus on the case of regulation using a cap $\bar{p}_i$ and a toll $\bar{\tau}_i \in [0, \tau^b]$ on ride-hailing vehicles. The case for the integrated monopoly is similar to the case of a monopoly with product differentiation considered in Vignon et al. (2021). Under our regulation, the Nash game becomes:

$$\begin{aligned} \pi_i = &\max_{f_i \geq 0,\, n_i \geq 0} \quad f_i \cdot \lambda_i - (c_i + \omega_i + \bar{\tau}_i) \cdot n_i \\ &\text{s.t} \quad (\omega_i + c_i + \bar{\tau}_i) \cdot n_i \geq (f_i - \bar{p}_i) \cdot \lambda_i \end{aligned} \tag{NEC-REG}$$

Let θ_i be the Lagrangian multiplier associated with the commission cap constraint. Then, a sufficient condition for the cap to replicate the first-best is given by:

$$\theta_i = \frac{1}{f_i^{ne} - (c_i + \bar{\tau}_i) \cdot \frac{n_i}{\lambda_i}} \cdot \left[\frac{f_i^{ne}}{\epsilon_i^{ne}} - (\tau^b - \bar{\tau}_i) \cdot \frac{n_i - n_i^I}{\lambda_i}\right] \geq 0 \tag{C.7}$$

where f_i^{ne} is the fare according to Eq. (13a) and all quantities are evaluated at the first-best. Now, because the first-best is sustainable, it must be that $f_i^{fb} > \tau^b \cdot \frac{n_i - n_i^I}{\lambda_i}$ where f_i^{fb} is the fare of service i under the first-best. Then, it follows that $f_i^{ne} > \tau^b \cdot \frac{n_i - n_i^I}{\lambda_i}$ and $f_i^{ne} - (c_i + \bar{\tau}_i) \cdot \frac{n_i}{\lambda_i} > 0$. It follows that the above condition is met, regardless of the value of $\bar{\tau}_i$ so long as the first-best is sustainable.

Appendix D. Numerical experiments

Functionally, we also assume that demand follows a logit model with dispersion parameter κ:

$$\lambda_i = \lambda^0 \cdot \frac{\exp(-\kappa \cdot \mu_i)}{\sum_j \exp(-\kappa \cdot \mu_j) + \exp(-\kappa \cdot \mu^0)} \tag{D.1}$$

We also assume that speed is a linear function of the number of vehicles in the system:

$$v = v^0 - v^c \cdot \left(\sum_i n_i + n^b\right) \tag{D.2}$$

Table D.1
Parameter values for numerical examples.

Notation	Interpretation	Value
β	Value of travel time	$27.69\,\frac{\$}{\text{h}}$
β^b	Value of travel time for background traffic	$20\,\frac{\$}{\text{h}}$
κ	Demand logit dispersion	0.5
κ^b	Background elasticity	0.01
a_1	Efficiency parameter street-hail	38.69
a_2	Efficiency parameter e-hail	1.625
d^r	Average trip distance	4 mi
$d^{r,b}$	Average background trip distance	5 mi
v^c	Slope of speed function	$0.0025\,\frac{\text{mph}\cdot\text{mi}^2}{\text{veh}}$
v^0	Free-flow speed	30 mph
μ^0	Cost of outside option	\$14.68
c^0	Driver opportunity cost	\$23

All the parameters and their values are described in Table D.1. We obtain a_1 and a_2 following Zhang et al. (2019). We also obtain β, κ, d^r, and μ^0 (through calculation) from Zhang and Nie (2021a). v^0 and v^c are taken from Vignon et al. (2021). To make certain points clearer, we let our market sizes range from 500 to 19025, noting that the observed passenger density in most cities of interest falls around 2000 while the population density in cities like NYC hovers around 20000. We assume that supply is perfectly elastic with cost c^0 – for which the value is based on earning information for NYC e-hailing drivers – and we set $\lambda^{b0} = 10000$.

Appendix E. Heterogeneous value of time

In this section, we relax the assumption that the value of time is homogeneous. That is, we assume that $\beta \sim G$ where G is the cumulative distribution function of β. We assume that, regardless of their value of time, all customers receive the same price and waiting time information when requesting a ride. It is straightforward to show that, under these assumptions, the marginal costs become:

$$mc_s = -\overline{\beta\lambda}_s \cdot w_s^{m'} \tag{E.1a}$$

$$mc_e = -\overline{\beta\lambda}_e \cdot w_e^{m'} \cdot \frac{1}{1 + \overline{\lambda}_e \cdot w_e^{m'}} \tag{E.1b}$$

where:

$$\overline{\beta\lambda}_i = \int_0^\infty \beta \cdot \lambda_{i,\beta} \cdot dG \tag{E.2a}$$

$$\overline{\lambda}_i = \int_0^\infty \lambda_{i,\beta} \cdot dG \tag{E.2b}$$

In the above, $\lambda_{i,\beta}$ is the demand rate of customers with value of time β served by platform i. In essence, the marginal cost of service i under heterogeneous value of time $\beta \sim G$ is a weighted average of the marginal cost faced by each customer group. More importantly, the resulting equations are mathematically similar to those in the homogeneous case. Thus, the conclusions derived in Sections 4 and 5 hold, even under the assumption of heterogeneous value of time.

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