Differential Pricing of Internet Traffic: Theory and Empirical Analysis*

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Abstract. This paper examines theoretically and empirically the welfare effects of differential pricing for Internet traffic in a network market. We first present a model of differential pricing by a monopolist Internet service provider (ISP), wherein charges are levied on content providers for traffic flow and on consumers for Internet access. Content providers differ in their demand for Internet traffic and in their value to consumers (network effects). Under linear demand, we show that compared to uniform pricing, differential pricing based solely on network effects is welfare-enhancing, while purely elasticity-based differential pricing reduces content provider surplus and social welfare. When both network effects and demand elasticities differ across content providers, the welfare effects are ambiguous, and we characterize conditions under which differential pricing is welfare-enhancing. Using monthly transaction data from a large ISP and major content providers in China, we estimate demand and recover effective marginal costs. Counterfactual analysis quantifies the increase in aggregate content provider surplus and establishes that Internet-user surplus also increases under differential pricing. However, several large content providers capture a disproportionate share of the increase in content provider surplus, while medium-sized providers tend to be worse off.

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1 Introduction

The expansion of digital networks has made the Internet the primary medium for information access and content distribution. Internet service providers (ISPs) are central to this infrastructure, acting as platforms that connect content providers (CPs) with end consumers. Content providers (e.g. YouTube, Netflix, and TikTok) rely on ISPs to carry data-intensive content to households, which in turn subscribe to ISPs for connectivity. With the rapid growth in bandwidth consumption, the allocation and pricing of network traffic have taken on renewed economic significance. This paper studies ISPs' pricing strategies toward content providers, particularly in the context of ISP-operated content delivery networks (CDNs). We use this setting to investigate a central question: should ISPs be permitted to set differential prices for different content providers?

The debate over whether ISPs may engage in discriminatory pricing toward content providers, often discussed under the rubric of net neutrality since Wu (2003), remains a central point of contention. Proponents of strict neutrality argue that ISPs must treat all traffic equally to prevent monopolistic gatekeeping and safeguard market diversity. In their view, nondiscrimination mandates can deter ISPs from deliberately constraining capacity (Choi and Kim, 2010), preserve universal access to online content (D'Annunzio and Russo, 2015), and foster innovation (Lee and Wu, 2009; Economides and Hermalin, 2012). Conversely, opponents contend that tiered services and differential pricing are necessary for network efficiency and growth and beneficial to end consumers (e.g., Becker *et al.*, 2010; Bourreau *et al.*, 2015). Economists have yet to reach a consensus, as the welfare consequences remain theoretically ambiguous and contingent on specific market primitives (Choi and Kim, 2015). High-profile disputes over Internet traffic charges—including Netflix's confrontation with Comcast over interconnection fees and Twitch's withdrawal from South Korea in 2024—illustrate the practical stakes of this debate. Despite extensive academic and policy debate, the welfare implications of differential Internet traffic pricing remain both theoretically unsettled and empirically underexplored.

This paper investigates, both theoretically and empirically, the welfare effects of ISP differential pricing. We focus specifically on the competing incentives an ISP faces when setting bandwidth prices for content providers. On one hand, an ISP has a standard monopolistic incentive to exploit different demand elasticities, charging higher prices to CPs with less elastic demand. On the other hand, it must account for positive cross-side network externalities: high-quality, data-intensive CPs attract a larger subscriber base, which in turn boosts the ISP's revenue from consumer subscription fees. In fact, the quality of specific online services, particularly data-intensive applications such as

online gaming and video streaming, has increasingly become a salient consideration for households in their choice of ISP.[1] Therefore, the ISP also has an incentive to subsidize or offer lower prices to CPs that generate strong positive network effects.

To formalize these ideas, we develop a model of monopolistic differential pricing in a two-sided Internet market. Building on the framework of Rochet and Tirole (2002), we allow content providers to differ in both their demand for Internet traffic and the network benefits they generate for subscribers. The ISP charges consumers a subscription fee and sets content-provider-specific bandwidth prices. Under linear demand and a fixed subscription fee, we characterize necessary and sufficient conditions under which differential pricing increases aggregate content provider surplus and Internet subscriber surplus relative to uniform pricing. These conditions link the welfare effects to the reallocation of traffic across content providers: the effect on aggregate content provider surplus depends on how traffic is redistributed across their demand curves, while the effect on subscribers depends on whether this reallocation increases total network benefits. When differential pricing raises both aggregate content provider surplus and Internet subscriber surplus, it also increases total social welfare, because the ISP can earn at least as much profit under differential pricing as under uniform pricing.

To clarify the economic forces behind these conditions, we examine two extreme cases. When content providers differ only in their network effects, the ISP charges lower prices to providers that generate greater benefits for subscribers. The resulting reallocation of traffic increases aggregate content provider surplus, subscriber surplus, and social welfare. Conversely, when providers generate identical network effects but differ in their demand elasticities, differential pricing reduces aggregate content provider surplus and social welfare, while leaving subscriber surplus unchanged. These conclusions also hold when the ISP endogenously chooses its subscription fee. When both sources of heterogeneity are present, neither force necessarily dominates. Our welfare conditions therefore provide a framework for empirical evaluation, identifying how the estimated demand characteristics and network incentives jointly determine whether differential pricing is welfare-enhancing.

We apply this framework to China's Internet market using a unique dataset on transactions between China Telecom, a major ISP serving a populous Chinese province, and 24 content providers over 2017–2020. The data record yearly contracted prices and monthly traffic usage for the ISP's content delivery network (CDN), a distributed network

[1] Figure A1 shows a screenshot of headlines and excerpts from various online media and consumer review platforms ranking different ISPs based on user experiences with online content like gaming and video streaming through an ISP.

of servers that delivers content from locations geographically close to Internet users. We estimate a linear demand system with content provider and month-year fixed effects, allowing demand slopes to vary across years. To address price endogeneity, we use server cabinet prices and expenditures on static bandwidth services as instruments. Combining the demand estimates with the ISP's optimal pricing conditions, we recover provider-specific effective marginal costs, which incorporate both the cost of delivering traffic and the subscription revenue generated through network effects. These estimates support two complementary counterfactual exercises.

The first counterfactual examines the role of network effects in the observed pricing structure. We hold estimated demand characteristics fixed and set every provider's effective marginal cost equal to that of Autohome.com.cn, which we assume generates minimal network benefits for the ISP. This common-cost benchmark removes differences in network incentives, so price differences arise solely from differences in demand elasticities. In 2017, counterfactual prices are on average 25.7% higher than observed prices, with particularly large increases for several providers receiving low prices in the data. This exercise suggests that the ISP's incentive to attract subscribers through content provision is an important source of favorable bandwidth prices, especially for traffic-intensive gaming and video services.

The second counterfactual evaluates a restriction requiring the ISP to charge a uniform bandwidth price. We compute the profit-maximizing uniform price and compare the resulting traffic allocation and welfare outcomes with observed differential pricing. In the baseline linear-demand model, total traffic is unchanged, so the welfare effects arise from its reallocation across content providers. In 2017, aggregate content provider surplus is approximately 61% higher under differential pricing. We also use our theoretical welfare condition to establish a positive effect on Internet subscriber surplus without separately identifying marginal costs and network effects. These aggregate gains conceal substantial distributional differences: half of the providers in the 2017 comparison lose surplus under differential pricing, while several large providers capture a disproportionate share of the gains. Traffic allocation also becomes more concentrated. Finally, we repeat the counterfactual exercises using a semi-log demand specification, where the qualitative findings persist, highlighting the value of the baseline linear model in allowing the welfare comparison to depend on the estimated market primitives.

The remainder of this paper is organized as follows. In Section 2, we discuss the related literature. In Section 3, we present a theoretical model of a two-sided Internet traffic market with a monopolist ISP and characterize the conditions for welfare-increasing differential pricing. In Section 4, we describe the institutional background of China's Inter-

net market and discuss the new dataset we use for this study. In Section 5, we present the main results of demand estimation and welfare comparisons between differential pricing and uniform pricing. Section 6 concludes.

2 Related Literature

Our analyses build upon two large bodies of literature on differential/discriminatory pricing and two-sided markets. Following a long strand of literature on third-degree price discrimination, Aguirre *et al*. (2010) and Cowan (2016) analyze the output and welfare effects of demand-driven third-degree price discrimination in two- and N-segment market settings, respectively. Valletti (2006) and Chen and Schwartz (2015) explore the welfare implications of cost-based monopolist differential pricing, where both price elasticities and marginal costs differ across markets. In this paper, we assume linear demand functions and extend the analysis to a network-industry context, where network effects introduce additional complexities in examining the welfare effects of differential pricing.

Our paper is closely related to the literature on two-sided markets, particularly payment card platforms (Rochet and Tirole, 2002; Wright, 2004; Rochet and Tirole, 2011; Bedre-Defolie and Calvano, 2013). The connection lies in the structure of the market: a payment platform facilitates transactions between merchants and cardholders, while an ISP facilitates content delivery between content providers and Internet subscribers. In both settings, the platform's pricing decisions must account for how charges on one side affect the benefits obtained by participants on the other side and, consequently, the revenue collected from that side. Payment card models emphasize the benefits generated by transactions between the two groups, while our model captures the benefits of content delivery through Internet traffic. Specifically, content providers choose how much traffic to purchase, and subscribers' willingness to pay for Internet access depends on the resulting content quality. Our framework thus combines a usage decision on the content provider side with a subscription decision on the consumer side. We abstract from retail pricing and payment choice, which are central to many payment card models, to focus on how heterogeneous demand and network benefits shape the ISP's pricing of traffic.

The payment card literature also provides a direct connection to differential pricing in two-sided markets. Wright (2012) shows that the privately chosen fee structure can remain biased toward cardholders even when the platform can perfectly price discriminate on both sides. Ding and Wright (2017) further examine discriminatory pricing in payment card systems and show that excessive card usage can persist even when cardholder fees are conditioned on retailer type. More broadly, Liu and Serfes (2013) show

that targeted price discrimination can soften competition between two-sided platforms, illustrating why conclusions from one-sided markets need not carry over to platform settings. Closest to our analysis, De Cornière *et al.* (2024) study third-degree price discrimination by a platform facing sellers with heterogeneous per-interaction benefits. In their linear-demand framework, discrimination increases participation on both sides and total welfare, and can make both seller types better off. These studies establish that the consequences of differential pricing depend on the interaction between participant heterogeneity and cross-side externalities.

We contribute to this literature by studying differential usage prices across N content providers that differ in both their demand for traffic and the network benefits their traffic generates for subscribers. In our baseline model, differential pricing leaves total traffic unchanged but reallocates it across providers. The welfare consequences therefore depend on which providers' traffic expands and which providers' traffic contracts, taking account of both providers' valuations and subscribers' network benefits. We characterize necessary and sufficient conditions for differential pricing to increase aggregate content provider surplus and subscriber surplus, and distinguish the opposing welfare implications of discrimination driven solely by demand elasticities and solely by network effects. We then bring this framework to transaction-level data on ISP-owned CDN services, using counterfactual analysis to evaluate both aggregate welfare effects and their distribution across content providers.

This paper also contributes to the existing literature, primarily theoretical, on analyzing discriminatory platform practices. For instance, Economides and Tåg (2012) analyze a monopolist ISP's pricing of Internet access in a two-sided market model. Economides and Hermalin (2012) consider the impact of tiered service schemes offered by an ISP. Choi and Kim (2010) investigate the investment incentives of ISPs, linking the welfare implications of second-degree price discrimination with ISPs' incentives for expanding the capacity of Internet infrastructure. Additionally, Choi and Kim (2015) present a theory involving competing and interconnected ISPs that engage in second-degree price discrimination toward content providers. They demonstrate that the welfare effects of neutrality rules depend critically on the business models of content providers. On the empirical side, Tudón (2022) estimates a structural model of a live-streaming platform (Amazon's Twitch.tv) with congestion externalities. He finds that an un-neutral policy with prioritization increases consumer welfare, as the platform allocates more traffic to online broadcasters that are of higher value to consumers. This paper presents a novel empirical analysis of ISP differential pricing using a unique dataset from China. In this distinctive regulatory environment, ISPs charge content providers different prices for Internet traffic

via ISP-owned CDNs. In this sense, this paper also adds to the economics literature on the Internet infrastructure (e.g., Greenstein, 2015; Jeon and Rysman, 2024; Caoui and Steck, 2025).

3 Theoretical Analysis

3.1 Model set-up

In this section, we analyze a theoretical model of differential pricing by a monopolist Internet service provider (ISP).[2] The ISP operates as a two-sided platform that connects content providers (CPs) and Internet users. In particular, it imposes charges on CPs for Internet traffic (through its CDN service) and levies subscription fees on Internet users. Later on, we also discuss the case in which differential pricing is not allowed and the ISP must charge a uniform price. Then we make welfare comparisons between these two pricing schemes.

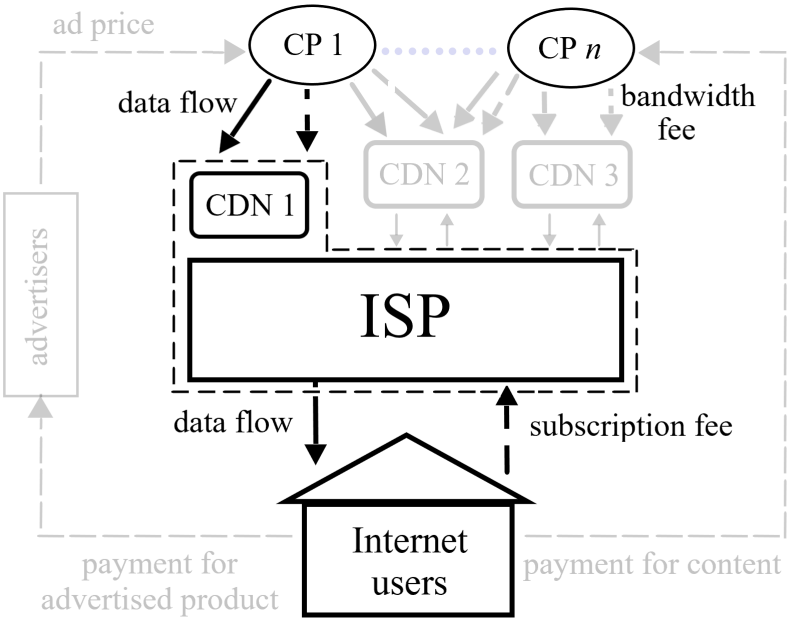
Notably, there may exist other potentially important interactions among users, content providers (CPs), and third parties (e.g., advertisers) within this digital market, which we do not explicitly model. These interactions are shown in gray in Figure 1. Our main focus is on the ISP's differential pricing of Internet traffic to content providers, for which we perform empirical analysis with a unique dataset on data-service transactions.

Internet users. Consumer utility from Internet usage depends on the quality of the online content provided by each content provider, indexed by $i = 1, 2, ..., N$, with $U(u_1, u_2, ..., u_N)$. Each content provider's quality (as perceived by consumers), denoted by u_i, depends on the Internet traffic allowance the ISP allocates to i, denoted by q_i. For tractability, we assume a one-to-one mapping between u_i and q_i; thus, we write $u_i(q_i)$. This assumption means that–in terms of the context of a video streaming service provider such as YouTube or Netflix–any level of Internet traffic usage corresponds to some quality level of service delivered to viewers. For example, providing a 720p HD video streaming service requires a specific level of Internet traffic to ensure seamless delivery to users.

The consumer demand for the Internet service is then characterized by the demand function $D(Q(q_1, ..., q_N), s)$, where $Q(q_1, ..., q_N)$ is the expected value of the Internet usage with $\frac{\partial D}{\partial Q} > 0$, and s is the subscription fee with $\frac{\partial D}{\partial s} < 0$. We measure Internet-user surplus

[2] As shown in Figure 1, the underlying market structure is a competitive bottleneck framework where content providers are multi-homing, and Internet users are single-homing. Thus, the ISP has monopoly market power when selling Internet traffic to content providers. On the user side of the Internet, we consider two cases: the Internet subscription fee is exogenously given and endogenously chosen by the ISP.

Figure 1: Structure of the market for Internet traffic



by consumer surplus $CS = \int_s^{\infty} D(Q,s)ds$.

For exposition and to facilitate comparison with existing results in the literature, we assume a unit mass of Internet users with the following indirect utility function:

$$u(x) = \begin{cases} \sum_{i=1}^{N} \kappa_i q_i - \delta s - x + \kappa_0, & \text{if a consumer subscribes to the ISP} \\ 0, & \text{if a consumer does not subscribe} \end{cases}$$

where $\kappa_0 > 0$ is users' utility if there is no content provider on the other side, $\kappa_i > 0$ measures the benefit Internet users obtain from provider i's content, and x represents users' horizontal taste heterogeneity and is uniformly distributed over $[0,1]$. In addition, we assume

$$\kappa_0 + \sum_{i=1}^{N} \kappa_i a_i < 1. \tag{1}$$

such that the ISP cannot capture the whole market.

Consequently, equilibrium subscription demand is

$$D = \sum_{i=1}^{N} \kappa_i q_i - \delta s + \kappa_0 \leq \kappa_0 + \sum_{i=1}^{N} \kappa_i a_i < 1. \tag{2}$$

The linear form of demand, along with a similar underlying utility function, resembles

the two-sided Internet market model presented in, for instance, Economides and Tåg (2012)'s analysis. Here, $Q = \sum_{i=1}^{N} \kappa_i q_i$ can be interpreted as the network benefits of content provision on Internet users. As $\frac{\partial D}{\partial q_i} = \kappa_i$, κ_i represents the increase in the number of users when the ISP allocates one more unit of Internet traffic allowance to content provider i.

Content providers. We do not explicitly model the interactions among consumers, content providers, and third parties such as advertisers. Instead, we assume parsimoniously that each content provider's payoff depends on its traffic usage, $V_i(q_i)$. This is a reasonable abstraction when there exists a one-to-one mapping between consumers' valuation of the content providers' products and its traffic flow, so a content provider choosing its quality for consumers is equivalent to choosing how much data traffic it ought to use.

Given that, the net payoff to a content provider is

$$\pi_i^{CP} = V_i(q_i) - p_i q_i,$$

where $V_i(q_i)$ denotes the gross payoff with $V_i' \equiv \frac{dV_i}{dq_i} > 0$. For any given unit price of Internet traffic, a content provider chooses optimally q_i^* such that

$$V_i'(q_i) = p_i,$$

which implicitly defines the demand function for Internet traffic $q_i(p_i)$.

Again, we use a linear demand function for Internet traffic:

$$q_i = a_i - b_i p_i.$$

where a_i and b_i are positive.[3]

discussion. Our modeling choices for content provider demand and Internet user demand share similarities with standard two-sided payment card models in the tradition of Rochet and Tirole (2002). In these models, the payoffs for both sides–card users and merchants–hinge on the volume of transactions rather than on the number of users.[4] Similar to the relationship between card users and merchants in the payment card context, consumer utility and content provider payoffs depend on Internet traffic resulting from consumer-CP interactions. As in standard two-sided market models, we do not explicitly

[3]The underlying gross payoff function is

$$V_i(q_i) = \frac{a_i}{b_i} q_i - \frac{1}{2b_i} q_i^2.$$

[4]Articles on payment card systems that also share these features include for instance Bedre-Defolie and Calvano (2013), Guthrie and Wright (2007), Wright (2012), Shy and Wang (2011).

model the interactions between consumers and CPs.[5] This modeling choice is also fitting for our purpose, particularly since we do not observe content consumption choices for our empirical analysis.

Heterogeneity among merchants and consumers has been extensively examined in seminal works in the payment card literature, including, but not limited to, Rochet and Tirole (2002); Wright (2004); Rochet and Tirole (2011); Wright (2012); Bedre-Defolie and Calvano (2013). Later in our analysis, we also show theoretical results for situations where (i) the payoff functions of CPs are identical and (ii) the network effects of distinct CPs on users are identical. These two sources of heterogeneity create distinct pricing incentives. Allowing both to vary helps explain the observed relationship between traffic usage and prices.

The ISP. Assuming a constant cost of Internet data provision c and zero additional cost for serving subscribing households (without loss of generality), the ISP's profit function is given by

$$\Pi^{ISP} = \sum_{i=1}^{N} (p_i - c)q_i + D\left(Q(q_1, ..., q_N), s\right)s$$

where the first part represents the profit from selling Internet traffic to content providers, and the second part represents the subscription profit.

Substituting the linear demand functions, the profit function becomes

$$\Pi^{ISP} = \sum_{i=1}^{N} (p_i - c + s\kappa_i)q_i(p_i) - \delta s^2 + \kappa_0 s. \tag{3}$$

Based on this formulation, we see that $s\kappa_i$ measures the additional subscription profit accruing to the ISP when incrementally more Internet traffic is allocated to CP i. In essence, it embodies an *indirect* network effect in this platform context. To continue with the video streaming example, this network effect pertains to the ISP's decision to allocate more Internet traffic to digital content providers like Netflix or YouTube to retain its Internet subscribers.

3.2 Baseline case with fixed s

We begin by examining the more tractable scenario with a fixed subscription fee for households. We endogenize s in the next section. In fact, many of the results and underlying insights for the more complex case with endogenous s can be established more

[5] For instance, Rochet and Tirole (2002) and subsequent works assume that the volume of card transactions is fixed (and normalized to one).

easily from the baseline case.

Under the differential pricing (DP) scheme, the ISP's profit maximization problem is given by

$$\max_{\mathbf{p}} \sum_{i=1}^{N} (p_i - c + s\kappa_i) q_i(p_i) - \delta s^2 + \kappa_0 s.$$

Utilizing the linear demand forms, the FOCs imply

$$p_i^* = \frac{a_i/b_i + v_i}{2}, \quad q_i^* = \frac{a_i - b_i v_i}{2},$$

where $v_i \equiv c - s\kappa_i$.

The pricing equations closely resemble the basic (one-sided) monopoly formulas with linear demands except for the network effect term $s\kappa_i$. Specifically, for content providers whose services generate higher network value for Internet users, the monopolist ISP tends to impose a lower price, *ceteris paribus*. This observation aligns with a key insight from the two-sided market literature in the tradition of Rochet and Tirole (2003) and Armstrong (2006). In particular, the network effect reduces the effective marginal cost of providing Internet traffic perceived by the ISP, denoted by v_i.

In general, do larger and more data-intensive content providers receive higher or lower unit prices for Internet traffic than less important ones? Equation (4) reveals two driving forces: demand conditions and network effects. The demand-side force is captured by $\frac{a_i}{b_i}$, which in the original CP's payoff function represents the maximum marginal payoff of Internet traffic. This is the driving force of price discrimination in the traditional context. Considering both forces, it is unclear *ex ante* whether the online game or video streaming service providers would receive a more favorable price from the ISP because presumably they are more dependent on Internet traffic while they also generate larger network effects.

Under the uniform pricing (UP) scheme, the ISP's profit maximization problem becomes

$$\max_{\bar{p}} \sum_{i=1}^{N} (\bar{p} - c + s\kappa_i) q_i(\bar{p}) - \delta s^2 + \kappa_0 s.$$

Assuming all CPs are served, the FOCs imply

$$\bar{p} = \frac{\sum_{j=1}^{N} (a_j + v_j b_j)}{2\sum_{j=1}^{N} b_j} = \left(\frac{\sum_{j=1}^{N} b_j p_j^*}{\sum_{j=1}^{N} b_j} \right); \qquad \bar{q}_i = a_i - b_i \frac{\sum_{j=1}^{N} a_j + v_j b_j}{2\sum_{j=1}^{N} b_j}.$$

Under UP, the optimal uniform price is a weighted average of the optimal prices under

the discriminatory scheme. Furthermore, if $b_i = b$ for all i (i.e., CP demand curves are parallel), we have

$$\bar{p}^* = \frac{1}{N}\sum_{i=1}^{N} p_i^*. \tag{4}$$

In this case, the optimal uniform price is simply the average of the discriminatory prices.

Moreover,

$$\sum_{i=1}^{N} q_i^* = \sum_{i=1}^{N} \bar{q}_i. \tag{5}$$

In our context, the total Internet traffic allocations are identical under the two pricing schemes.

Referring to the profit function (3) and the associated FOCs, we shall point out that for a fixed subscription price, our model of differential pricing with network effects is isomorphic to a canonical model of monopoly differential pricing with linear demands and N market segments that differ in both demand elasticities and marginal costs of product provision. Therefore, it is not surprising that conditions similar to (4) and (5) have been shown by Valletti (2006) and Bertoletti (2009) in their settings. Our novel addition to the modeling is the Internet user side, which is important for calculating total social surplus in a two-sided context.

3.2.1 Welfare analysis

Let CPS^{DP} and CPS^{UP} denote aggregate content provider surplus under the DP and UP schemes, respectively. Using the particular functional forms, we write the change in the aggregate content provider surplus as follows:

$$\Delta CPS \equiv CPS^{DP} - CPS^{UP} = \sum_{i=1}^{N} \frac{1}{2b_i}(q_i^{*2} - \bar{q}_i^{\,2}).$$

Plugging in the price and quantity equations yields the following necessary and sufficient condition for aggregate content provider surplus to rise under DP:

$$\sum_{i=1}^{N}\left[(3a_i - b_i v_i - b_i \frac{\sum_{j=1}^{N}(a_j + v_j b_j)}{\sum_{j=1}^{N} b_j})(\frac{\sum_{j=1}^{N}(a_j + v_j b_j)}{\sum_{j=1}^{N} b_j} - \frac{a_i}{b_i} - v_i)\right] > 0. \tag{A1}$$

Again, condition A1 reveals the *ex ante* ambiguity regarding the welfare effect of DP vis-à-vis UP.

For Internet users, we have

$$\Delta CS = (Q^* - \bar{Q})\left[\frac{1}{2\delta}(D^* + \bar{D})\right],$$

where $Q^* = \sum_{i=1}^{N} \kappa_i q_i^*$ and $\bar{Q} = \sum_{i=1}^{N} \kappa_i \bar{q}_i$.

Since the bracketed term is positive, the direction of the change in CS depends on $Q^* - \bar{Q}$. Intuitively, the effect of DP on consumer surplus depends on whether DP raises the overall network benefits to users. The overall quality captured by Q functions like a demand shifter.

Formally, the necessary and sufficient condition for consumer surplus to increase under DP is

$$Q^* - \bar{Q} = \sum_{i=1}^{N} \kappa_i (q_i^* - \bar{q}_i) > 0. \tag{A2}$$

Proposition 1 *Compared to UP, DP increases aggregate content provider surplus if and only if condition* (A1) *holds, and it increases consumer surplus if and only if condition* (A2) *holds.*

Thus far, we have presented the conditions under which DP can enhance both aggregate CP surplus and consumer surplus. However, the precise effects of DP hinge on the interplay among parameters related to demand curves, costs, and network effects. To gain further insights, we investigate two extreme cases in the subsequent analysis, in which DP is driven solely by demand elasticities or by network effects.

3.2.2 Extreme cases

First, we consider the case when DP is purely based on network effects. Suppose all content providers have the same demand function: $a_i = a, b_i = b$ for all i. In this case, condition (A1) becomes

$$\begin{aligned} &\sum_{i=1}^{N}\left[(\frac{2a}{b} - \bar{v} - v_i)(\bar{v} - v_i)\right] > 0 \\ \Longleftrightarrow &\sum_{i=1}^{N}(v_i + \bar{v})(v_i - \bar{v}) > 0, \end{aligned} \tag{6}$$

where $\bar{v} = \frac{\sum_{j=1}^{N} v_j}{N}$. In this case, DP always increases total CP surplus and the proof is relegated to the appendix. This result is analogous to the previous finding by Valletti (2006),

who studies cost-based differential pricing with linear demands. Content providers in our contexts correspond to buyers/consumers in traditional (one-sided) markets.

Turning to the Internet user side, we show in the appendix that DP unambiguously increases the welfare of Internet users, since $Q^* > \bar{Q}$. Intuitively, when differential pricing is based solely on network effects, the ISP sets a lower price for a content provider with larger network effects. Consequently, any content provider facing lower Internet prices optimally uses more Internet traffic, leading to higher perceived service quality among Internet users. The overall network benefits of Internet traffic usage by content providers, Q, is a weighted sum of individual q_i; in this case, higher κ_i translates to higher q_i. This "allocation effect" of differential pricing renders it more favorable to consumers compared to uniform pricing.

In total, DP also raises social welfare, which is the sum of consumer surplus, aggregate CP surplus, and ISP profit.

Next, we examine the scenario in which DP is based solely on differences in content providers' demand elasticities. Suppose all content providers have the same level of network effects with $\kappa_i = \kappa$ for all i. Following the literature, we retain the assumption of $b_i = b$ for all i and let a_i differ.

In this case, condition (A1) becomes

$$\begin{aligned} & \sum_{i=1}^{N}\left[(3a_i - 2bv - \bar{a})(\frac{\bar{a}}{b} - \frac{a_i}{b})\right] \geq 0 \\ \iff & \sum_{i=1}^{N}[(3a_i - 2bv - \bar{a})(a_i - \bar{a})] \leq 0 \qquad (7) \\ \iff & \sum_{i=1}^{N}[(3a_i - \bar{a})(a_i - \bar{a})] \leq 0, \end{aligned}$$

where $\bar{a} = \frac{\sum_{j=1}^{N} a_j}{N}$. In the appendix, we show that the opposite of the above condition always holds in this case. In other words, purely elasticity-based DP reduces aggregate CP surplus. This result also echoes an analogous finding by Valletti (2006).

On the Internet user side, it is easy to see that $Q^* = \bar{Q}$ in this case. This is because by assumption $\kappa_i = \kappa$ for all i and $\sum_{i=1}^{N} \bar{q}_i = \sum_{i=1}^{N} q_i^*$, as established previously. When DP is driven solely by differences in content providers' demands for Internet traffic, DP and UP yield the same level of consumer surplus.

Turning to social welfare, recall that $\Delta CS = 0$ in this case. Since

$$\bar{q}_i - q_i^* = \frac{a_i - \bar{a}}{2}, \qquad \bar{p} - p_i^* = -\frac{a_i - \bar{a}}{2b},$$

we obtain

$$\begin{aligned} \Delta W &\equiv \Delta CPS + \Delta CS + \Delta \Pi^{ISP} \\ &= \frac{1}{2}\sum_{i=1}^{N}(\bar{q}_i - q_i^*)(\bar{p} - p_i^*) \\ &= -\frac{1}{8b}\sum_{i=1}^{N}(a_i - \bar{a})^2 \leq 0. \end{aligned} \tag{8}$$

The inequality is strict whenever the demand intercepts a_i are not all identical. Thus, purely elasticity-based differential pricing reduces social surplus whenever it induces distinct prices across content providers.

Proposition 2 *(i) When DP is purely based on network effects, compared with UP, aggregate CP surplus and CS are both higher under DP; hence, social surplus is higher under DP; (ii) When DP is purely based on demand elasticities, compared with UP, aggregate CP surplus is lower and CS is the same under DP. Social surplus is lower under DP.*

3.3 Extension: endogenous s

We now turn to endogenizing the ISP's subscription price s. That is, the ISP sets not only the bandwidth prices but also the subscription fee. Under the DP scheme, the ISP's optimization problem becomes

$$\max_{\mathbf{p}, s^{DP}} \sum_{i=1}^{N}(p_i - c + s\kappa_i)q_i(p_i) - \delta s^2 + \kappa_0 s.$$

To ensure that the ISP's profit is jointly concave in the bandwidth prices and subscription fee under differential pricing, we assume $4\delta > \sum_{i=1}^{N} b_i \kappa_i^2$. This also ensures strict concavity under uniform pricing, since the Cauchy–Schwarz inequality implies

$$\frac{\left(\sum_{i=1}^{N} b_i \kappa_i\right)^2}{\sum_{i=1}^{N} b_i} \leq \sum_{i=1}^{N} b_i \kappa_i^2.$$

We restrict attention to parameter values for which the resulting solutions are interior: the subscription fee is positive, all content providers purchase positive traffic quantities,

and household subscription demand lies strictly between zero and one. If bandwidth prices are constrained to be nonnegative, we additionally require the derived bandwidth prices to be positive. Under these conditions, the first-order conditions characterize the unique interior optimum in each pricing regime. Solving the FOCs yields

$$s^{DP} = \frac{\sum \kappa_j (a_j - c b_j) + 2\kappa_0}{4\delta - \sum \kappa_j^2 b_j}, \qquad p_i^* = \frac{a_i + c b_i}{2 b_i} - \frac{\kappa_i}{2} \frac{\sum \kappa_j (a_j - c b_j) + 2\kappa_0}{4\delta - \sum \kappa_j^2 b_j}.$$

Similarly, under the UP scheme, solving the FOCs yields

$$s^{UP} = \frac{\sum \kappa_j (2a_j - c b_j) - \frac{\sum \kappa_j b_j \cdot \sum a_j}{\sum b_j} + 2\kappa_0}{4\delta - \frac{(\sum \kappa_j b_j)^2}{\sum b_j}}.$$

and for ease of exposition, we omit the expression of $\bar{p}$.

The optimal quantities under differential and uniform pricing are obtained by substituting s^{DP} and s^{UP}, respectively, into the following expressions:

$$q_i^* = \frac{a_i - b_i v_i^{DP}}{2} = \frac{a_i - b_i (c - s^{DP} \kappa_i)}{2},$$
$$\bar{q}_i = a_i - b_i \frac{\sum (a_j + b_j v_j^{UP})}{2 \sum b_j} = a_i - b_i \frac{\sum a_j + b_j (c - s^{UP} \kappa_j)}{2 \sum b_j}.$$

Relegating the detailed calculations to the appendix, we obtain the following proposition.

Proposition 3 *With endogenous subscription price, (i) when DP is purely based on network effects, compared with UP, aggregate CP surplus and CS are both higher under DP; hence, social surplus is higher under DP; (ii) When DP is purely based on demand elasticities, compared with UP, aggregate CP surplus is lower and CS is the same under DP. Social surplus is lower under DP.*

In summary, we investigate the welfare implications of DP compared to UP in a two-sided market for Internet traffic. We use extreme cases to shed light on the underlying forces driving the welfare comparison. Additionally, for any intermediate cases, we present precise conditions for conducting welfare comparisons. These conditions also inform our subsequent empirical analysis, where we aim to quantify the demand elasticity and network effects that jointly determine the ISP's pricing of Internet traffic.

3.4 Further extensions

So far, our results are based on linear demand functions often used in the literature (Valletti, 2006; Bertoletti, 2009; Chen and Schwartz, 2015). Recall that our model is partially similar to the differential pricing model with N market segments and differences in both demand elasticities and the costs of serving different customers, with an additional twist of network effects. The analysis is inherently intricate, and moving beyond linear demand is challenging. For instance, Chen and Schwartz (2015) considers–in their context–more general demand forms but only two market segments. That would translate to our context as a monopolist ISP serving only two content providers, the analysis of which is relatively straightforward but less useful in our industry setting.

We instead consider the following demand functions that are commonly used and empirically relevant: $\ln q_i = a_i - b_i \ln p_i$ and $\ln q_i = a_i - b_i p_i$. Section A.4 includes more details on the micro-underpinnings of these demand forms.

The empirical versions of the above functions require the parameter b to be constant across i. However, unlike linear demand, assuming a common b takes away some of the important forces driving price differences. In particular, for log-linear demand $\ln q_i = a_i - b \ln p_i$, it implies isoelasticity of content providers' demand curves. We showed that, for those demand functions, differential pricing always yields higher consumer surplus and aggregate content provider surplus than uniform pricing, rendering empirical analysis less meaningful. In other words, those functional forms lead to "built-in" theoretical properties. In comparison, the linear demand form does not have such automatic welfare implications. Readers are referred to Appendix Section A.4 for more details of the proofs.

4 Industry Background and Data

4.1 Market for Internet traffic in China: ISP-owned CDN services

Building on the theoretical analysis presented in the preceding section, in this paper we perform a novel empirical investigation into the welfare impact of differential pricing of Internet traffic. The context of our empirical analysis is China's Internet market. Specifically, we focus on a major ISP in China, which not only offers Internet subscription services to commercial customers and household subscribers but also provides content delivery network (CDN) services to digital content providers. CDN technology facilitates the delivery of content to the devices of Internet users through networks of servers located geographically closer to the targeted users, effectively reducing data transmission

delays (Greenstein, 2020).[6] Nowadays, most online content is delivered via CDNs.

In contrast to many advanced economies, including the US and EU countries, where ISPs and CDN providers typically operate as separate entities and integration between the two is prohibited, the Chinese market presents a distinct scenario. Here, leading ISPs, which are the major state-owned telecommunication conglomerates, own CDN services alongside other critical components of the digital infrastructure. Consequently, the Chinese context presents a unique "counterfactual" world for researchers to observe and analyze differential pricing by an ISP that directly interacts with both Internet subscribers and content providers through its CDN services in a network environment.

This study leverages transaction-level data from China Telecom, one of the three major telecommunication companies in China, operating in a large Chinese province.[7] With a population exceeding 90 million, this province surpasses Turkey in size and has a provincial GDP comparable to that of Switzerland. Within this province, China Telecom serves over 50 million Internet users, maintaining its position as the largest ISP in the region. Notably, China Telecom's CDN services serve a wide range of major digital firms in China, including Alibaba, ByteDance (owner of TikTok), NetEase, and Tencent. The ISP also offers additional services, including server storage cabinets and various Internet bandwidth options.

China Telecom maintains a dominant market presence in the studied province, operating 28 data centers strategically located throughout the region to provide high-speed data transmission services. Figure 2 illustrates the number of IP nodes for CDN in the studied province for four major content providers. A higher number of IP nodes from an ISP correlates with increased CDN bandwidth purchased from that ISP. Notably, China Telecom has the largest number of IP nodes among the four major content providers, underscoring its significant market presence and infrastructure capacity.

To emphasize, the Chinese context provides an invaluable setting for examining the ISP as a platform in the network market for digital infrastructure. In this context, the ISP cares about both Internet subscription revenues and profits from the CDN service market. Importantly, due to the absence of regulations imposed on state-owned telecommunication giants, the practice of differential pricing of Internet traffic, particularly in the form of CDN services, is prevalent and thus becomes observable with data.

[6] Figure A2 presents a screenshot of a post from Zhihu, a major Chinese question-and-answer platform, detailing the geographical locations of various League of Legends regional servers across China. To minimize gaming latency, the post advises players to select a server physically closer to their location and to choose a server region that matches their specific ISP.

[7] The other two leading telecommunication companies are China Mobile and China Unicom.

4.2 Data

Our dataset comprises monthly transaction-level information spanning from January 2017 to December 2020, covering interactions between China Telecom and 24 content providers, including all major Chinese digital firms. For each content provider, we observe the yearly contracted unit price of CDN traffic and monthly CDN traffic usage. We also observe unit price and payment details for other relevant services, such as server storage cabinets and static bandwidth service. Notably, unit prices for these services are fixed at the beginning of each year and remain constant throughout the year.

Table 1 presents the summary statistics. The unit of observation is a content provider-month. The dataset covers 24 content providers over 2017–2020 and contains 775 provider-month observations with CDN transaction data due to a few missing data. To understand the precise meaning of contracted prices and CDN usage, we ought to describe in detail ISP's pricing procedure. When monitoring a content provider's Internet traffic, the ISP samples and records the average Internet traffic in gigabytes per second at 5-minute intervals. The average usage is then calculated based on the aggregate Internet traffic in all 5-minute intervals within a given time period, such as a month.[8] Consequently, a content provider's total payment is determined by multiplying the contracted unit price by its average usage. To render the price and quantity data more comprehensible, we convert them into more intuitive units, which we also use throughout the empirical analysis. For example, an average contracted unit price of CNY 14,400 translates to a charge of approximately 0.74 cents per gigabyte of real-time internet traffic via CDN services. Using a similar conversion process, the average monthly CDN usage is estimated to

Figure 2: CDN-related IP nodes in the focal Chinese province

ISP / CP	China Telecom	China Unicom	China Mobile
Alibaba	5050	352	2272
Baidu	2179	78	72
Tencent	1358	292	182
NetEase	21	3	3

[8] In practice, the traffic usage of content providers is sampled, and the 95th percentile usage is recorded for pricing purposes. While percentile and mean pricing models can differ in terms of profitability in general, they are revenue-equivalent under certain conditions (e.g., when the traffic distribution is highly left-skewed with a fixed number of user visits; see Hosanagar *et al.* (2008) more details). For simplicity, this paper assumes away such subtle differences. At the ISP's suggestion, we adopt the rule of thumb that the mean equals 0.75 times the 95th percentile to convert the unit.

be approximately 658 million gigabytes. To put these figures into perspective, consider a high-definition movie of 1 gigabyte or an hour of online gaming of 100 megabytes. With the average content provider's monthly CDN traffic, they can potentially provide 0.66 billion movie downloads or 6.73 billion hours of online gaming to their users. Given that the ISP has 50 million Internet subscribers in the province, this equates to 12.5 1-gigabyte movie downloads and 135 hours of 100-megabyte game time per potential user.

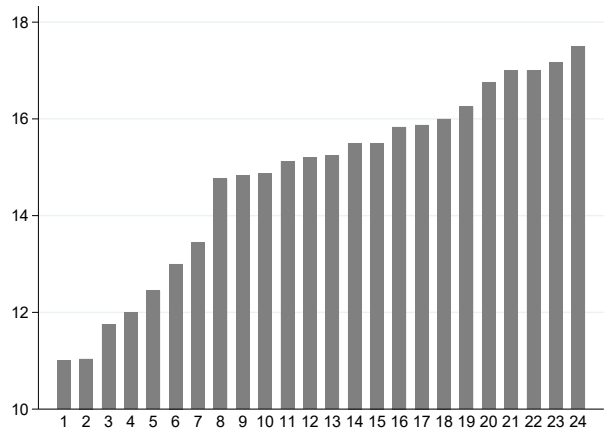
Table 1: Summary statistics for main variables

Variable	Obs.	Mean	S.D.	Min	Max
CP-year level					
Prices					
Unit CDN price (CNY 10^4)	70	1.44	0.21	0.87	1.75
Converted CDN price (*cents per 100 GB*)	70	74.13	10.70	44.94	90.02
Server cabinet price (CNY 10^4)	70	0.55	0.06	0.44	0.70
Content genres (dummy)					
Video streaming	96	0.33	0.47	0	1
Game	96	0.08	0.28	0	1
News	96	0.21	0.41	0	1
Social Media	96	0.17	0.37	0	1
Shopping	96	0.21	0.41	0	1
Life service	96	0.25	0.44	0	1
CP-month level					
Traffic usage					
Recorded CDN traffic (*GBPS*)	775	338.63	578.03	6.15	3803.82
Converted CDN traffic (10^6 *GB*)	775	658.29	1123.70	11.95	7394.62
No. server cabinets	775	216.76	324.07	8	1420
Expenditure					
CDN service (CNY 10^4)	775	417.51	581.39	10.75	3580.00
Server cabinets (CNY 10^4)	775	117.66	172.53	4.80	710.00

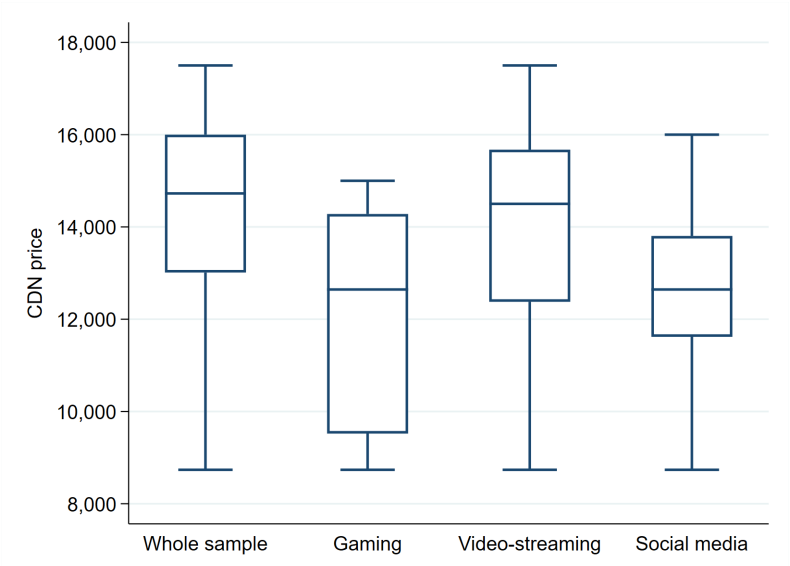
The average unit CDN price is CNY 14432 yuan, with one standard deviation of 2063, indicating large dispersion in prices. The lowest rate (8736 yuan) paid by a content provider is only 60% of the mean and 50% of the highest price. This price dispersion persists even within specific genres. Figure 3 illustrates the distribution of unit prices paid by content providers in gaming, video-streaming, and social media categories. For instance, despite gaming content providers facing lower average CDN prices, those encountering higher prices pay 72% more than the average and 5 times the lowest price. Our theoretical analysis suggests such price differences can stem from differences in content

providers' demand elasticities and their network effects on Internet subscriptions. In the following sections, we quantitatively evaluate these two factors through a counterfactual calculation.

Figure 3: CDN prices by content provider and service genre



(a) CDN prices by content provider



(b) Distribution of CDN prices

Notes: Prices are in CNY 1,000.

5 Empirical Analysis

Our theoretical analysis demonstrates that when differential pricing of Internet traffic is based on both demand elasticity and network effects, the welfare comparison of dif-

ferential pricing versus uniform pricing yields ambiguous results. Utilizing our unique dataset on ISP-owned CDN services in China, in this section, we provide an empirical analysis of differential pricing. In particular, we begin by estimating a model of Internet traffic demand by content providers with linear demand to recover a set of parameters characterizing both Internet traffic demand and the ISP's effective marginal cost of serving each content provider. Combining the estimates and our theoretical framework, we conduct counterfactual analysis to compute various outcomes under the scenario of uniform pricing. Our main objective is to analyze the welfare effects of differential pricing in comparison with uniform pricing.

5.1 Estimating demand for Internet traffic

For estimation, we further parameterize the linear demand model for content providers in the preceding theoretical analysis (equation (3)). Specifically, we employ the following estimable specification:

$$q_{imt} = \alpha - \beta_t p_{it} + F_i + F_{mt} + \varepsilon_{imt}, \tag{9}$$

where q_{imt} is the *monthly* quantity of CDN traffic used by content provider i in month m of year t, and p_{it} is the *yearly* contracted price. In order to generate flexible demand structures, we allow the price coefficient β_t to vary across years. The terms F_i and F_{mt} represent content provider and month-year fixed effects, respectively. These fixed effects capture any unobserved content-provider-specific but time-invariant heterogeneity and month-year-specific factors common across content providers. ε_{imt} is the idiosyncratic component.

Estimating the linear model above using OLS raises concerns about price endogeneity. Specifically, price endogeneity arises from omitted variables (e.g., unobserved demand factors) and from simultaneity between price and quantity in demand estimation. However, in our study, the observation of monthly quantity data in response to predetermined yearly prices partially mitigates the common endogeneity concern. Moreover, we use detailed fixed effects at both the content provider and month-year levels, effectively accounting for unobserved factors specific to individual content providers and monthly periods that could simultaneously influence both prices and quantities.

To address the remaining endogeneity issue, we use an IV approach. The instruments include (i) the unit server cabinet price charged to a content provider and (ii) the total payment for static bandwidth of a content provider. The identifying assumption is that both IVs are correlated with a content provider's CDN price for supply-side reasons but

uncorrelated with unobserved factors that drive a content provider's yearly demand level for CDN traffic, after controlling for both content provider and month-year fixed effects.

5.1.1 Estimation results

Table 2 summarizes the estimation results obtained using OLS and 2SLS regressions. We present results for specifications with and without year-specific β. The OLS estimates in columns (1) and (2), which are highly significant, indicate a negative slope of the demand curve for Internet traffic. A unit increase in the annual CDN price is associated with a 117.35-unit drop in average monthly traffic. In column (2) where we allow year-specific slopes, the estimates imply significant differences in the slope of CDN demand across years.

Table 3 reports the first-stage estimates for the specification with a common demand slope. Both instruments are statistically significantly associated with the CDN price. Table 2 reports Kleibergen–Paap (KP) F-statistics of 185.55 for the common-slope specification and 51.74 for the specification with year-specific slopes. In columns (3) and (4), the IV estimates differ from the OLS estimates, with the direction and magnitude of the differences varying across specifications. In the specification with a common demand slope, the IV estimate is smaller in absolute value than the OLS estimate. In the specification with year-specific slopes, the estimated effects vary across years.

Figure 4 presents the distribution of estimated effective (perceived) marginal costs of CDN bandwidth. Remarkably, a lower effective marginal cost is usually associated with a lower price. To interpret our demand estimates, we compute the elasticities of content provider demand and then recover v_{it} using the following equation derived from the monopoly pricing condition (4) (i.e., the inverse elasticity pricing formula):

$$v_{it} = p_{it} - \frac{q_{it}}{b_{it}}. \tag{10}$$

Here, $q_{it} = \sum_m q_{imt}$ denotes the yearly quantity, and b_{it} represents the slope of content provider demand aggregated at the year level, calculated as $b_{it} = M_{it}\beta_t$, where M_{it} is the number of active months of CP i in year t. In implementation, we use the observed yearly price and quantity data, along with the estimated demand coefficient $\hat{\beta}_t$. Notably, v_{it} encompasses both the marginal cost of Internet traffic and the network effect of content providers on Internet subscribers. In our analysis, we are unable to separately identify these two components without additional assumptions or information about Internet users' behaviors

Evidence of network-effect-based pricing. Before comparing the welfare effects of

Table 2: Estimation results

	Dependent variable: CDN traffic usage			
	(1) OLS	(2) OLS	(3) IV	(4) IV
CDN price	-117.349***	-121.354***	-93.271***	-139.585***
	(10.386)	(7.601)	(12.010)	(10.671)
2017∗CDN price	-	107.212***	-	110.363***
		(7.523)		(8.287)
2018∗CDN price	-	85.821***	-	74.966***
		(6.266)		(6.598)
2019∗CDN price	-	41.111***	-	47.073***
		(5.860)		(6.694)
F-stat	127.66	89.50	60.31	86.79
KP F-statistic	-	-	185.55	51.74
R^2	0.24	0.68	0.23	0.67
Observations	775	775	775	775

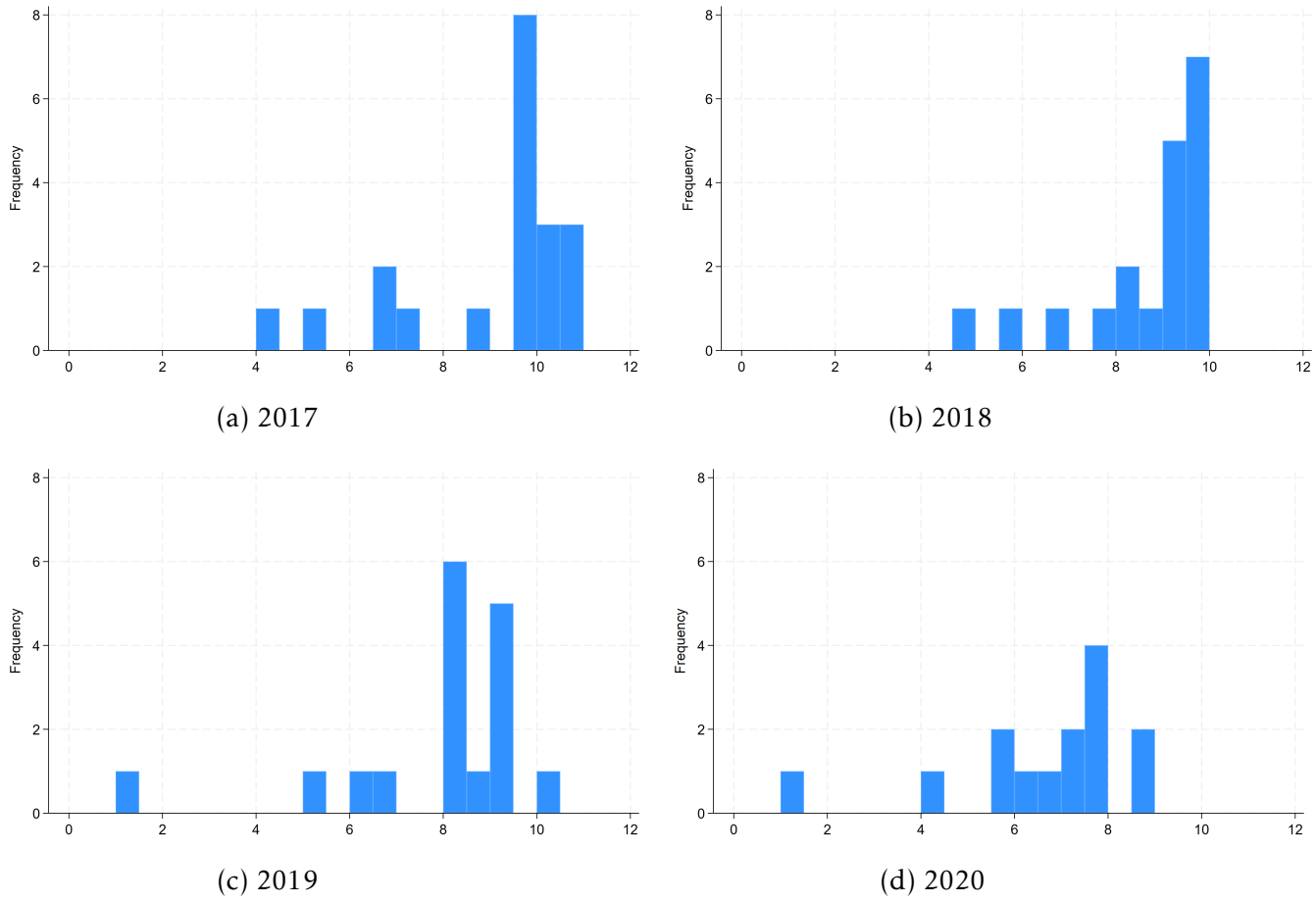
Notes: All models include content provider and year-month fixed effects. Significance at * 10%, ** 5%, and *** 1% levels.

Table 3: IV estimation: first-stage results

	Dependent variable: CDN price
Server cabinet price	9.588***
	(0.554)
Static bandwidth revenue	-0.484***
	(0.099)
F-stat	185.55
R^2	0.40
Observations	775

Notes: All models include content provider and year-month fixed effects. Significance at * 10%, ** 5%, and *** 1% levels.

Figure 4: Estimated v_{it} (CNY per 100 GB)



(a) 2017

(b) 2018

(c) 2019

(d) 2020

Notes: The figure shows estimated effective marginal costs of serving content providers, measured in CNY per 100 GB.

Table 4: Estimated price elasticities

Variable: elasticity	Obs.	Mean	S.D.	Median	5%	95%
Whole sample	775	52.09	77.32	30.27	2.51	156.29
2017	233	38.34	33.51	31.68	2.79	107.53
2018	222	55.75	54.24	40.15	3.04	166.22
2019	161	77.49	139.47	30.60	1.33	311.77
2020	159	41.45	52.50	18.39	1.35	156.59

differential pricing versus uniform pricing, we undertake an additional exercise to understand the role of network effects in pricing Internet traffic. Specifically, we calculate the counterfactual CDN prices for each content provider by assuming each provider's effective marginal cost equals that of *Autohome.com.cn*, under the assumption that *Autohome.com.cn* generates minimal network effects for the ISP. Autohome.com.cn has the highest estimated effective marginal cost in the 2017 sample, and therefore we make it the benchmark for this counterfactual.

Figure 5 presents the counterfactual prices alongside the observed prices for 2017[9]. We find that if ISP prices were based on the same estimated marginal cost of serving *Autohome.com.cn*, content providers would, on average, face a 25.7% price increase. For the top 6 content providers with low observed traffic prices, their prices would rise by 19.5%–137%. In essence, this analysis suggests that if differential pricing were solely determined by content providers' demand elasticities, many content providers—primarily online video and gaming platforms—would experience substantially higher charges, reflecting their greater reliance on ISP services. In summary, these results underscore the importance of network effects in shaping the observed pattern of price differences in the data.

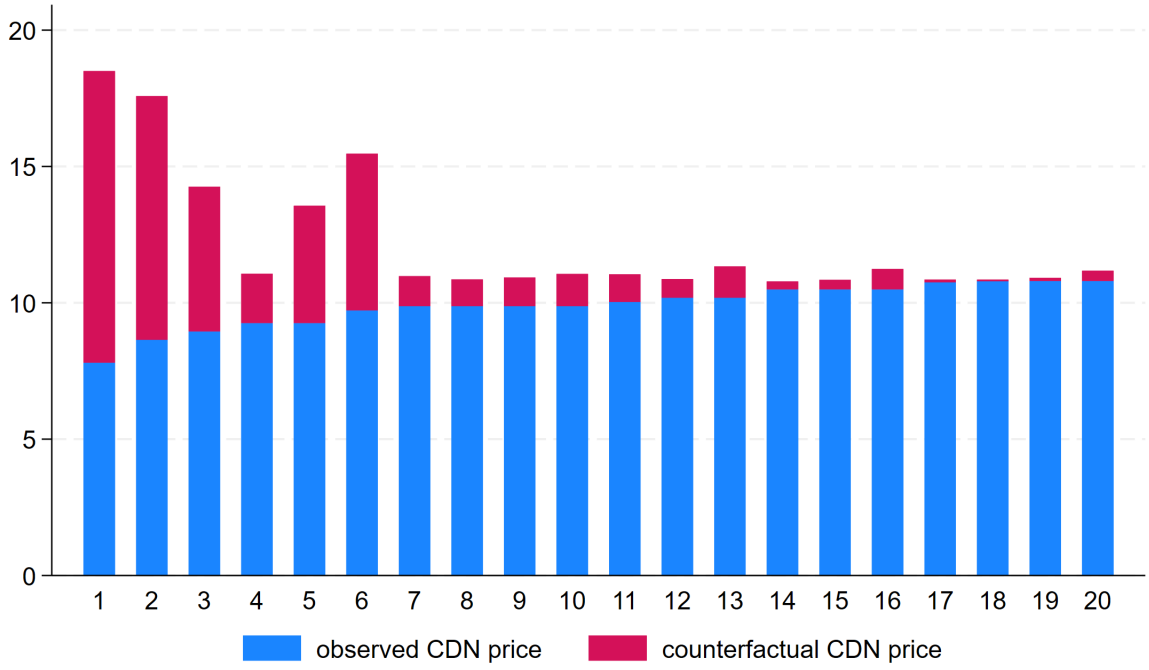
5.2 Welfare Comparisons

We now compare the welfare effects of differential pricing with uniform pricing of Internet traffic. Utilizing the estimated demand parameters and $\hat{v}_{it}$, which capture both marginal costs and network effects, we compute the counterfactual uniform price $\bar{p}_t$ using equation (4). Subsequently, we calculate the counterfactual CDN traffic usage of each content provider $\hat{q}_{it}(\bar{p}_t)$.

To examine the effects on content provider surplus, we calculate monthly surplus using the estimated monthly demand function and then sum across months. Let $\mathcal{M}_{it}$ denote

[9]The 2017 counterfactual analysis includes the 20 content providers with observed CDN transactions in that year.

Figure 5: Counterfactual: differential pricing solely based on demand elasticity



Notes: CDN price measured in CNY per 100 GB.

the set of active months for provider i in year t. Annual CP surplus under the two pricing regime is

$$CPS_{it}^{DP} = \sum_{m \in \mathcal{M}_{it}} \frac{(q_{imt}^*)^2}{2\hat{\beta}_t}, \; CPS_{it}^{UP} = \sum_{m \in \mathcal{M}_{it}} \frac{(\bar{q}_{imt})^2}{2\hat{\beta}_t}, \tag{11}$$

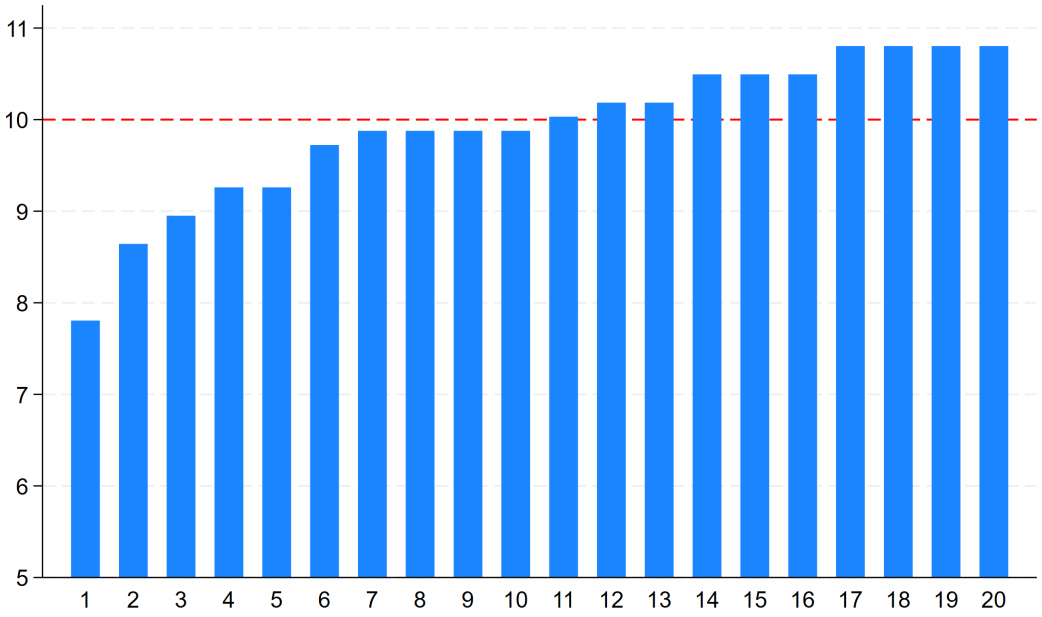
where $\hat{\beta}_t > 0$ is the magnitude of the estimated monthly demand slope. Holding monthly demand shifters fixed, counterfactual monthly quantities under uniform pricing are

$$\bar{q}_{imt} = q_{imt}^* + \hat{\beta}_t(p_{it} - \bar{p}_t). \tag{12}$$

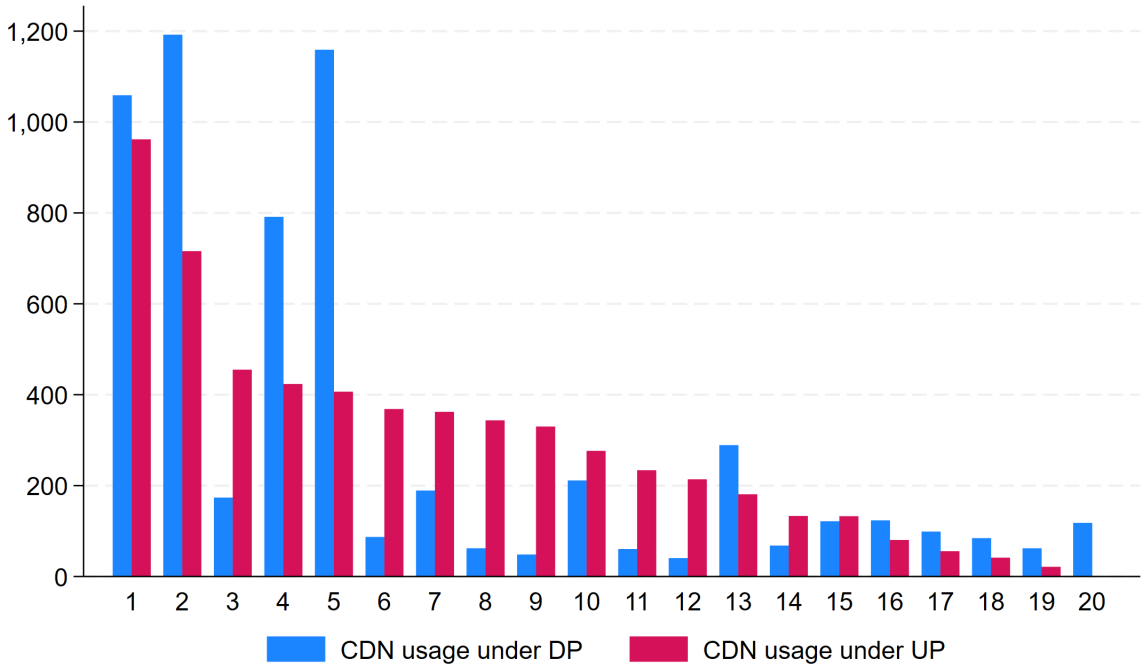
These calculations maintain positive monthly quantities and the same set of active months under both regimes.

Figure 6b graphs the distribution of CDN usage under the counterfactual scheme of uniform pricing compared to differential pricing observed in the data. Content providers are presented in order of their traffic usage under uniform pricing. Compared with uniform pricing, under differential pricing, exactly half of content providers experience increased traffic usage, whereas the other half experience decreased traffic usage. Content providers at both ends of the ranking, including those with the highest and lowest us-

Figure 6: Counterfactual: differential pricing vs. uniform pricing (2017)



(a) CDN prices under differential vs. uniform pricing



(b) Yearly CDN traffic (10^6 GB) under differential vs. uniform pricing

Notes: The red horizontal line represents the counterfactual uniform CDN price. CDN price measured in CNY per 100 GB.

age, benefit from differential pricing as their usage increases. Several content providers experience substantial increases in usage, ranging from 10% to 195%. However, content providers with medium usage levels under uniform pricing observe a decrease in traffic quantity under differential pricing. Recall that total Internet traffic remains constant under both schemes, a property inherent in linear demand systems (as shown in Section 3.2). Consequently, the total increase in CDN traffic among the 10 content providers precisely offsets the total decrease in usage among the other 10 content providers.

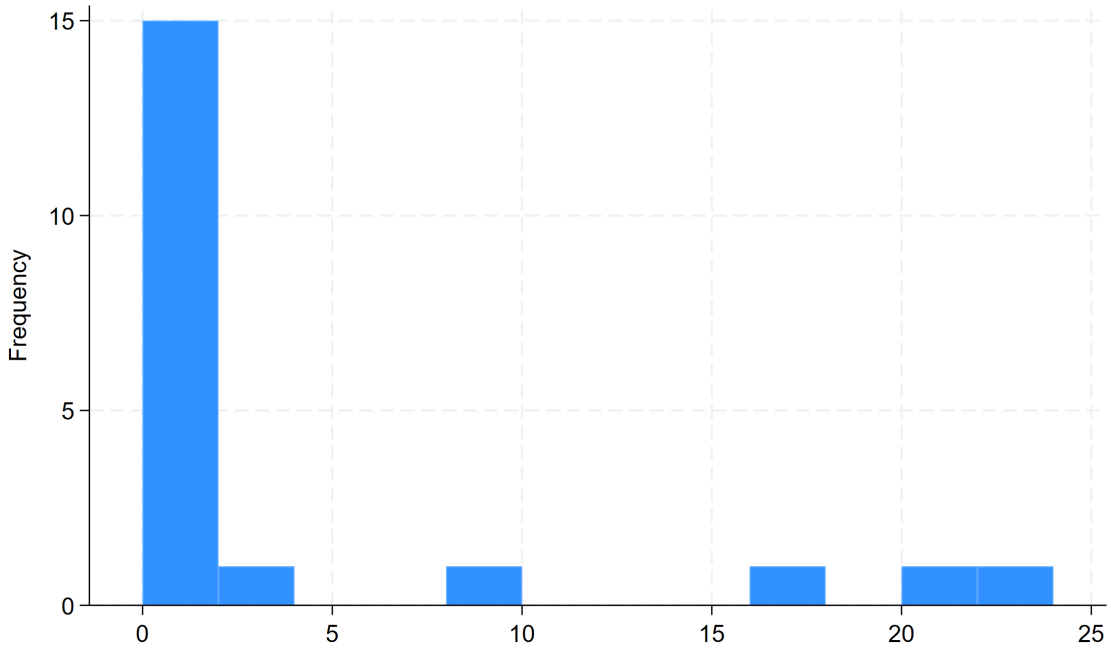
Content provider surplus. Regarding the content provider surplus, we have shown theoretically that, even with linear demand, it is unclear ex ante whether differential pricing is welfare-superior to uniform pricing when both demand elasticities and network effects are taken into account. Figure 7 graphs the distribution of content provider surplus under the two pricing schemes for 2017. In 2017, aggregate content provider surplus under differential pricing is approximately CNY 74 million, which is 61% higher than under uniform pricing. Together with Figure 6, these results indicate that the aggregate surplus gain is associated with increased traffic among providers with high usage under uniform pricing. Linking these results to Figure 5, we observe that these traffic-intensive content providers are also the ones generating larger network effects, such as those providing gaming or video-streaming services. Overall, we find that differential pricing leads to higher aggregate content provider surplus compared to uniform pricing.

A notable aspect of the Internet traffic market is that buyers in this context are themselves Internet firms, warranting regulatory attention. Therefore, we also examine the implications of differential pricing for individual providers. Figure 8 shows the distribution of the percentage change in content provider surplus, with uniform pricing used as the baseline scheme. Evidently, while aggregate surplus increases, half of the content providers become worse off with lower surplus. The other half of content providers see an increase in surplus under differential pricing; nevertheless, their total gain in surplus outweighs the total loss of surplus experienced by the remaining content providers.

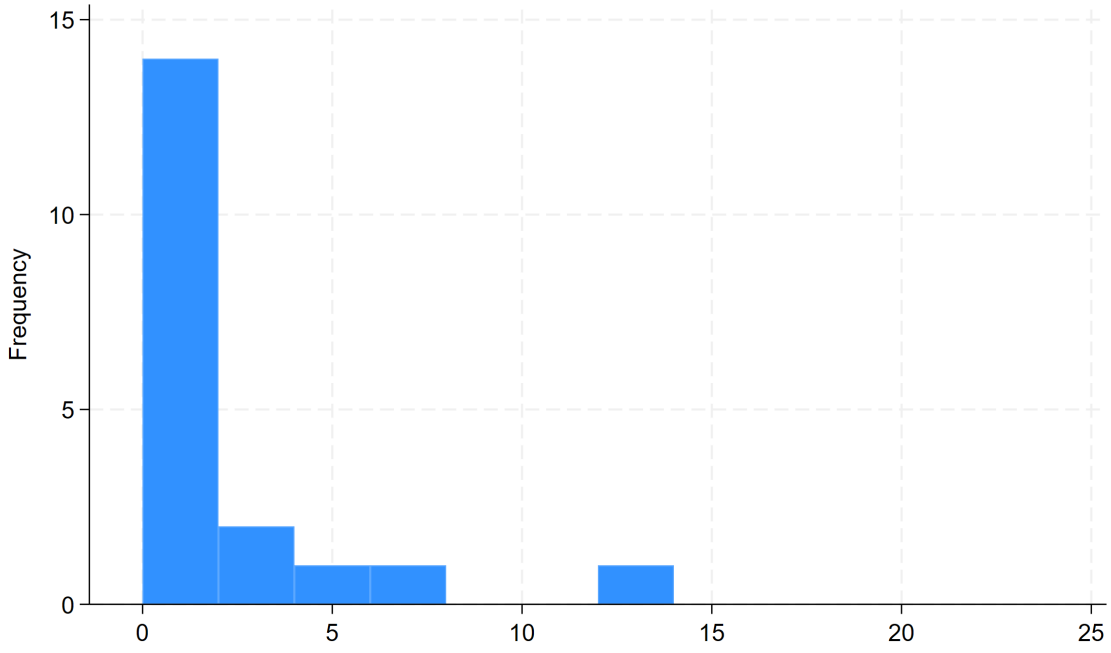
To further quantify the distributional impact, we calculate a revenue-based HHI for each scheme. Under differential pricing, the concentration in terms of CDN traffic allocation increases from 0.083 to 0.132. Because our theoretical analysis does not explicitly model any market interactions between content providers and Internet subscribers, we are unable to quantify the welfare implications of concentration in content providers' traffic usage. This effect of differential pricing underscores its relevance in assessing related regulatory or antitrust concerns pertaining to digital firms.

Internet subscriber surplus. Assessing the impact of the two pricing schemes on Internet user surplus poses a significant challenge, primarily due to the lack of data en-

Figure 7: Content provider surplus under DP vs. UP



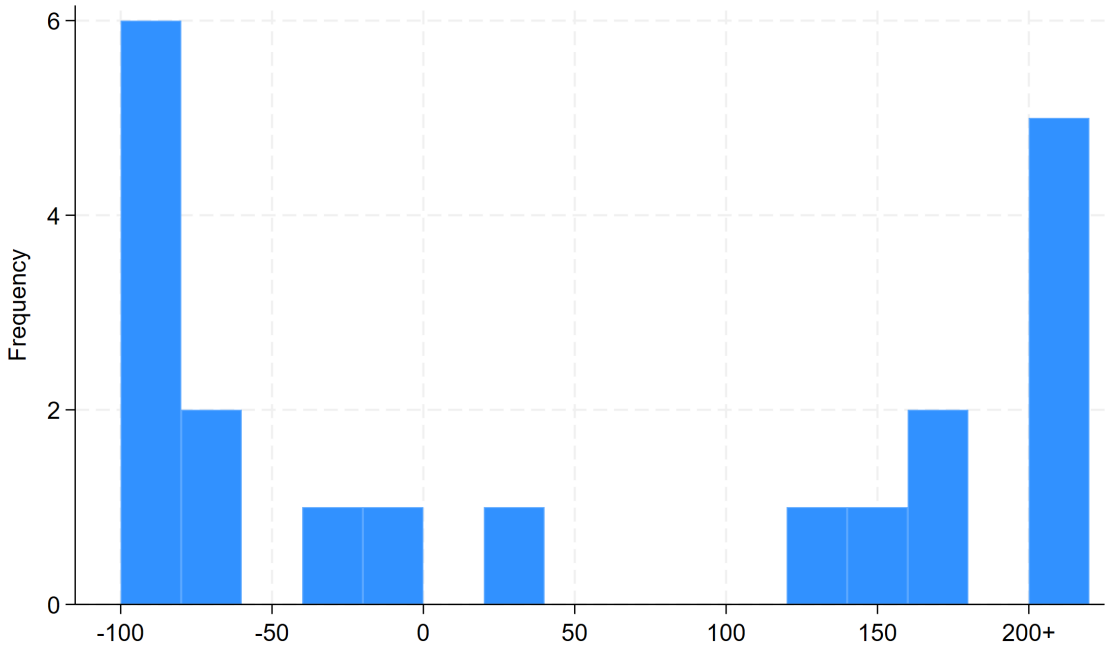
(a) Under differential pricing
(mean=3.70)



(b) Under uniform pricing
(mean=2.29)

Notes: The histograms show annual content provider surplus across 20 providers in 2017, measured in millions of CNY. Mean surplus is higher under differential pricing (3.70 versus 2.29).

Figure 8: Change (%) in content provider surplus under UP vs. DP



Notes: The figure shows the percentage change in content provider surplus under differential pricing relative to uniform pricing.

abling recovery of parameters characterizing consumption choices regarding both Internet subscriptions and online content use. Theoretically, we have shown that differential pricing raises Internet user surplus if and only if condition A2 holds. Quantitatively assessing the condition requires estimates of κ_i, which we do not have enough information to estimate. However, we argue that it is still possible to qualitatively examine the change in user surplus with given data. Specifically, given the condition that the total provision of CDN traffic is the same under both schemes, we derive the following equivalent condition that uses information of v_i:

$$\sum_{i=1}^{N}(s\kappa_i - c)(q_i^* - \bar{q}_i) = \sum_{i=1}^{N} -v_i(q_i^* - \bar{q}_i) > 0. \tag{A2'}$$

Intuitively, condition (A2) implies that differential pricing raises Internet subscriber surplus if and only if differential pricing yields a higher level of total network benefits than uniform pricing. Total network benefits are represented as a weighted sum of content providers' CDN traffic, with the weights given by κ_i. Under the assumption of a constant marginal cost, having a larger weighted sum of content providers' traffic with

weights given by κ_i is equivalent to having a smaller weighted sum of CDN traffic with weights given by v_i, the ISP's effective marginal cost of serving content provider i, which we estimate using equation (10).

Figure 9a and Figure 9b show the distribution of $\hat{v}q^*$ and $\hat{v}\bar{q}$, respectively. A simple calculation shows that compared to uniform pricing, Internet users benefit more from differential pricing. Intuitively, differential pricing allows the ISP to allocate more CDN traffic to content providers generating higher network benefits for subscribers, which aligns with our findings.

5.3 Robustness

To check the robustness of our empirical results, we consider alternative demand forms. As shown in Section 3.4, beyond linear demand, commonly used functions such as $\ln q_i = a_i - b \ln p_i$ and $\ln q_i = a_i - bp_i$ introduce "built-in" theoretical properties that make empirical analysis less meaningful. In particular, under those demand functions with a common parameter b, both consumer surplus and aggregate content provider surplus are always higher under differential pricing than uniform pricing. Moreover, the log-linear function $\ln q_i = a_i - b \ln p_i$ implies isoelasticity across content providers, so demand estimation based on this specification does not yield a distribution of price elasticities that can be used for comparison.

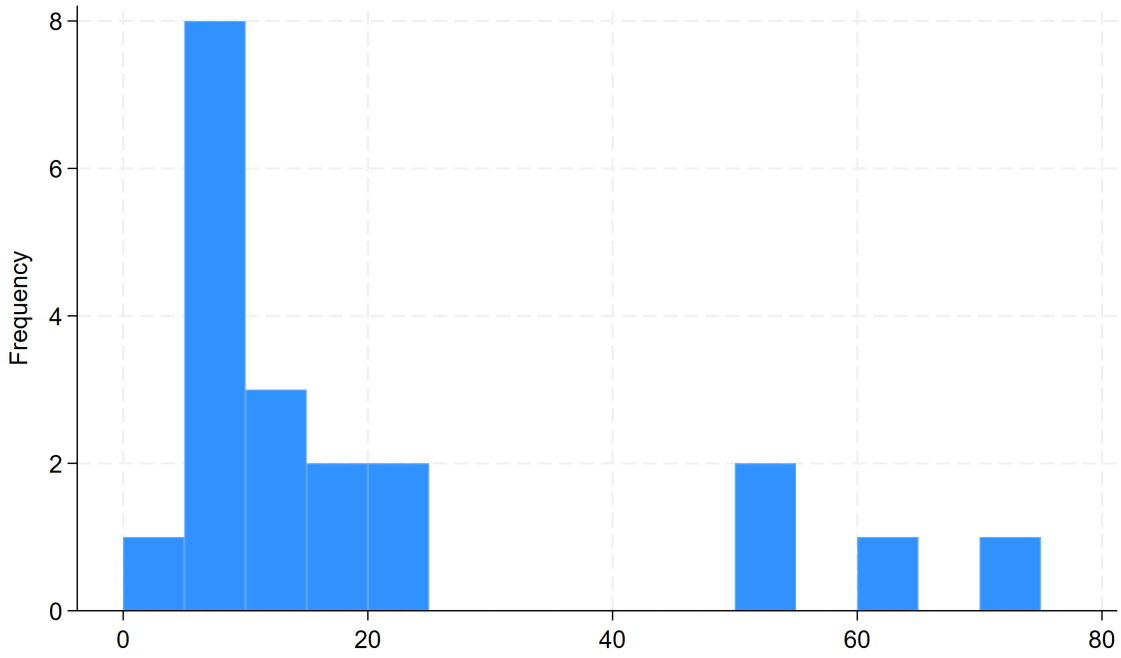
Then, we are left with the functional form: $\ln q_i = a_i - bp_i$. We repeat the estimation procedure described in the previous section using this alternative demand specification. Appendix Section A.4 includes more details on the theoretical underpinnings.

Figure 10 shows the distribution of v_{it}, which we back out using the inverse elasticity rule with the new estimates. Compared to Figure 4, it shows a set of estimated v_{it} with a smaller dispersion. Nonetheless, the shape of the distributions is similar to our main findings, giving us more confidence in the validity of our empirical analysis.

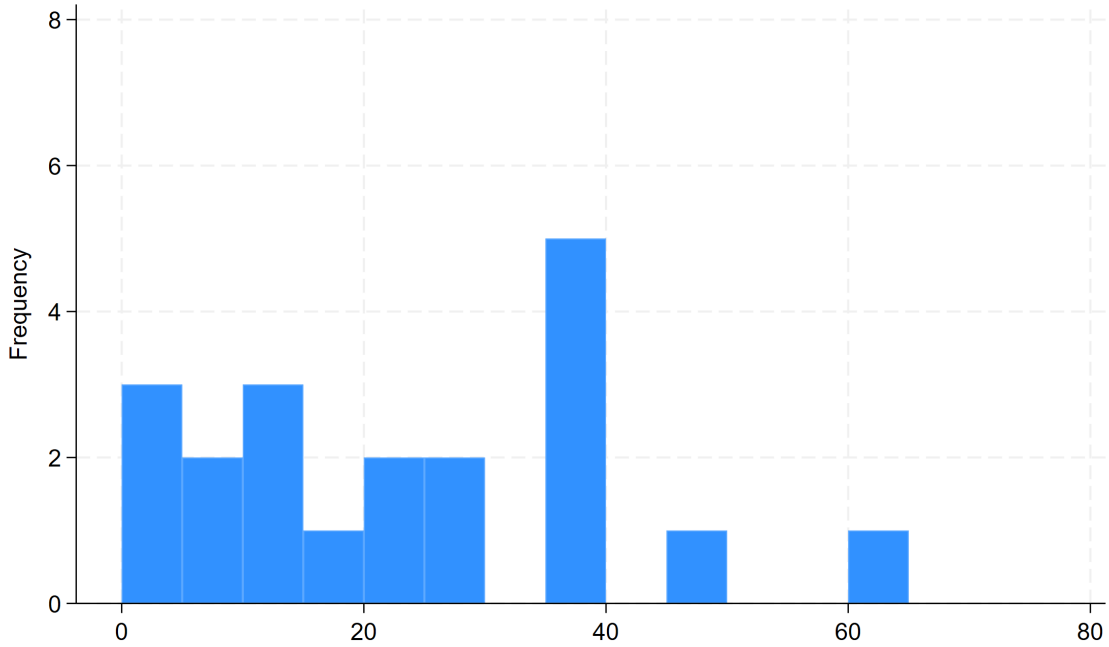
Figure 11 repeats the exercise in which we equalize all content providers' effective marginal costs at the level of Autohome.com.cn. Under the semi-log demand specification, the optimal price is $p_i^* = v_i + 1/b$, so a common effective marginal cost and a common demand coefficient imply identical counterfactual prices across providers. Consistent with the baseline results, removing differences in network effects raises Internet traffic prices for providers that previously benefited from lower effective marginal costs.

Figure 12 shows the distribution of content provider surplus under the two schemes. Under the alternative demand specification, aggregate content provider surplus is approximately 3.9 times as high under differential pricing as under uniform pricing, cor-

Figure 9: Effective marginal cost-weighted traffic under DP and UP



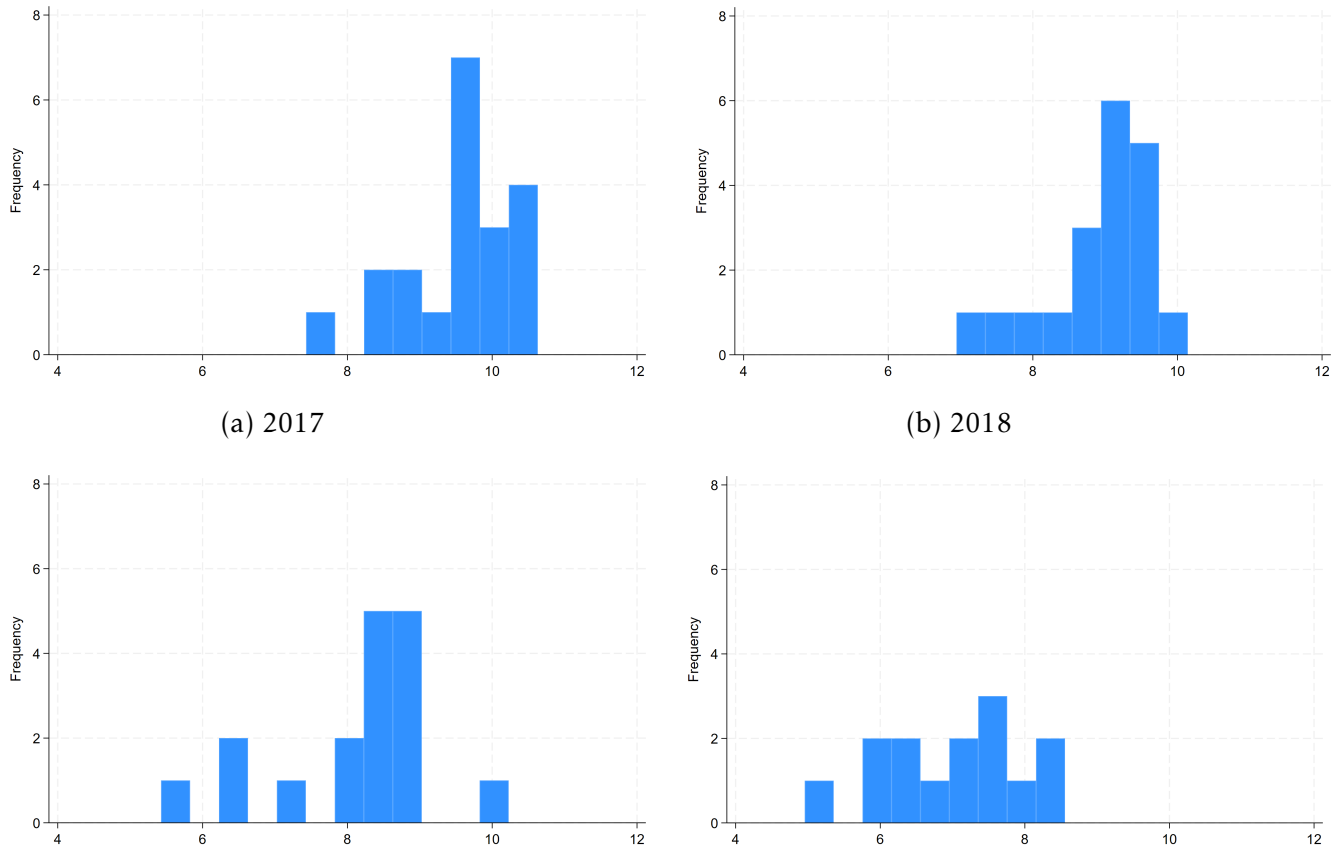
(a) Under differential pricing ($\hat{v}q^*$)
(mean=20.61)



(b) Under uniform pricing ($\hat{v}\bar{q}$)
(mean=23.66)

Notes: The lower mean of $\hat{v}_i q_i$ under differential pricing (20.61 versus 23.66) indicates greater network benefits and higher Internet user surplus. This comparison establishes only the direction of the welfare change, as its magnitude also depends on the unestimated term $(D^* + \bar{D})/(2\delta)$ in the Internet user surplus expression.

Figure 10: Estimated effective marginal costs (robustness)



(a) 2017

(b) 2018

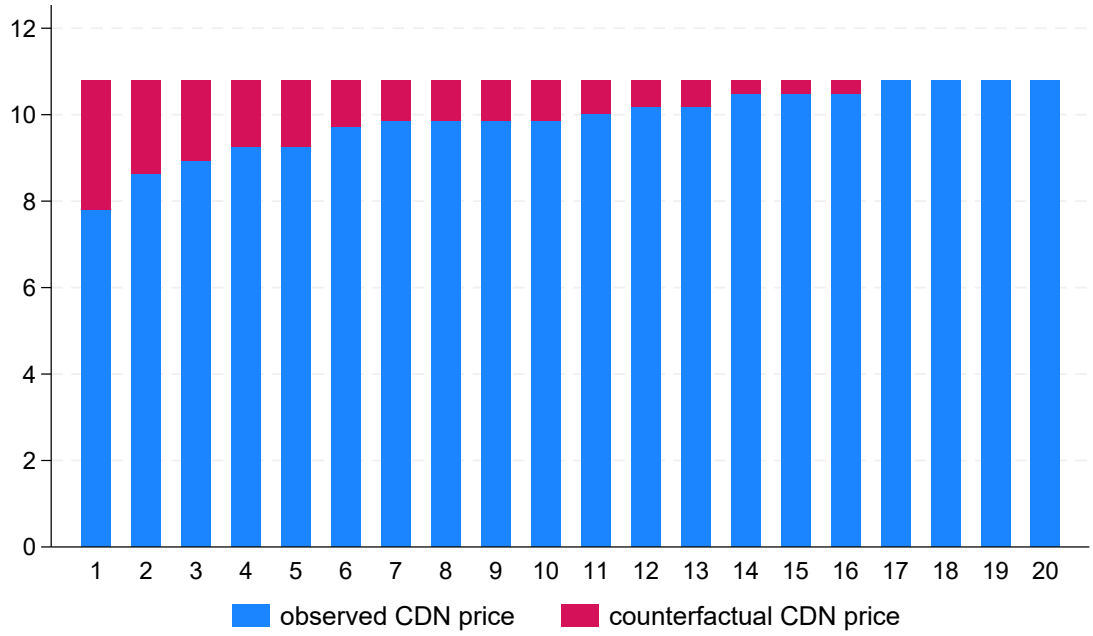
(c) 2019

(d) 2020

Notes: The unit is CNY per 100 GB. Effective marginal costs are recovered using the alternative semi-log demand specification: $\ln q_i = a_i - bp_i$.

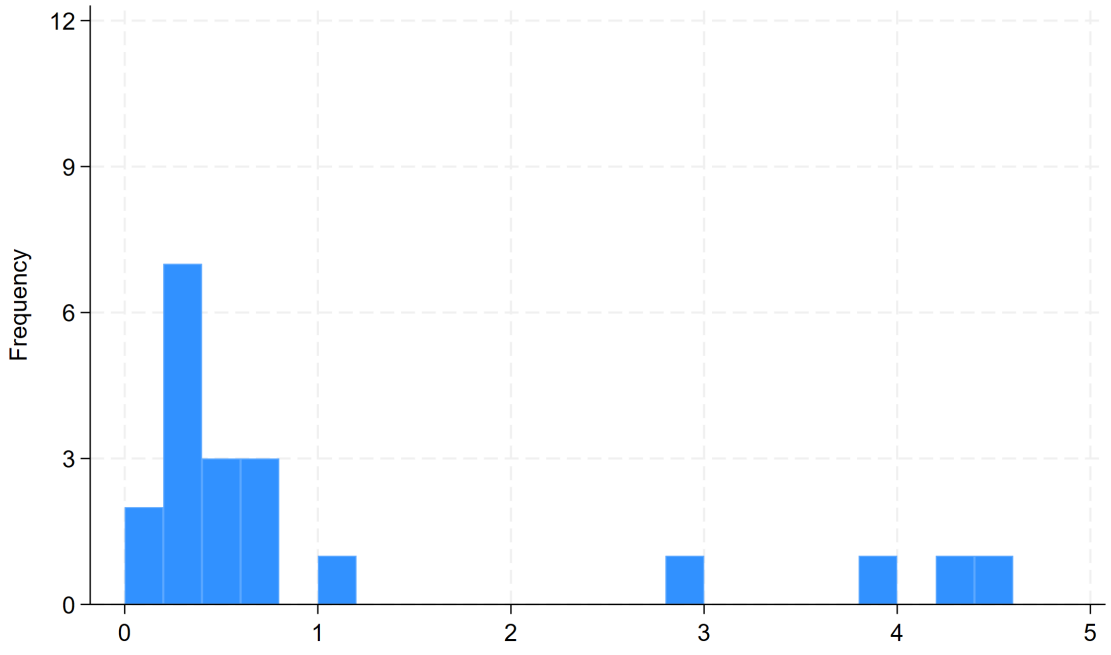
responding to an increase of about 290%. The increase in aggregate content provider surplus is consistent with the baseline results, although its direction is implied by the semi-log specification. The empirical exercise quantifies the size of this increase and shows how surplus is distributed across providers under the two pricing regimes.

Figure 11: Counterfactual prices with equalized effective marginal costs (robustness)

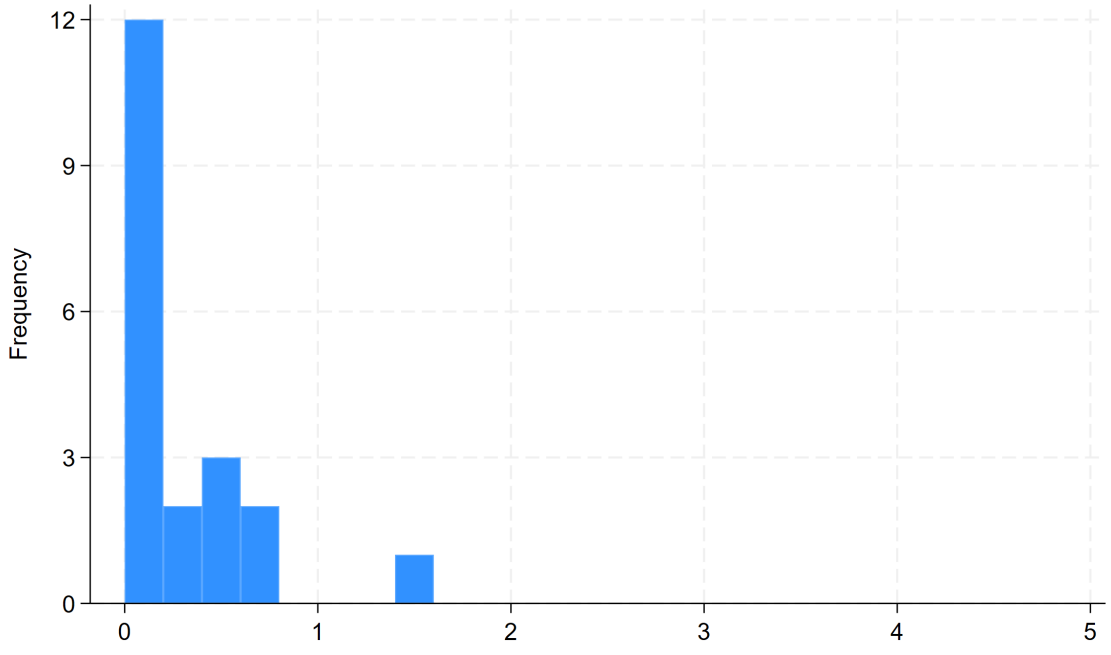


Notes: CDN price measured in CNY per 100 GB. Blue segments show observed prices, and red segments show the gap to the common counterfactual price under semi-log demand, with effective marginal costs equalized at Autohome's level.

Figure 12: Content provider surplus under DP vs. UP (robustness)



(a) Under differential pricing
(mean=1.13)



(b) Under uniform pricing
(mean=0.29)

Notes: The histograms show annual content provider surplus across 20 providers in 2017, measured in millions of CNY. Content provider surplus is calculated using the alternative semi-log demand specification: $\ln q_i = a_i - bp_i$.

6 Conclusion

In this paper, we study differential pricing by a monopoly ISP in a network-industry context. We first present a theoretical model in which both content providers and consumers have linear demands, and content providers are heterogeneous in their network effects and demand elasticities. We characterize the conditions under which differential pricing increases welfare for content providers and Internet users, and then analyze two extreme cases–where heterogeneity arises solely from network effects or solely from demand elasticities–to derive sharp predictions and guide our empirical analysis.

Using a unique transaction-level dataset from a large ISP in China, we estimate the demand for Internet bandwidth, addressing identification concerns using fixed effects and an IV strategy. Based on the estimated demand functions, we perform counterfactual comparisons between differential and uniform pricing. Although aggregate content provider surplus and Internet-user surplus both increase under differential pricing, only half of content providers are welfare gainers. This uneven distribution, together with the resulting cost advantage for large providers, creates competitive challenges for smaller firms. Our model captures the ISP's pricing incentives and the network benefits that content provision generates for Internet users, but abstracts from downstream competition among content providers. Differences in bandwidth prices and the uneven distribution of surplus gains may affect providers' competitive positions, pricing and investment decisions. These downstream responses could alter both aggregate welfare and the distribution of gains across providers and consumers, but their effects remain outside the scope of our analysis.

Several avenues remain for future research. In the theoretical part, the welfare implications of differential pricing are generally ambiguous as we study a two-sided market with N content providers. Researchers can simplify the model and derive more succinct and clearer conditions for welfare-increasing differential pricing by assuming only two content providers. In addition, bargaining between the ISP and content providers during contract negotiations may play a role in affecting the welfare analysis. We leave these extensions for future work.

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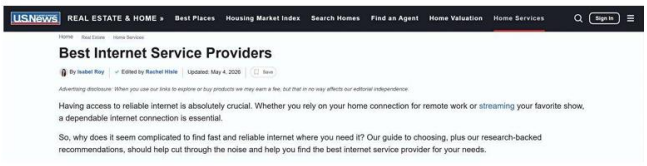
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Appendix

A.1 Descriptive evidence

Figure A1: Media ranking of ISPs

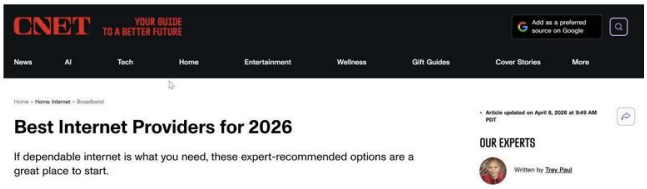
US News.com



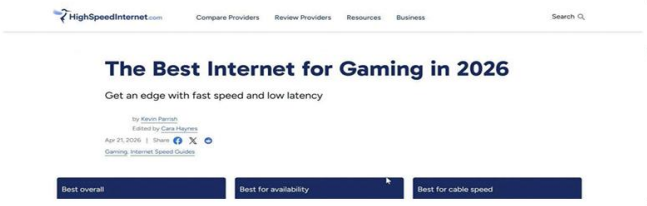
CableTV.com



CNET.com



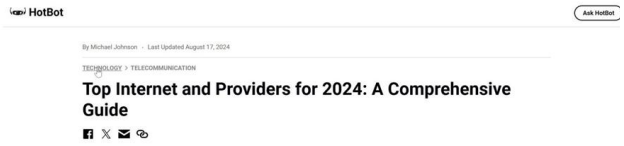
HighSpeed.com



Reviews.com



Hotbot.com



PCmag.com



Nasdaq.com



Reviews.com



Notes: This figure presents a screenshot of a compilation of headlines and excerpts from online media and consumer review platforms evaluating ISPs. The selected clippings highlight how online media categorize ISP evaluations based on specific consumer needs, emphasizing crucial factors such as optimized performance for data-intensive online content, like gaming and video streaming.

Figure A2: Online discussion about user experiences with an online game via different ISPs in China



Notes: This figure displays a screenshot of a post from Zhihu, the Chinese *Quora*, discussing the geographical locations of various League of Legends regional servers across China. To minimize gaming latency, the post advises players to select a server physically closer to their location and choose a region that matches their ISP. The included tables categorize the servers by internet service providers such as China Telecom and China Unicom, and map specific game servers to host cities, including Dongguan, Hangzhou, Shanghai, etc.

A.2 Proof of Proposition 2

We maintain the interior-solution assumptions, with all content providers served under both pricing schemes, and hold the subscription fee $s > 0$ fixed.

We first consider differential pricing based solely on network effects. Suppose $a_i = a$ and $b_i = b$ for all i, and define $\bar{\kappa} = \frac{1}{N}\sum_{i=1}^{N} \kappa_i$. Moreover, we assume that κ_i is not identical across all content providers. Under differential pricing,

$$q_i^* = \frac{a - b(c - s\kappa_i)}{2} = \frac{a - bc}{2} + \frac{bs}{2}\kappa_i.$$

Under uniform pricing, each content provider purchases the same quantity:

$$\bar{q}_i = \bar{q} = \frac{a - bc}{2} + \frac{bs}{2}\bar{\kappa}.$$

Consequently,

$$q_i^* - \bar{q} = \frac{bs}{2}(\kappa_i - \bar{\kappa}), \qquad \sum_{i=1}^{N}(q_i^* - \bar{q}) = 0.$$

The change in aggregate content provider surplus is

$$\begin{aligned}
\Delta CPS &= \frac{1}{2b}\sum_{i=1}^{N}\left[(q_i^*)^2 - \bar{q}^2\right] \\
&= \frac{1}{2b}\sum_{i=1}^{N}\left[2\bar{q}(q_i^* - \bar{q}) + (q_i^* - \bar{q})^2\right] \\
&= \frac{1}{2b}\sum_{i=1}^{N}(q_i^* - \bar{q})^2 \\
&= \frac{bs^2}{8}\sum_{i=1}^{N}(\kappa_i - \bar{\kappa})^2.
\end{aligned}$$

Thus, aggregate content provider surplus is strictly higher under differential pricing since network effects differ across providers.

For Internet users, the change in total network benefits is

$$\begin{aligned} Q^* - \bar{Q} &= \sum_{i=1}^{N} \kappa_i (q_i^* - \bar{q}) \\ &= \frac{bs}{2} \sum_{i=1}^{N} \kappa_i (\kappa_i - \bar{\kappa}) \\ &= \frac{bs}{2} \left[\sum_{i=1}^{N} (\kappa_i - \bar{\kappa})^2 + \bar{\kappa} \sum_{i=1}^{N} (\kappa_i - \bar{\kappa}) \right] \\ &= \frac{bs}{2} \sum_{i=1}^{N} (\kappa_i - \bar{\kappa})^2 > 0, \end{aligned}$$

where the last equality follows from $\sum_i (\kappa_i - \bar{\kappa}) = 0$. Since the subscription fee is fixed,

$$\Delta CS = (Q^* - \bar{Q}) \frac{D^* + \bar{D}}{2\delta} > 0.$$

Finally, the ISP's maximized profit is weakly higher under differential pricing because uniform pricing remains feasible. Therefore,

$$\Delta W = \Delta CPS + \Delta CS + \Delta \Pi^{ISP} > 0.$$

We then consider differential pricing based solely on demand elasticities. Suppose $b_i = b$ and $\kappa_i = \kappa$ for all i, while a_i is not identical across all content providers. Define

$$v = c - s\kappa, \qquad \bar{a} = \frac{1}{N} \sum_{i=1}^{N} a_i, \qquad q_0 = \frac{\bar{a} - bv}{2}.$$

The optimal prices are

$$p_i^* = \frac{a_i/b + v}{2}, \qquad \bar{p} = \frac{\bar{a}/b + v}{2},$$

and the corresponding quantities can be written as

$$q_i^* = q_0 + \frac{a_i - \bar{a}}{2}, \qquad \bar{q}_i = q_0 + (a_i - \bar{a}).$$

Using $\sum_i (a_i - \bar{a}) = 0$, the change in aggregate content provider surplus is

$$\begin{aligned}\Delta CPS &= \frac{1}{2b}\sum_{i=1}^{N}\left[\left(q_0 + \frac{a_i - \bar{a}}{2}\right)^2 - (q_0 + a_i - \bar{a})^2\right] \\ &= -\frac{3}{8b}\sum_{i=1}^{N}(a_i - \bar{a})^2 < 0.\end{aligned}$$

Since all providers generate the same network effect and total traffic is unchanged,

$$Q^* - \bar{Q} = \kappa \sum_{i=1}^{N}(q_i^* - \bar{q}_i) = 0.$$

The subscription fee is also unchanged, so $\Delta CS = 0$.

To calculate the change in ISP profit, note that the terms $-\delta s^2 + \kappa_0 s$ cancel between the two regimes. Moreover, $p_i^* - v = q_i^*/b$, $\bar{p} - v = q_0/b$, and $\sum_i \bar{q}_i = N q_0$. Therefore,

$$\begin{aligned}\Delta\Pi^{ISP} &= \sum_{i=1}^{N}\left[(p_i^* - v)q_i^* - (\bar{p} - v)\bar{q}_i\right] \\ &= \frac{1}{b}\left[\sum_{i=1}^{N}(q_i^*)^2 - N q_0^2\right] \\ &= \frac{1}{4b}\sum_{i=1}^{N}(a_i - \bar{a})^2.\end{aligned}$$

Combining these expressions gives

$$\Delta W = \Delta CPS + \Delta CS + \Delta\Pi^{ISP} = -\frac{1}{8b}\sum_{i=1}^{N}(a_i - \bar{a})^2 < 0.$$

The strict inequalities in each case require heterogeneity in κ_i or a_i. If all network effects and all demand intercepts are identical, differential and uniform pricing yield the same outcomes.

A.3 Proof of Proposition 3

Under the DP scheme, the ISP's optimization problem becomes

$$\max_{\mathbf{p},s^{DP}} \sum_{i=1}^{N}(p_i - c + s\kappa_i)q_i(p_i) - \delta s^2 + \kappa_0 s.$$

The FOCs imply

$$p_i^* = \frac{a_i}{2b_i} + \frac{c - s^{DP}\kappa_i}{2}, \qquad s^{DP} = \frac{\sum_{j=1}^{N}\kappa_j q_j^* + \kappa_0}{2\delta}.$$

Further solving yields

$$s^{DP} = \frac{\sum \kappa_j(a_j - cb_j) + 2\kappa_0}{4\delta - \sum \kappa_j^2 b_j}, \qquad p_i^* = \frac{a_i + cb_i}{2b_i} - \frac{\kappa_i}{2}\frac{\sum \kappa_j(a_j - cb_j) + 2\kappa_0}{4\delta - \sum \kappa_j^2 b_j},$$

Under the UP scheme, the FOCs imply

$$\bar{p} = \frac{\sum\left(a_j + (c - s^{UP}\kappa_j)b_j\right)}{2\sum b_j}, \qquad s^{UP} = \frac{\sum \kappa_j \bar{q}_j + \kappa_0}{2\delta}.$$

Further solving yields

$$s^{UP} = \frac{\sum \kappa_j(2a_j - cb_j) - \frac{\sum \kappa_j b_j \cdot \sum a_j}{\sum b_j} + 2\kappa_0}{4\delta - \frac{(\sum \kappa_j b_j)^2}{\sum b_j}},$$

and for ease of exposition, we omit the expression of $\bar{p}$.

The optimal quantities under differential and uniform pricing are obtained by substituting s^{DP} and s^{UP}, respectively, into the following expressions:

$$q_i^* = \frac{a_i - b_i v_i^{DP}}{2} = \frac{a_i - b_i(c - s^{DP}\kappa_i)}{2},$$
$$\bar{q}_i = a_i - b_i\frac{\sum(a_j + b_j v_j^{UP})}{2\sum b_j} = a_i - b_i\frac{\sum a_j + b_j(c - s^{UP}\kappa_j)}{2\sum b_j}.$$

Similarly, to study the welfare effect on content providers, we modify condition (A1)

to obtain the following condition for CP surplus to rise under DP:

$$\sum_{i=1}^{N}\left[(3a_i - b_i v_i^{DP} - b_i\frac{\sum(a_j + b_j v_j^{UP})}{\sum b_j})(\frac{\sum(a_j + b_j v_j^{UP})}{\sum b_j} - \frac{a_i}{b_i} - v_i^{DP})\right] > 0, \qquad \text{(A1')}$$

where $v^{DP} = c - s^{DP}\kappa$ and $v^{UP} = c - s^{UP}\kappa$.

On the Internet user side, the necessary and sufficient condition for consumer surplus to increase under DP remains the same as condition A2. The subscription-fee first-order conditions imply

$$\begin{aligned} Q^* - \bar{Q} &= 2\delta\left(s^{DP} - s^{UP}\right), \\ D^* - \bar{D} &= \frac{Q^* - \bar{Q}}{2}. \end{aligned} \qquad (13)$$

Since household demand is positive under both regimes, consumer surplus is higher under differential pricing if and only if total network benefits are higher. Once again, the conditions are useful for determining the welfare effects of DP for a given set of parameters. To deliver further insights, we consider the two extreme cases.

First, consider the case of purely network-effect-based differential pricing. The optimal subscription fees under the two schemes are

$$s^{DP} = \frac{2\kappa_0 + (a - bc)\sum\kappa_j}{4\delta - b\sum\kappa_j^2}, \qquad s^{UP} = \frac{2\kappa_0 + (a - bc)\sum\kappa_i}{4\delta - b(\sum\kappa_i)^2/N}.$$

Since $\sum\kappa_j^2 \geq (\sum\kappa_j)^2/N$, we have $s^{DP} \geq s^{UP}$. That is, when DP pricing is based on the network effects only, the ISP charges a (weakly) higher subscription fee to households under DP than UP. The subscription-fee first-order conditions imply that the higher equilibrium subscription fee under differential pricing is associated with greater total network benefits for Internet users.

To analyze the welfare effect, we define a hypothetical, "would-be" price, p_i^w, which is the discriminatory price evaluated at s^{UP}. Thus, for each content provider i, we have

$$p_i^w \equiv \frac{a}{2b} + \frac{c - s^{UP}\kappa_i}{2} \geq p_i^*.$$

Since for each i, the would-be price is higher and the quantity is lower, it follows that $CPS^{DP} \geq CPS^w$. In addition, following the key proposition from our previous analysis, for the same subscription price, the aggregate CP surplus is higher under DP than under UP, that is, $CPS^w \geq CPS^{UP}$. Therefore, $CPS^{DP} \geq CPS^{UP}$ in this case.

To compare consumer surplus, we must account for changes in both network benefits

and the subscription fee. Under interior subscription demand, the change in consumer surplus is

$$\begin{aligned} CS^{DP} - CS^{UP} &= \frac{(D^*)^2 - (\bar{D})^2}{2\delta} \\ &= \frac{D^* + \bar{D}}{2\delta}\left[Q^* - \bar{Q} - \delta\left(s^{DP} - s^{UP}\right)\right] \\ &= \frac{\delta}{2}\left[(s^{DP})^2 - (s^{UP})^2\right] \\ &= \frac{\delta}{2}\left(s^{DP} - s^{UP}\right)\left(s^{DP} + s^{UP}\right) \geq 0. \end{aligned} \tag{14}$$

The inequality is strict whenever network effects differ across content providers. Thus, purely network-effect-based differential pricing increases consumer surplus despite the higher subscription fee.

Collectively, our findings suggest that with an endogenous subscription price, when DP is driven solely by network effects, it increases not only aggregate CP surplus and consumer surplus but also overall social surplus.

Next, consider the purely elasticity-based DP of the ISP. Let $b_i = b, \kappa_i = \kappa$ for all i. In this case,

$$s^{DP} = s^{UP} = \frac{2\kappa_0 + \kappa \sum (a_i - cb_i)}{4\delta - \kappa^2 \sum b_i}.$$

That is, the ISP optimally charges the same subscription price to households under the two distinct pricing schemes. This makes our previous results applicable here.

A.4 Alternative demand functions

Similar to the linear demand case, we maintain the interior-solution assumptions, with all content providers served under both pricing schemes, and hold the subscription fee $s > 0$ fixed. Moreover, we assume that a_i and κ_i are not identical across all content providers.

We first consider the log-linear demand function

$$\ln q_i = a_i - b \ln p_i. \tag{15}$$

In this case, the underlying net payoff to a content provider is

$$\pi_i^{CP} = \frac{A_i^{\beta}}{1-\beta} q_i^{1-\beta} - p_i q_i,$$

where $a_i = \ln A_i, b = \frac{1}{\beta} > 1$ in the demand function.

The welfare effects on content providers, who correspond to buyers in this setting, are established in the literature (Chen and Schwartz, 2015). We provide an alternative proof and extend the analysis to Internet users.

The prices under DP and UP are:

$$p_i^* = \frac{bv_i}{b-1} = \frac{b(c-s\kappa_i)}{b-1},$$
$$\bar{p} = \frac{\sum_{i=1}^{N} e^{a_i} p_i^*}{\sum_{i=1}^{N} e^{a_i}} = \frac{b}{b-1} \frac{\sum_{i=1}^{N} e^{a_i} v_i}{\sum_{i=1}^{N} e^{a_i}}.$$

Rewriting $\bar{p}$ yields

$$\bar{p} = \sum_{i=1}^{N} \omega_i p_i^*, \text{ where } \omega_i = \frac{\exp a_i}{\sum_{j=1}^{N} \exp a_j}.$$

Note that, for all i, $0 < \omega_i < 1$, and $\sum_i \omega_i = 1$.

With the FOCs plugged in, the total CP surplus under DP and UP are, respectively,

$$CPS^{DP} = \frac{1}{b-1} \sum_{i=1}^{N} A_i p_i^{*1-b},$$
$$CPS^{UP} = \frac{1}{b-1} \sum_{i=1}^{N} A_i \bar{p}^{1-b}.$$

For consumer surplus, the comparison of UP and DP still hinges on the sign of $Q^* - \bar{Q}$, where

$$Q^* = \sum_{i=1}^{N} \kappa_i q_i^* = \sum_{i=1}^{N} \kappa_i A_i \left(\frac{b}{b-1}\right)^{-b} (v_i)^{-b},$$
$$\bar{Q} = \sum_{i=1}^{N} \kappa_i \bar{q}_i = \sum_{i=1}^{N} \kappa_i A_i \left(\frac{b}{b-1}\right)^{-b} \left(\sum_{i=1}^{N} \omega_i v_i\right)^{-b}.$$

We can show that total CP surplus and Internet user surplus both increase under DP.

Proof: From the expressions for aggregate CP surplus, it is sufficient to establish the following inequality:

$$\sum_{i=1}^{N} A_i p_i^{*1-b} > \sum_{i=1}^{N} A_i \bar{p}^{1-b}.$$

Dividing both sides by $\sum_{i=1}^{N} A_i$ and substituting the expression for $\bar{p}$ yields

$$\sum_{i=1}^{N} \omega_i p_i^{*1-b} > \left(\sum_{i=1}^{N} \omega_i p_i^* \right)^{1-b}. \tag{16}$$

The above inequality always holds as $f(\cdot) = (\cdot)^{1-b}$ is a convex function.

For the surplus of Internet users, we show $Q^* > \bar{Q}$, or explicitly,

$$\sum_{i=1}^{N} \kappa_i A_i (v_i)^{-b} > \sum_{i=1}^{N} \kappa_i A_i \left(\sum_{i=1}^{N} \omega_i v_i \right)^{-b}.$$

Dividing both sides by $\sum_{i=1}^{N} \kappa_i A_i$, we have

$$\sum_{i=1}^{N} \mu_i (v_i)^{-b} > \left(\sum_{i=1}^{N} \omega_i v_i \right)^{-b}, \text{ where } \mu_i = \frac{\kappa_i A_i}{\sum_{j=1}^{N} \kappa_j A_j}.$$

Since $f(\cdot) = (\cdot)^{-b}$ is a convex function, we have

$$\sum_{i=1}^{N} \mu_i (v_i)^{-b} > \left(\sum_{i=1}^{N} \mu_i v_i \right)^{-b}.$$

Therefore, it is sufficient to show

$$\begin{aligned}
&\left(\sum_{i=1}^{N} \mu_i v_i \right)^{-b} > \left(\sum_{i=1}^{N} \omega_i v_i \right)^{-b} \\
\Leftrightarrow &\sum_{i=1}^{N} \mu_i v_i < \sum_{i=1}^{N} \omega_i v_i \\
\Leftrightarrow &\sum_{i=1}^{N} \mu_i (c - s\kappa_i) < \sum_{i=1}^{N} \omega_i (c - s\kappa_i) \\
\Leftrightarrow &\sum_{i=1}^{N} \mu_i \kappa_i > \sum_{i=1}^{N} \omega_i \kappa_i.
\end{aligned}$$

Let $K = \sum_i^N \omega_i \kappa_i > 0$. Since $\mu_i = \frac{\omega_i \kappa_i}{K}$, we have

$$\sum_i^N \mu_i \kappa_i - \sum_i^N \omega_i \kappa_i = \frac{\sum_i^N \omega_i \kappa_i^2}{K} - K$$
$$= \frac{\sum_i^N \omega_i (\kappa_i - K)^2}{K} > 0.$$

The inequality is strict since network effects are not identical across providers. Therefore, for $s > 0$,

$$\sum_i^N \mu_i v_i = \sum_i^N \omega_i v_i - \frac{s}{K} \sum_i^N \omega_i (\kappa_i - K)^2 < \sum_i^N \omega_i v_i.$$

Together with the preceding convexity argument, this establishes $Q^* > \bar{Q}$ and hence higher Internet user surplus under differential pricing.

Second, we consider the following demand function:

$$\ln q_i = a_i - b p_i. \tag{17}$$

The underlying net payoff to a content provider is

$$\pi_i^{CP} = \frac{a_i + 1}{b} q_i - \frac{1}{b} q_i \ln q_i - p_i q_i,$$

which we use for the robustness welfare calculation.

Although demand elasticities evaluated at observed prices may differ across content providers, all providers have the same elasticity bp at any common price p. Consequently, differences in demand intercepts alone do not generate discriminatory prices and optimal price differences arise entirely from differences in effective marginal costs.

The prices under DP and UP are:

$$p_i^* = \frac{1}{b} + v_i = \frac{1}{b} + c - s\kappa_i,$$
$$\bar{p} = \frac{\sum_{i=1}^N e^{a_i} p_i^*}{\sum_{i=1}^N e^{a_i}}.$$

Rewriting $\bar{p}$ yields

$$\bar{p} = \sum_{i=1}^N \omega_i p_i^*, \text{ where } \omega_i = \frac{\exp a_i}{\sum_{j=1}^N \exp a_j}.$$

To notice, for all i, $0 < \omega_i < 1$, and $\sum_i \omega_i = 1$.

With the FOCs plugged in, total CP surplus under DP and UP are, respectively,

$$CPS^{DP} = \frac{1}{b}\sum_{i=1}^{N} \exp(a_i - bp_i^*) \left(= \frac{1}{b}\sum_{i=1}^{N} q_i^* \right)$$
$$CPS^{UP} = \frac{1}{b}\sum_{i=1}^{N} \exp(a_i - b\bar{p}) \left(= \frac{1}{b}\sum_{i=1}^{N} \bar{q}_i \right).$$

Aggregate CP surplus is proportional to the total Internet usage.

For consumer surplus, the comparison of UP and DP hinges on the sign of $Q^* - \bar{Q}$, where

$$Q^* = \sum_{i=1}^{N} \kappa_i q_i^* = \sum_{i=1}^{N} \kappa_i \exp(a_i - bp_i^*),$$
$$\bar{Q} = \sum_{i=1}^{N} \kappa_i \bar{q}_i = \sum_{i=1}^{N} \kappa_i \exp(a_i - b\bar{p}).$$

We can show that total CP surplus and Internet user surplus both increase under DP.

Proof: To show that aggregate CP surplus is higher under DP, it is sufficient to show that the total Internet traffic allocation is higher under DP; that is,

$$\sum_{i=1}^{N} \exp(a_i - bp_i^*) > \sum_{i=1}^{N} \exp(a_i - b\bar{p}),$$
$$\Leftrightarrow \sum_{i=1}^{N} \frac{\exp(a_i)}{\exp(bp_i^*)} > \frac{\sum_{i=1}^{N} \exp(a_i)}{\exp(b\bar{p})}.$$

Dividing $\sum_{i=1}^{N} \exp(a_i)$ on both sides and plugging the expression of $\bar{p}$, we have

$$\sum_{i=1}^{N} \frac{\omega_i}{\exp(bp_i^*)} > \frac{1}{\exp\left(b\sum_i \omega_i p_i^*\right)}. \tag{18}$$

The above inequality always holds as $f(\cdot) = \frac{1}{\exp(\cdot)}$ is a strictly convex function.

For the surplus of Internet users, we show $Q^* > \bar{Q}$, or explicitly,

$$\sum_{i=1}^{N} \kappa_i \exp(a_i - bp_i^*) > \sum_{i=1}^{N} \kappa_i \exp(a_i - b\bar{p}).$$

Dividing both sides by $\sum_{i=1}^{N} \kappa_i \exp(a_i)$, we have

$$\sum_{i=1}^{N} \frac{\mu_i}{\exp(bp_i^*)} > \frac{1}{\exp(b\bar{p})}, \text{ where } \mu_i = \frac{\kappa_i \exp(a_i)}{\sum_{j=1}^{N} \kappa_j \exp(a_j)}.$$

Let $K = \sum_i^N \omega_i \kappa_i > 0$. As above,

$$\sum_{i}^{N} \mu_i \kappa_i - K = \frac{\sum_i^N \omega_i (\kappa_i - K)^2}{K}. \tag{19}$$

Using $p_i^* = 1/b + c - s\kappa_i$ and $\bar{p} = \sum_i^N \omega_i p_i^*$, we obtain

$$\sum_{i}^{N} \mu_i p_i^* = \bar{p} - \frac{s}{K} \sum_{i}^{N} \omega_i (\kappa_i - K)^2 \leq \bar{p}. \tag{20}$$

Because $f(p) = \exp(-bp)$ is convex and decreasing for $b > 0$, Jensen's inequality implies

$$\begin{aligned} \sum_{i}^{N} \mu_i \exp(-bp_i^*) &\geq \exp\left(-b \sum_{i}^{N} \mu_i p_i^*\right) \\ &> \exp(-b\bar{p}). \end{aligned} \tag{21}$$

Since $s > 0$ and network effects differ across providers, the second inequality is strict. Multiplying by $\sum_i^N \kappa_i \exp(a_i) > 0$ therefore yields $Q^* > \bar{Q}$, establishing higher Internet user surplus under differential pricing.