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Consumer Flexibility, Data Quality and Location Choice*

Irina Baye† Irina Hasnas‡

April 2014

Abstract

We analyze firms' location choices in a Hotelling model with two-dimensional consumer heterogeneity, along addresses and transport cost parameters (flexibility). Firms can price discriminate based on perfect data on consumer addresses and (possibly) imperfect data on consumer flexibility. We show that firms' location choices depend on how strongly consumers differ in flexibility. Precisely, when consumers are relatively homogeneous, equilibrium locations are socially optimal regardless of the quality of customer flexibility data. However, when consumers are relatively differentiated, firms make socially optimal location choices only when customer flexibility data is perfect. These results are driven by the optimal strategy of a firm on its turf, monopolization or market-sharing, which in turn depends on consumer heterogeneity in flexibility. Our analysis is motivated by the availability of customer data, which allows firms to practice third-degree price discrimination based on both consumer characteristics relevant in spatial competition, addresses and transport cost parameters.

JEL-Classification: D43; L13; R30; R32.

Keywords: Location Choice, Price Discrimination, Customer Data.

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1 Introduction

The widespread use of modern information technologies allows firms to collect, store and analyze customer data in many industries. For example, loyalty programs and consumers' online activity are very important sources of customer data in the retailing industry.[1,2] Collected data allows firms to conclude on both consumer characteristics relevant in spatial competition, consumers' addresses and transport cost parameters (flexibility).[3] Customer location data is one of the first information items provided by consumers while signing up for a loyalty program and can be deducted from the IP address of a computer during the online purchase. This data is easily accessible and can be considered as (almost) perfect. In contrast, firms can estimate consumer flexibility only with less than perfect accuracy. Gained customer insights can be used by firms in two ways. First, customer data allows targeted advertising and pricing where firms can practice third-degree price discrimination based on both consumer locations and their flexibility.[4,5,6]

[1] Jeff Berry, senior director of Knowledge Development and Application at LoyaltyOne Inc., global provider of loyalty solutions in different industries including retailing, said that "*For most organizations today, the loyalty program actually becomes the core of the ability to capture consumer data ...*" (Linkhorn, 2013).

[2] Electronic Privacy Information Center (EPIC), public interest research group with a focus on privacy protection, notes that "Online tracking is no longer limited to the installation of the traditional "cookies" that record websites a user visits. Now, new tools can track in real time the data people are accessing or browsing on a web page and combine that with data about that user's location, income, hobbies, and even medical problems. These new tools include flash cookies and beacons. Flash cookies can be used to re-install cookies that a user has deleted, and beacons can track everything a user does on a web page including what the user types and where the mouse is being moved." ("Online Tracking and Behavioral Profiling" at http://epic.org/privacy/consumer/online_tracking_and_behavioral.html).

[3] The term "flexibility" captures the intuition that depending on whether transport costs are high or low, consumers are less or more likely to buy from the farther firm, respectively. Consumers with high (low) transport costs can be referred to as less (more) flexible.

[4] CEO of Safeway Inc., second-largest supermarket chain in the U.S., Steve Burd, said that "*There's going to come a point where our shelf pricing is pretty irrelevant because we can be so personalized in what we offer people.*" (Ross, 2013). Similarly, the spokesman of Rosetta Stone, which sells software for computer-based language learning said that "*We are increasingly focused on segmentation and targeting. Every customer is different.*" (Valentino-Devries, 2012).

[5] EPIC notes that "Advertisers are no longer limited to buying an ad on a targeted website because they instead pay companies to follow people around on the internet wherever they go. Companies then use this information to decide what credit-card offers or product pricing to show people, potentially leading to price discrimination." ("Online Tracking and Behavioral Profiling" at http://epic.org/privacy/consumer/online_tracking_and_behavioral.html).

[6] In electronic commerce there is evidence of both discrimination based on consumer locations and flexibility. Mikians et al. (2012) find that some sellers returned different prices to consumers depending on whether a consumer accessed a seller's website directly or through price aggregators and discount sites (like nextag.com). Those price differences can be explained through differences in price sensitivity (flexibility) of the two types of consumers. Consumers accessing a seller's website through price aggregators are likely to be more price-sensitive. Similarly, vice president of corporate affairs at Orbitz Worldwide Inc., which operates a website for travel booking, said that "*Many hotels have proven willing to provide discounts for mobile sites.*" (Valentino-Devries et al., 2012). The latter can also be explained as price discrimination based on consumer flexibility since smartphone users

Second, customer data is widely used to decide on the optimal store location.[7]

In this article we consider a Hotelling model, where consumers differ both in their locations and transport cost parameters. There are two firms which compete in prices and have access to perfect data on consumers locations. Additionally, firms may acquire data on consumer flexibility of an exogenously given quality, which allows them to distinguish between different flexibility segments and attribute every consumer to one of them. We consider two versions of our model depending on how strongly consumers differ in flexibility, with relatively homogeneous and differentiated consumers. We analyze firms' location choices in the two versions of our model depending on the quality of customer flexibility data.

Our article contributes to the literature on spatial competition in Hotelling-type models where firms first choose locations and then compete in prices given the ability to practice perfect third-degree price discrimination based on consumer addresses. The famous result in Lederer and Hurter (1986) states that in the latter case in equilibrium every firm chooses its location so as to minimize social costs equal to the minimal costs of serving a consumer at each address. In a standard Hotelling model (with a uniform distribution of consumers along a line segment) this result implies socially optimal equilibrium locations. Hamilton and Thisse (1992) introduce a vertical dimension of consumer heterogeneity along which firms can practice first-degree price discrimination. They get the same optimality result as in Lederer and Hurter and conclude that "*...we see that the Hurter-Lederer efficient location result relies on perfectly inelastic consumer demands. For firms to locate efficiently when demands are price-sensitive, they need more flexibility in pricing...*" (Hamilton and Thisse, 1992, p. 184) On the one hand, our results support this conclusion, as we show that when the quality of customer flexibility data improves (and firms can identify more flexibility segments) equilibrium locations become closer to the socially optimal ones. However, this happens only when consumers are relatively differentiated in flexibility. With relatively homogeneous consumers in equilibrium firms choose socially optimal locations regardless of their ability to discriminate based on consumer flexibility. Our results imply that in a model with price-sensitive demands at each address socially optimal locations

can be considered as more price-sensitive due to the availability of different mobile applications, which collect special offers depending on a user's location. The evidence of price discrimination based on consumer locations is provided in Valentino-Devries et al. (2012) who find the strongest correlation between the differences in online prices and the distance to a rival's store from the center of a ZIP Code of a buyer.

[7] To mention just one of many examples, Waitrose, a British supermarket chain, used services of data analytics company BeyondAnalysis to analyze data on their customers' Visa card transactions to decide on new store locations (see Ferguson, 2013).

can be an equilibrium under weaker requirements on the quality of customer data available to the firms than perfect data.

Valletti (2001) is another article, which introduces heterogeneity along the vertical dimension of consumer preferences and assumes that consumers can be of two types depending on their valuation for quality. While firms can practice perfect third-degree price discrimination based on consumer addresses, they do not observe their types and, hence, have to rely on second-degree price discrimination at each address. Valletti shows that firms' location choices influence their discriminating ability. Different from Valletti, in our model firms' ability to discriminate is given exogenously and depends on the quality of customer flexibility data, such that a firm's location choice influences only its market share (along the horizontal dimension of consumer preferences) and the profit on a given location. Our results show that for the same data quality firms make different location choices depending on how strongly consumers differ in flexibility.

Overall, our article contributes to Hamilton and Thisse (1992) and Valletti (2002) by introducing third-degree price discrimination along the vertical dimension of consumer preferences enabled by customer data, while the former assume first-degree and the latter considers second-degree price discrimination.

Our article is also related to Anderson and de Palma (1988) who assume that products are heterogeneous not only in the spatial dimension, but also in the characteristic space, which also leads to price-sensitive demands at each location. Similar to Anderson and de Palma we show that socially optimal prices and locations are not always an equilibrium, in contrast to models where only spatial dimension of heterogeneity is considered. However, different from Anderson and de Palma, we show that socially optimal prices and locations can also be an equilibrium in a model with price-sensitive demands. This happens in two cases. First, if consumers are relatively homogeneous in transport cost parameters. Second, if firms have perfect data on consumer flexibility and, hence, can perfectly discriminate along that dimension. The intuition for our results is as follows. When consumers are relatively homogeneous, in equilibrium every firm serves all consumers on its turf, even when firms do not hold data on consumer flexibility. This happens because if a firm targets at some address its most loyal customer (with the highest transport cost parameter), it suffice to decrease the price slightly to gain even the least loyal customer (with the lowest transport cost parameter). As a result, similar to Lederer and Hurter (1986), every firm chooses its location so as to minimize social (transport) costs, which implies socially optimal locations. However, when consumers are relatively differentiated, in equilibrium on any address on its turf a firm serves only the more loyal consumers and loses the less loyal ones to the rival. To mitigate competition firms deviate from the socially optimal locations, and the interfirm distance is larger in equilibrium compared to both the first-best and the second-best. With the improvement in the quality of customer flexibility data distortions in firms' equilibrium locations become smaller, because every firm can better target consumers on its turf, which weakens the rival's ability to attract its loyal consumers. When flexibility data becomes perfect, firms make socially optimal location choices with relatively differentiated consumers too.

Tabuchi (1994) and Irmen and Thisse (1998) assume that products are differentiated along different dimensions and analyze firms' locations in each dimension. The result of Tabuchi that firms choose maximal differentiation in one dimension and minimal differentiation in the other is generalized by Irmen and Thisse in a model of spatial competition in a multi-characteristic space who show that the Nash equilibrium implies maximal differentiation only in the dominant product characteristic. While in our model products differ only in one (horizontal) dimension, we introduce consumer heterogeneity in the strength of their preferences along that dimension. In contrast, in Tabuchi and Irmen and Thisse it is assumed that the transport cost parameters related to each product characteristic are same among all consumers. We show that firms' location choices depend on how strongly consumers differ in transport cost parameters and firms' ability to discriminate along that dimension of consumer preferences.

Finally, our article is related to Jenzsch, Sapi and Suleymanova (2013) and Sapi and Suleymanova (2013). Both articles assume that consumers differ in the strength of their brand preferences. In the former article the authors analyze firms' incentives to share different types of customer data depending on how strongly consumers differ in flexibility. In the latter paper the authors analyze firms' incentives to acquire customer flexibility data depending on its quality and consumer heterogeneity along that dimension. The focus of our article is the analysis of firms' location choices depending on the quality of customer flexibility data and on how strongly consumers differ in flexibility.

Our article is organized as follows. In the next section we present the model. In Section 3 we provide the equilibrium analysis, state our results and compare them in detail with Lederer and Hurter (1986) and Anderson and de Palma (1988). Finally, in Section 4 we conclude.

2 The Model

We analyze Bertrand competition between two firms, A and B, located at $0 \leq d_A \leq 1$ and $0 \leq d_B \leq 1$ on a unit-length Hotelling line, respectively. Firms produce the same product of two different brands, A and B, respectively. There is a unit mass of consumers, each buying at most one unit of the product. We follow Jenzsch, Sapi and Suleymanova (2013) and assume that consumers are heterogeneous not only in locations, but also in transport cost parameters (flexibility). Each consumer is uniquely characterized by a pair (x, t), where $x \in [0, 1]$ denotes a consumer's address and $t \in [\underline{t}, \overline{t}]$ her transport cost parameter, with $\overline{t} > \underline{t} \geq 0$. We assume that x and t are uniformly and independently distributed with density functions $f_x(x) = 1$ and $f_t(t) = 1/(\overline{t} - \underline{t})$, to which we will refer as f_t, respectively. If a consumer does not buy at her location, she has to incur linear transport costs proportional to the distance to the firm. The utility of a consumer (x, t) from buying at firm $i = A, B$ at price p_i is

$$U_i(x, t) = v - p_i - t\,|x - x_i|\,,$$

where $v > 0$ is the basic utility, which is assumed to be high enough such that all consumers buy in equilibrium. A consumer buys from a firm, which delivers her a higher utility. In case of equal utilities we assume that a consumer buys from a closer firm.[8]

Firms know perfectly the location of each consumer in the market and can discriminate among consumers respectively. Firms can also acquire flexibility data, which is imperfect. To model imperfect customer data we follow Liu and Serfes (2004) and Sapi and Suleymanova (2013) and assume that data quality is characterized by the exogenously given parameter $k = 0, 1, 2, ..., \infty$. This data allows a firm to identify 2^k flexibility segments and allocate each consumer to one of them. Segment $m = 1, 2, ..., 2^k$ consists of consumers with transport cost parameters $t \in [\underline{t}^m(k); \overline{t}^m(k)]$, where $\underline{t}^m(k) = \underline{t} + (\overline{t} - \underline{t})(m-1)/2^k$ and $\overline{t}^m(k) = \underline{t} + (\overline{t} - \underline{t})\,m/2^k$ denote the most and the least flexible consumers on segment m, respectively. With the improvement in data quality (k becomes larger), firms are able to allocate consumers to finer flexibility segments. If $k \to \infty$, a firm with flexibility data knows perfectly the location and transport cost parameter of each consumer in the market and can charge individual prices. Otherwise, a firm has to charge group prices (to consumers with the same address and on the same flexibility

[8] This is a standard assumption in Hotelling-type models, where firms can practice perfect discrimination based on consumer addresses, and allows to avoid relying on ε-equilibrium concepts (see Lederer and Hurter, 1986).

segment). With $p_{im}(x)$, $i = \{A, B\}$, we will denote the price of firm i on address x on segment m.

Following Jenzsch, Sapi and Suleymanova (2013) and Sapi and Suleymanova (2013) we will consider two extreme versions of our model with respect to consumer heterogeneity in flexibility, measured by the ratio $l := \bar{t}/\underline{t}$. In the version with *relatively homogeneous* consumers we assume that $\underline{t} > 0$ and $\bar{t}/\underline{t} \leq 2$. In the version with *relatively differentiated* consumers we assume that $\underline{t} = 0$, in which case $\lim_{\underline{t}\to 0} \bar{t}/\underline{t} = \infty$. In a similar way we can distinguish between flexibility segments. Precisely, we will say that consumers on segment m are relatively homogeneous if $\underline{t}^m(k) > 0$ and $\bar{t}^m(k)/\underline{t}^m(k) \leq 2$. We will say that consumers are relatively differentiated there if $\underline{t}^m(k) = 0$. It is straightforward to show that in the version of our model with relatively homogeneous consumers for any data quality consumers on all flexibility segments are relatively homogeneous. In the version of our model with relatively differentiated consumers, for any data quality consumers are relatively differentiated only on the segment $m = 1$ and are relatively homogeneous on all other segments.

We consider a standard sequence of firms' moves where firms first choose their locations and then make pricing decisions (see, for example, Lederer and Hurter, 1986; Anderson and de Palma, 1988; Irmen and Thisse, 1998). Hence, the game unfolds as follows:

Stage 1 (Location choices). Independently from each other firms A and B choose locations d_A and d_B, respectively.

Stage 2 (Flexibility data acquisition and prices). Firms decide simultaneously and independently from each other whether to acquire flexibility data and choose prices to different consumer groups.

3 Equilibrium Analysis

We solve for a subgame-perfect Nash equilibrium and start from the second stage. Similar to Liu and Serfes (2007), both firms acquire customer data in equilibrium, because by refraining from data acquisition a firm cannot influence the decision of the rival to acquire customer data and only decreases its degrees of freedom in pricing. We next analyze firms' optimal prices given their location choices in the first stage. Without loss of generality we will assume that the firm which is located closer to $x = 0$ is firm A, such that $d_A \leq d_B$.

Stage 2: Prices. As firms know consumer addresses, they can charge different prices on each location. It is useful to consider separately four intervals of the unit line: *i)* interval $x \leq d_A$, which constitutes the hinterland of firm A, *ii)* interval $d_A < x \leq (d_A + d_B)/2$ with consumers between the two firms, which are closer to firm A, *iii)* interval $(d_A + d_B)/2 < x \leq d_B$ with consumers between the two firms, which are closer to firm B, *iv)* interval $x > d_B$, which constitutes the hinterland of firm B. In the following we will refer to the intervals *i)* and *ii)* as "the turf of firm A" and to consumers there as "loyal consumers of firm A." Symmetrically, we will refer to the intervals *iii)* and *iv)* as "the turf of firm B" and to consumers there as "loyal consumers of firm B."

We consider first the turf of firm A, which consists of consumers located closer to firm A. Under moderate prices only consumers with relatively small transport cost parameters switch to firm B, because buying from the farther firm is not very costly for them. On interval $x \leq d_A$ on some segment m these are consumers with

$$t < \widetilde{t}\,(d_A, d_B, p_{Am}(x), p_{Bm}(x); x|\, x \leq d_A) := \frac{p_{Am}(x) - p_{Bm}(x)}{d_B - d_A},$$

provided $\widetilde{t}\,(\cdot|\, x \leq d_A) \in \left[\underline{t}^m(k), \overline{t}^m(k)\right]$, where $p_{im}(x)$ is the price of firm $i = \{A, B\}$ on address x on segment m. The transport cost parameter of the indifferent consumer, $\widetilde{t}\,(\cdot|\, x \leq d_A)$, does not depend on her address directly, only (possibly) through firms' prices. The reason is that a consumer with address $x \leq d_A$ always has to travel the distance $d_A - x$ independently of whether she buys from firm A or from firm B. In the latter case compared to the former she has to travel additionally the distance $d_B - d_A$. Hence, the difference in utility from buying at the two firms does not depend on consumer's address.

If $d_A < x \leq (d_A + d_B)/2$, then on segment m the transport cost parameter of the indifferent consumer is

$$\widetilde{t}\left(d_A, d_B, p_{Am}(x), p_{Bm}(x); x|\, d_A < x \leq \frac{d_A + d_B}{2}\right) := \frac{p_{Am}(x) - p_{Bm}(x)}{d_A + d_B - 2x},$$

provided $\widetilde{t}(\cdot|\, d_A < x \leq (d_A + d_B)/2) \in \left[\underline{t}^m(k), \overline{t}^m(k)\right]$. Those consumers buy from firm A, who have relatively high transport cost parameters: $t \geq \widetilde{t}(\cdot|\, d_A < x \leq (d_A + d_B)/2)$. Different from $\widetilde{t}\,(\cdot|\, x \leq d_A)$, $\widetilde{t}(\cdot|\, d_A < x \leq (d_A + d_B)/2)$ depends on the address of the indifferent consumer. Precisely, when x increases, for given firms' prices the transport cost parameter of the indifferent consumer becomes larger. If a consumer is located close to firm B, she may find it optimal to buy from firm B even if she has a relatively high transport cost parameter.

Consider now the turf of firm B. On address $(d_A + d_B)/2 < x \leq d_B$ on segment m the transport cost parameter of the indifferent consumer is

$$\widetilde{t}\left(d_A, d_B, p_{Am}(x), p_{Bm}(x); x \middle| \frac{d_A + d_B}{2} < x \leq d_B\right) := \frac{p_{Bm}(x) - p_{Am}(x)}{2x - d_A - d_B},$$

provided $\widetilde{t}(\cdot|\,(d_A + d_B)/2 < x \leq d_B) \in \left[\underline{t}^m(k), \overline{t}^m(k)\right]$. And on address $x > d_B$ on segment m the transport cost parameter of the indifferent consumer is

$$\widetilde{t}(d_A, d_B, p_{Am}(x), p_{Bm}(x); x|\, x > d_B) := \frac{p_{Bm}(x) - p_{Am}(x)}{2x - d_A - d_B},$$

provided $\widetilde{t}(\cdot|\, x > d_B) \in \left[\underline{t}^m(k), \overline{t}^m(k)\right]$. On both intervals those consumers buy from firm B who have relatively high transport cost parameters: $t \geq \widetilde{t}(\cdot)$.

Each firm maximizes its profit separately on each address x and each segment m. For example, on some $x \leq d_A$ and some m firm A solves the optimization problem

$$\begin{aligned} \max_{p_{Am}(x)} \Pi_{Am}\left(d_A, d_B, p_{Am}(x), p_{Bm}(x); x, k|\, x \leq d_A\right) &= f_t \left[\overline{t}^m(k) - \widetilde{t}\left(\cdot|\, x \leq d_A\right)\right] p_{Am}(x), \\ \text{s.t. } \widetilde{t}\left(\cdot|\, x \leq d_A\right) &\in \left[\underline{t}^m(k), \overline{t}^m(k)\right], \end{aligned}$$

where $\Pi_{im}\left(\cdot|\, x \leq d_A\right)$ denotes the profit of firm $i = \{A, B\}$ on address $x \leq d_A$ on segment m. The optimization problem of firm B is

$$\begin{aligned} \max_{p_{Bm}(x)} \Pi_{Bm}\left(d_A, d_B, p_{Am}(x), p_{Bm}(x); x, k|\, x \leq d_A\right) &= f_t \left[\widetilde{t}\left(\cdot|\, x \leq d_A\right) - \underline{t}^m(k)\right] p_{Bm}(x), \\ \text{s.t. } \widetilde{t}\left(\cdot|\, x \leq d_A\right) &\in \left[\underline{t}^m(k), \overline{t}^m(k)\right]. \end{aligned}$$

In the following lemma we state firms' equilibrium prices, demand regions and profits depending on their location choices in the first stage of the game in the version of our model with relatively differentiated consumers. We will use the subscripts "*d*" and "*h*" to denote the equilibrium values in the versions of our model with relatively differentiated and homogeneous consumers, respectively.

Lemma 1 *(Stage 2: optimal prices. Relatively differentiated consumers). Assume that con-*

sumers are relatively differentiated in flexibility. Equilibrium prices and demand regions depend on consumer's address, flexibility segment and the quality of customer flexibility data.

i) Consider some x in the hinterland of firm $i = \{A, B\}$. On $m = 1$ firms charge prices $p^d_{i1}(d_A, d_B; x, k) = 2\bar{t}\,(d_B - d_A)\,/\left(3 \times 2^k\right)$ and $p^d_{j1}(d_A, d_B; x, k) = \bar{t}\,(d_B - d_A)\,/\left(3 \times 2^k\right)$, where firm i serves consumers with $t \geq \bar{t}/\left(3 \times 2^k\right)$, $j = \{A, B\}$ and $i \neq j$. On $m \geq 2$ firms charge prices $p^d_{im}(d_A, d_B; x, k) = \underline{t}^m(k)\,(d_B - d_A)$ and $p^d_{jm}(d_A, d_B; x, k) = 0$, where firm i serves all consumers.

ii) Consider some $x \in [d_A, d_B]$ on the turf of firm $i = \{A, B\}$. On $m = 1$ firms charge prices $p^d_{i1}(d_A, d_B; x, k) = 2\bar{t}\,|d_A + d_B - 2x|\,/\left(3 \times 2^k\right)$ and $p^d_{j1}(d_A, d_B; x, k) = \bar{t}\,|d_A + d_B - 2x|\,/\left(3 \times 2^k\right)$, where firm i serves consumers with $t \geq \bar{t}/\left(3 \times 2^k\right)$, $j = \{A, B\}$ and $i \neq j$. Firms' prices on $m \geq 2$ are $p^d_{im}(d_A, d_B; x, k) = \underline{t}^m(k)\,|d_A + d_B - 2x|$ and $p^d_{jm}(d_A, d_B; x, k) = 0$, where firm i serves all consumers.

Firms realize profits

$$\begin{aligned}
\Pi^d_A(d_A, d_B; k) &= \frac{\bar{t}\,(d_B - d_A)\left[9 \times 2^k\left(2^k - 1\right)(3d_A + d_B) + 2\,(11d_A + d_B) + 8\right]}{9 \times 2^{2k+3}} \quad \textit{and} \\
\Pi^d_B(d_A, d_B; k) &= \frac{\bar{t}\,(d_B - d_A)\left[32 - 9 \times 2^k(2^k - 1)\,(3d_B + d_A - 4) - 2\,(11d_B + d_A)\right]}{9 \times 2^{2k+3}}.
\end{aligned}$$

Proof. See Appendix.

For the intuition behind Lemma 1 we will consider the turf of firm A. On any address and any segment there firm A charges in equilibrium a higher price than the rival, because in case of buying at firm A consumers have to bear smaller transport costs. While all equilibrium prices of firm A are positive, firm B charges positive prices only on segment $m = 1$. Also, firm B serves consumers only on that segment. The differences in firms' equilibrium prices on segments $m = 1$ and $m \geq 2$ are driven by the differences in the equilibrium strategy of firm A on its turf, as shown in Sapi and Suleymanova (2013). Consider, for example, the interval $x \leq d_A$. On segment $m = 1$, where consumers are relatively differentiated, firm A follows a so-called market-sharing strategy, such that its best-response function takes the form

$$p_{A1}(\,d_A, d_B, p_{B1}(x); x, k|\, x \leq d_A) = \begin{cases} \frac{\bar{t}^1(k)(d_B - d_A) + p_{B1}(x)}{2} & \text{if} \quad p_{B1}(x) < \bar{t}^1(k)\,(d_B - d_A) \\ p_{B1}(x) & \text{if} \quad p_{B1}(x) \geq \bar{t}^1(k)\,(d_B - d_A)\,. \end{cases} \tag{1}$$

To monopolize segment $m = 1$ firm A has to charge a price equal to that of the rival, because the most flexible consumer (with $\underline{t}^1 = 0$) can switch brands costlessly. The best-response function (1) shows that firm A finds it optimal to monopolize segment $m = 1$ only if the rival's price is relatively high: $p_{B1}(x,k) \geq \bar{t}^1(k)\,(d_B - d_A)$. Otherwise, if the rival's price is relatively low ($p_{B1}(x,k) < \bar{t}^1(k)\,(d_B - d_A)$), firm A optimally charges a higher price and loses the more flexible consumers. To attract the loyal consumers of the rival firm B charges in equilibrium a low price ($p_{B1}(x) < \bar{t}^1(k)\,(d_B - d_A)$), which makes the market-sharing outcome optimal for firm A.

In contrast, on segments $m \geq 2$, where consumers are relatively homogeneous, firm A follows a so-called monopolization strategy, such that its best-response function takes the form

$$p_{Am}(d_A, d_B, p_{Bm}(x); x, k|\, x \leq d_A) = p_{Bm}(x) + \underline{t}^m(k)\,(d_B - d_A)\,, \text{ for any } p_{Bm}(x). \qquad (2)$$

$p_{Am} = p_{Bm}(x) + \underline{t}^m(k)\,(d_B - d_A)$ is the highest price, which allows firm A to monopolize segment m on some address $x \leq d_A$ on its turf for a given price of the rival, $p_{Bm}(x)$. As the best-response function (2) shows, regardless of the rival's price firm A prefers to charge a relatively low price to serve all consumers on segment m. As a result, in equilibrium firm B cannot do better than charging the price of zero. Firm A serves all consumers on segment m although it charges a positive price there.

The type of the equilibrium strategy of a firm on some flexibility segment on its turf, market-sharing or monopolization, depends on how strongly consumers differ there in flexibility. When consumers are relatively homogeneous on some segment, it suffice for a firm to decrease slightly the price targeted at the least flexible consumer to serve all consumers there, such that regardless of the rival's price a firm finds it optimal to monopolize the segment. In contrast, when consumers are relatively differentiated on a given segment, serving all consumers there requires a substantial reduction in the price targeted at the least flexible consumer (because the most flexible consumer can switch brands costlessly), which makes the monopolization outcome optimal only when the rival's price (which serves as an anchor for a firm's price) is high enough.

It is also worth noting that the equilibrium distribution of consumers between the firms depends only on which firm's turf and on which flexibility segment (with relatively homogeneous or differentiated consumers) they are located. Precisely, in equilibrium all consumers on segments $m \geq 2$ buy from their preferred firms and on segment $m = 1$ one third of the more flexible consumers switches to the less preferred firm.[9] However, the equilibrium prices of a firm on its

[9] Note that $\lim_{k\to\infty} \bar{t}^m(k) = 0$, such that when firms can perfectly discriminate based on consumer flexibility,

turf depend also on whether a consumer is located between the two firms or in its hinterland. Precisely, to consumers on the same segment on its turf a firm charges a higher price if they are located in its hinterland because switching to the other firm is more costly for them. In the next lemma we characterize the equilibrium of the second stage of the game in the version of our model with relatively homogeneous consumers.

Lemma 2 *(Stage 2: optimal prices. Relatively homogeneous consumers). Assume that consumers are relatively homogeneous in flexibility. Equilibrium prices and demand regions depend on consumer's address, flexibility segment and the quality of customer flexibility data.*

i) Consider some x in the hinterland of firm $i = \{A, B\}$. On $m \geq 1$ firms charge prices $p^h_{im}(d_A, d_B; x, k) = \underline{t}^m(k)(d_B - d_A)$ and $p^h_{jm}(d_A, d_B; x, k) = 0$, where firm i serves all consumers, $j = \{A, B\}$ and $i \neq j$.

ii) Consider some $x \in [d_A, d_B]$ on the turf of firm $i = \{A, B\}$. On $m \geq 1$ firms charge prices $p^h_{im}(d_A, d_B; x, k) = \underline{t}^m(k)|d_A + d_B - 2x|$ and $p^h_{jm}(d_A, d_B; x, k) = 0$, where firm i serves all consumers, $j = \{A, B\}$ and $i \neq j$.

Firms realize profits

$$\begin{aligned}
\Pi^h_A(d_A, d_B; k) &= \frac{\underline{t}\left[\left(2^k + 1\right) + l\left(2^k - 1\right)\right](d_B + 3d_A)(d_B - d_A)}{2^{k+3}} \text{ and} \\
\Pi^h_B(d_A, d_B; k) &= \frac{\underline{t}\left[\left(2^k + 1\right) + l\left(2^k - 1\right)\right](4 - d_A - 3d_B)(d_B - d_A)}{2^{k+3}}
\end{aligned}$$

Proof. See Appendix.

In the version of our model with relatively homogeneous consumers, consumers are relatively homogeneous on any flexibility segment for any quality of customer data. As we showed above, in that case every firm follows a monopolization strategy on any segment on its turf. As a result, the rival charges the prices of zero on a firm's turf and serves no consumers there. We next analyze firms' location choices given their optimal prices in the second stage of the game.

Stage 1: Location choices. We first derive socially optimal locations. Following Anderson and de Palma (1988) we will distinguish between first-best and second-best locations. In the former case social planner determines both prices and locations. In the latter case social planer only determines locations, while firms choose noncooperatively prices to maximize their profits under

every firm serves in equilibrium all consumers on its turf.

the prescribed locations. In the following lemma we state first-best and second-best locations in both versions of our model.

Lemma 3 *(Socially optimal locations). In both versions of our model first-best prices satisfy*

$$p_{im}^{FB}(x) \leq t|x-x_j| - t|x-x_i| + p_{jm}^{FB}(x) \text{ if } |x-x_i| \leq |x-x_j|,$$

and first-best locations are $d_A^{FB} = 1/4$ *and* $d_B^{FB} = 3/4$*. Second-best locations depend on consumer heterogeneity in flexibility.*

i) If consumers are relatively homogeneous, then second-best locations coincide with first-best locations: $d_A^{SB,h} = 1/4$ *and* $d_B^{SB,h} = 3/4$*.*

ii) If consumers are relatively differentiated, then second-best locations are

$$d_A^{SB,d}(k) = \frac{9 \times 2^{2k}}{36 \times 2^{2k} - 4} > d_A^{FB} \text{ and } d_B^{SB,d}(k) = \frac{27 \times 2^{2k} - 4}{36 \times 2^{2k} - 4} < d_B^{FB}, \text{ for any } k \geq 0,$$

such that $\lim_{k\to\infty} d_A^{SB,d}(k) = 1/4$ *and* $\lim_{k\to\infty} d_B^{SB,d}(k) = 3/4$*.*

Proof. See Appendix.

For any locations first-best prices must induce an allocation of consumers between the firms where every consumer buys from the closer firm. Then first-best locations which minimize transport costs are symmetric, and every firm is located in the middle of the interval between one end of the unit line and the rival's location, which yields $d_A^{FB} = 1/4$ and $d_B^{FB} = 3/4$.

For given locations firms' equilibrium prices and the resulting distribution of consumers between the firms differ in the two versions of our model, such that we also get different second-best locations. As stated in Lemma 1, with relatively differentiated consumers every firm loses on its turf the more flexible consumers. Compared to the first-best, in the second-best firms are located closer to each other, which minimizes the transport costs of those consumers. In contrast, with relatively homogeneous consumers first-best and second-best locations coincide, because as stated in Lemma 2, in equilibrium every consumer buys from its preferred firm under any firms' locations. In the next proposition we characterize firms' equilibrium locations and compare them with the socially optimal ones.

Proposition 1 *(Stage 1: location choices). Equilibrium locations depend on consumer heterogeneity in flexibility.*

i) If consumers are relatively homogeneous, then for any data quality $k \geq 0$ in equilibrium firms choose locations:

$$d_A^h = 1 - d_B^h = \frac{1}{4},$$

which coincide with both first-best and second-best locations. Firms realize profits

$$\Pi_i^h(k) = \frac{3\underline{t}\left[\left(2^k+1\right) + l\left(2^k-1\right)\right]}{2^{k+5}},\ i = \{A, B\}.$$

ii) If consumers are relatively differentiated, then in equilibrium firms choose locations:

$$d_A^d(k) = 1 - d_B^d(k) = \frac{9 \times 2^{2k} - 9 \times 2^k + 6}{36 \times 2^{2k} - 36 \times 2^k + 32}, \tag{3}$$

where $\partial d_A^d(k)/\partial k > 0$ and $\partial d_B^d(k)/\partial k < 0$, such that with the improvement in data quality firms locate closer to each other. It holds that $d_A^d(k) < d_A^{FB}(k) < d_A^{SB,d}(k)$ for any $k \geq 0$. Moreover, $\lim_{k\to\infty} d_A^d(k) = d_A^{FB}(k)$ and $\lim_{k\to\infty} d_A^d(k) = d_B^{FB}(k)$. Firms realize profits

$$\Pi_i^d(k) = \frac{\bar{t}\left(9 \times 2^{2k} - 9 \times 2^k + 10\right)^2\left(27 \times 2^{2k} - 27 \times 2^k + 22\right)}{9 \times 2^{2k+5}\left(9 \times 2^{2k} - 9 \times 2^k + 8\right)^2},\ i = \{A, B\}.$$

Proof. See Appendix.

In the following we will explain and provide intuition for our results in each version of our model using the approach of Lederer and Hurter (1986, in the following: LH).

Comparison with LH: Relatively homogeneous consumers. When consumers are relatively homogeneous, firms make socially optimal location choices, such that the equilibrium locations coincide with both first-best and second-best locations. This result is driven by the fact that every firm follows a monopolization strategy on any address on its turf. As a result, in equilibrium every firm serves all consumers on its turf and charges on any address the highest price, which allows to monopolize a given flexibility segment. This price is proportional to the difference in the distances between the consumer and each of the firms. Following LH and using the results of Lemma 2 we can state the equilibrium prices of firm $i = \{A, B\}$ as

$$\begin{aligned} p_{im}^h(d_i, d_j; x, k) &= \underline{t}^m(k)\left[D_j(d_j; x) - D_i(d_i; x)\right] \text{ if } D_j(d_j; x) > D_i(d_i; x) \text{ and} \\ p_{im}^h(d_i, d_j; x, k) &= 0 \text{ if } D_j(d_j; x) \leq D_i(d_i; x), \end{aligned}$$

where $D_i(d_i; x) := |x - d_i|$. Then the equilibrium profit of firm i for given locations d_i and d_j can be written as

$$\begin{aligned} \Pi_i^h(d_i, d_j; k) &= \frac{1}{2^k}\sum_1^{2^k} \underline{t}^m(k) \int\limits_{D_j(d_j;x) > D_i(d_i;x)} \left[D_j(d_j; x) - D_i(d_i; x)\right] dx \\ &= \frac{\underline{t}\left[\left(2^k+1\right) + l\left(2^k-1\right)\right]}{2^{k+1}} \int\limits_{D_j(d_j;x) > D_i(d_i;x)} \left[D_j(d_j; x) - D_i(d_i; x)\right] dx, \end{aligned}$$

where $i \neq j$ and $j = \{A, B\}$. Similar to Lemma 4 in LH we can rewrite $\Pi_i^h(d_A, d_B; k)$ as

$$\begin{aligned} \frac{\Pi_i^h(d_i, d_j; k) \times 2^{k+1}}{\underline{t}\left[\left(2^k+1\right) + l\left(2^k-1\right)\right]} &= \int\limits_{D_j(d_j;x) > D_i(d_i;x)} D_j(d_j; x)\, dx - \int\limits_{D_j(d_j;x) > D_i(d_i;x)} D_i(d_i; x)\, dx \\ &= \int\limits_{D_j(d_j;x) > D_i(d_i;x)} D_j(d_j; x)\, dx + \int\limits_{D_j(d_j;x) \leq D_i(d_i;x)} D_j(d_j; x)\, dx \\ &\quad - \int\limits_{D_j(d_j;x) \leq D_i(d_i;x)} D_j(d_j; x)\, dx - \int\limits_{D_j(d_j;x) > D_i(d_i;x)} D_i(d_i; x)\, dx \\ &= \int_0^1 D_j(d_j; x)\, dx - \int_0^1 \min\left\{D_j(d_j; x), D_i(d_i; x)\right\} dx. \end{aligned}$$

Hence, when firm i chooses the optimal location its optimization problem is equivalent to

$$\min_{d_i}\left[\frac{\left(\bar{t} + \underline{t}\right)}{2}\int_0^1 \min\left\{D_j(d_j; x), D_i(d_i; x)\right\} dx\right]. \tag{4}$$

Following LH, we can define the expression $\left(\bar{t} + \underline{t}\right)\left[\int_0^1 \min\left\{D_j(d_j; x), D_i(d_i; x)\right\} dx\right]/2$ as *social transport costs*, which are the total transport costs incurred by consumers when they are served by firms in a cooperative manner minimizing transport costs. The latter implies that every consumer buys from the closer firm. It follows from (4) that the location choice of firm i minimizes social transport costs given the location of the rival, d_j, yielding first-best locations in equilibrium.[10,11] Equilibrium locations also coincide with the second-best locations. The latter minimize transport costs given the equilibrium allocation of consumers, which in the case of homogeneous consumers implies that every consumer buys from the closer firm. Hence, second-best locations also minimize social transport costs. Indeed, they solve the optimization problem

$$\min_{d_A,d_B}\left[\frac{(\bar{t}+\underline{t})}{2}\int\limits_{D_A(d_A;x)<D_B(d_B;x)} D_A\left(d_A;x\right)dx+\frac{(\bar{t}+\underline{t})}{2}\int\limits_{D_B(d_B;x)\leq D_B(d_B;x)} D_B\left(d_B;x\right)dx\right],$$

which is equivalent to the problem

$$\min_{d_A,d_B}\left[\frac{(\bar{t}+\underline{t})}{2}\int_0^1 \min\left\{D_A\left(d_A;x\right),D_B\left(d_B;x\right)\right\}dx\right].$$

Comparison with LH: Relatively differentiated consumers. When consumers are relatively differentiated, equilibrium locations differ both from first-best and second-best locations. Precisely, compared to both the first-best and the second-best, in equilibrium the interfirm distance is larger. Only when the quality of flexibility data becomes perfect, the equilibrium locations coincide with both first-best and second-best locations. In that case in equilibrium every firm serves all consumers on its turf on any address, and we get the same results as in the case with relatively homogeneous consumers. When the quality of flexibility data is imperfect, as shown in Lemma 1, given any locations every firm serves on its own turf the more loyal consumers and the less loyal consumers on the rival's turf. In a similar way as above, following

[10] To be more precise, in our case the equilibrium location of a firm minimizes *directly* the total distance travelled by consumers. In LH the equilibrium location of a firm minimizes directly social transport costs (if production costs are zero). This difference is related to the fact that in our model firms do not know the transport cost parameter of an individual consumer unless $k \to \infty$. Then in equilibrium in the version with relatively homogeneous consumers every consumer pays a price equal to the difference in the distances between the consumer and the two firms multiplied by the transport cost parameter of the most flexible consumer on the segment to which consumer belongs, and not consumer's own transport cost parameter. However, this difference between LH and our model does not change the main result that with relatively homogeneous consumers firms make socially optimal location choices.

[11] LH analyze firms' location choices in a two-dimensional market region. LH show that in that case equilibrium locations do not necessarily minimize social (transport) costs globally. However, this is always the case in our model (in a version with relatively homogeneous consumers), where firms choose locations on a unit-length Hotelling line over which consumers are distributed uniformly.

LH and using the results of Lemma 1 we can state the equilibrium prices of firm $i = \{A, B\}$ as

$$\begin{aligned}
p_{im}^{d}(d_i, d_j; x, k) &= \underline{t}^{m}(k)\left[D_j(d_j; x) - D_i(d_i; x)\right] \text{ if } D_j(d_j; x) > D_i(d_i; x) \text{ and } m \geq 2, \\
p_{im}^{d}(d_i, d_j; x, k) &= 2\bar{t}^{m}(k)\left[D_j(d_j; x) - D_i(d_i; x)\right]/3 \text{ if } D_j(d_j; x) > D_i(d_i; x) \text{ and } m = 1, \\
p_{im}^{d}(d_i, d_j; x, k) &= 0 \text{ if } D_j(d_j; x) \leq D_i(d_i; x) \text{ and } m \geq 2, \\
p_{im}^{d}(d_i, d_j; x, k) &= \bar{t}^{m}(k)\left[D_i(d_j; x) - D_j(d_i; x)\right]/3 \text{ if } D_j(d_j; x) \leq D_i(d_i; x) \text{ and } m = 1.
\end{aligned}$$

Then the profit of firm i for given locations d_i and d_j can be written as

$$\begin{aligned}
\Pi_i^d(d_i, d_j; k) &= \left[\frac{1}{2^k}\sum_{2}^{2^k}\underline{t}^{m}(k) + \frac{4\bar{t}}{9\times 2^{2k}}\right]\int_{D_j(d_j;x)>D_i(d_i;x)}\left[D_j(d_j; x) - D_i(d_i; x)\right]dx \\
&\quad + \frac{\bar{t}}{9\times 2^{2k}}\int_{D_j(d_j;x)\leq D_i(d_i;x)}\left[D_i(d_i; x) - D_j(d_j; x)\right]dx \\
&= \left[\frac{\bar{t}\left(2^k - 1\right)}{2^{k+1}} + \frac{4\bar{t}}{9\times 2^{2k}}\right]\int_{D_j(d_j;x)>D_i(d_i;x)}\left[D_j(d_j; x) - D_i(d_i; x)\right]dx \\
&\quad + \frac{\bar{t}}{9\times 2^{2k}}\int_{D_j(d_j;x)\leq D_i(d_i;x)}\left[D_i(d_i; x) - D_j(d_j; x)\right]dx.
\end{aligned}$$

Similar to Lemma 4 in LH we can rewrite $\Pi_i^d(d_A, d_B; k)$ as

$$\begin{aligned}
\frac{\Pi_i^d(d_i, d_j; k)}{\left[\frac{\bar{t}\left(2^k-1\right)}{2^{k+1}} + \frac{4\bar{t}}{9\times 2^{2k}}\right]} &= \int_0^1 D_j(d_j; x)\,dx + \frac{2}{9\times 2^k\left(2^k - 1\right) + 8}\int_0^1 D_i(d_i; x)\,dx \\
&\quad - \left[1 + \frac{2}{9\times 2^k\left(2^k - 1\right) + 8}\right]\int_0^1 \min\left\{D_j(d_j; x), D_i(d_i; x)\right\}dx.
\end{aligned} \tag{5}$$

Hence, when firm i chooses location d_i, its optimization problem is equivalent to

$$\min_{d_i}\left[(1 + \alpha(k))\frac{\bar{t}}{2}\int_0^1 \min\left\{D_j(d_j; x), D_i(d_i; x)\right\}dx - \alpha(k)\frac{\bar{t}}{2}\int_0^1 D_i(d_i; x)\,dx\right], \tag{6}$$

where $\alpha(k) = 2/\left[9\times 2^k\left(2^k - 1\right) + 8\right]$. Different from the optimization problem with relatively homogeneous consumers (4), where every firm minimizes social transport costs, in the optimization problem (6) firm i minimizes the weighted difference between social transport costs and transport costs of buying at firm i given by the first and the second terms in (6), respectively. Compared to the case of relatively homogeneous consumers, the latter term is new and is driven by the incentive of a firm to locate further apart from the rival to mitigate competition under the imperfect ability of a firm to protect market shares on its turf. Consider, for example, firm A. For a given location of the rival, the location choice which minimizes social transport costs is $d_A(d_B) = d_B/3$. And the location choice, which maximizes the transport costs of buying at firm A is $d_A = 0$. Then depending on $\alpha(k)$, $d_A(d_B; k)$ which solves (6), takes some value between $d_A(d_B) = d_B/3$ and $d_A = 0$. As first-best locations solve the optimization problem

$$\min_{d_A, d_B} \left[\frac{\bar{t}}{2} \int_0^1 \min \{D_A(d_A; x), D_B(d_B; x)\} dx \right],$$

it is straightforward that compared to them, equilibrium locations are closer to the end points of the unit interval and the interfirm distance is larger in equilibrium than in the first-best.

Second-best locations minimize the transport costs

$$\begin{aligned} & \left[\int_{D_A(d_A;x)<D_B(d_B;x)} D_A(d_A; x) dx + \int_{D_B(d_B;x)<D_A(d_A;x)} D_B(d_B; x) dx \right] \int_{\frac{\bar{t}}{3\times 2^k}}^{\bar{t}} f_t t dt \\ & + \left[\int_{D_A(d_A;x)>D_B(d_B;x)} D_A(d_A; x) dx + \int_{D_B(d_B;x)>D_A(d_A;x)} D_B(d_B; x) dx \right] \int_0^{\frac{\bar{t}}{3\times 2^k}} f_t t dt \\ = & \frac{\bar{t}[1-\beta(k)]}{2} \int_0^1 \min\{D_A(\cdot), D_B(\cdot)\} dx + \frac{\bar{t}\beta(k)}{2} \int_0^1 \max\{D_A(\cdot), D_B(\cdot)\} dx, \end{aligned} \tag{7}$$

where $\beta(k) = 1/\left[9 \times 2^{2k}\right]$. Different from first-best locations, which minimize social transport costs, second-best locations minimize the weighted sum of the social transport costs and the maximal transport cost given by the first and the second terms in (7), respectively. The first term in (7) is the transport costs of consumers who buy from their preferred firms, and the second term in (7) is the transport costs of consumers who buy from the farther firms. The latter costs are minimized under minimal differentiation when both firms are located at the middle of the unit interval.[12] Then second-best locations are closer to the middle of the unit interval compared to first-best locations, and the interfirm distance is larger in equilibrium than in the second-best too.

Combing our results in both versions of our model we make the following conclusions on firms' location choices in a Hotelling model with two-dimensional consumer heterogeneity, where firms

[12] Note that $\int_0^1 \max\{D_A(d_A; x), D_B(d_B; x)\} dx = d_A - 1/2 - (d_A + d_B)^2/4$. It is straightforward to show that the values $d_A = d_B = 1/2$ solve the following constrained optimization problem: $\max_{d_A, d_B} \left[d_A - 1/2 - (d_A + d_B)^2/4\right]$, s.t. $d_A - d_B \le 0$, $-d_A \le 0$ and $d_B \le 1$.

can practice perfect third-degree price discrimination based on consumer addresses and (possibly) imperfect one based on consumer flexibility. *First*, firms choose socially optimal locations in two cases. If either consumers are relatively homogeneous in flexibility or if firms have perfect customer flexibility data and thus can practice perfect third-degree price discrimination along that dimension too. In both cases every firm serves all consumers on its turf. We conclude that the optimality result of LH may also hold when customer data is imperfect. *Second*, when consumers are relatively differentiated in flexibility and customer flexibility data is imperfect, firms make socially suboptimal location choices. However, with the improvement in the quality of customer data equilibrium locations become closer to the socially optimal ones. This result supports the intuition of Hamilton and Thisse (1984, p. 184) that more flexibility in pricing leads to more efficient location choices when demands at each location are price-sensitive. However, as our first conclusion shows, flexibility in pricing (based on consumer transport cost parameters) is not a necessary condition for socially optimal locations. In the following we compare our results with the other closely related article of Anderson and de Palma (1988, in the following: AP).

Comparison with AP. AP assume that products are heterogeneous not only in the spatial dimension, but also in the characteristic space, which leads to price-sensitive demands at each location. While both versions of our model imply price-sensitive demands, our results are similar to those of AP only in the version with relatively differentiated consumers, where firms' markets overlap in equilibrium and most importantly, in equilibrium firms do not choose optimal locations (apart from the case where firms can perfectly discriminate based on consumer flexibility). As we showed above, when consumers are relatively homogeneous, in equilibrium every firm serves all consumers on its turf, such that firms' markets do not overlap, which leads to socially optimal equilibrium locations.[13]

In the following we will provide a more detailed comparison of AP and the version of our model with relatively differentiated consumers. In that case the equilibrium prices on segment $m = 1$ (with relatively differentiated consumers) can be derived from Proposition 1 in AP. Consider, for example, the interval $x \leq d_A$.[14] We need to set $c_A = c_B = 0$ and replace F_1 with

[13] In AP the monopolization outcome is not possible, because regardless of the difference in firms' prices on a given address, some consumers choose the other firm than the majority of consumers. In contrast, in our model one firm gains all consumers on a given address and flexibility segment if firms' prices there are very different.

[14] On the other intervals one should proceed in a similar way.

the demand of firm A on segment $m = 1$:

$$d_{A1}\left(p_{A1}(x) - p_{B1}(x), d_B - d_A, \bar{t}^1(k) \middle| x \leq d_A\right) := 1 - \frac{p_{A1}(x) - p_{B1}(x)}{\bar{t}^1(k)(d_B - d_A)}. \tag{8}$$

In AP (in the logit model) equilibrium locations depend on parameter $\mu \geq 0$, which is interpreted as a measure of consumer/product heterogeneity. In our case it makes sense to define μ as $\mu_1(k) := \bar{t}(d_B - d_A)/2^k$. Then from (8) we get that $|\partial d_{i1}(\cdot)/\partial p_{j1}(x)| = 1/\mu_1(k)$ $(i, j = \{A, B\})$, such that with an increase in $\mu_1(k)$ firms' prices become less important in determining their demands.

Parameter $\mu_1(k)$ is inversely related to the quality of customer flexibility data. If $k = 0$, then for any x, $\mu_1(k)$ gets its highest value of $\mu_1(0) = \bar{t}(d_B - d_A)$. Similar to AP we can draw a graph, which represents the optimal location of firm A depending on the ratio $\mu(k) := \mu_1(k)/\bar{t}(d_B - d_A) = 1/2^k$, where $\mu(k) \in (0, 1]$ (see Figure 1).

As Figure 1 shows, our results correspond to those in AP where μ is relatively small ($\mu/cl < \widehat{\mu}$). Precisely, the first-best location of firm A is constant, the second-best location of firm A increases in $\mu(k)$ and its equilibrium location decreases in $\mu(k)$. In our model in the first best firms are always located in the first and the third quartiles, because the optimal allocation of consumers is driven only by consumer heterogeneity in the spatial dimension, which implies that firms' markets should not overlap. This is not so in AP, and the socially optimal allocation of consumers depends on both consumer heterogeneity in the spatial dimension and product heterogeneity in the characteristic space. When the latter becomes strong enough, in the first best some consumers should buy from the farther firm, which makes it optimal for the social planer to locate the firms closer to the middle of the interval to decrease the transport costs of those consumers.

To explain the behavior of the equilibrium locations, AP identify two effects. With an increase in μ from $\mu = 0$ in AP products become heterogeneous (at each location) and a firm loses the monopoly power over its turf. As a result, firms move further apart to mitigate competition (*first effect*). At the same time higher μ implies the increased ability of each firm to gain consumers on the rival's turf. With an increase in the size of the latter group firms tend to locate closer to the center to minimize the transport costs of serving those consumers (*second effect*). At the point $\mu/cl = \widehat{\mu}$ in AP the second effect starts to dominate, and the interfirm distance decreases in equilibrium. When μ increases from $\mu = 0$ in our model, a firm loses the perfect targeting ability on its turf, which allows the rival to gain the less loyal consumers of a firm. To mitigate competition firms move further apart according to the first effect in AP. On the other hand, the weakened ability of the rival to target consumers on its own turf allows a firm to gain more consumers there, which creates an incentive to move closer to the rival according to the second effect in AP. However, different from AP the second effect never dominates in our model, as a firm gains at most only one third of consumers on the rival's turf.[15]

Compared to AP, our analysis highlights the importance of the ability to discriminate along the vertical dimension of consumer preferences for firms' location choices. When data on consumer flexibility improves (μ decreases), firms choose locations as if their products became more homogeneous (at each location), which mitigates competition and pushes the equilibrium locations in the direction of the socially optimal ones.

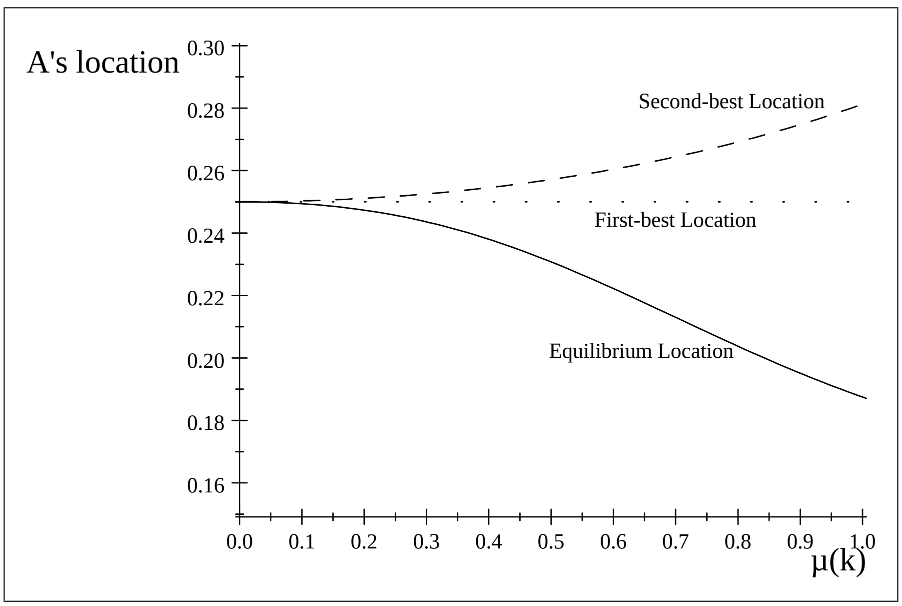

Figure 1: Equilibrium and optimal locations of firm A depending on $\mu(k)$

[15] This result depends on the assumption of the uniform distribution of consumer transport cost parameters on each location. For example, if there were two large consumer groups with relatively high and low transport cost parameters, it could be optimal for a firm to serve only the former group on its turf, while the latter would switch to the rival. In that case every firm could serve in equilibrium more loyal consumers of the rival than the own loyal consumers.

4 Conclusions

In this article we analyzed firms' location choices in a Hotelling model with two-dimensional consumer heterogeneity, along addresses and transport cost parameters (flexibility). We assumed that firms have perfect data on consumer locations, while the quality of customer flexibility data can be imperfect. Our results show that the optimality result of Lederer and Hurter (1986) holds even when firms' ability to practice third-degree price discrimination based on consumer transport cost parameters is imperfect, provided consumers are relatively homogeneous along that dimension. In that case under any location choices in equilibrium every firm serves all consumers on its turf, as in the case where firms have perfect data on consumer flexibility. In contrast, when consumers are relatively differentiated in flexibility, firms make socially suboptimal locations choices (unless the quality of customer flexibility data is perfect). However, with the improvement in the quality of customer flexibility data firms' location choices become closer to the socially optimal ones. This result supports the intuition of Hamilton and Thisse (1992) that to make socially optimal location choices firms need more flexibility in pricing. Our analysis is motivated by the availability of customer data, which allows firms to practice third-degree price discrimination based on both consumer characteristics relevant in spatial competition, addresses and transport cost parameters. It highlights the importance of consumer heterogeneity in flexibility and the quality of customer flexibility data for firms' location choices.

5 Appendix

Proof of Lemma 1. As firms are symmetric, we will derive equilibrium on the two intervals on the turf of firm A.

i) Interval 1: $x \leq d_A$. Consider some $x \leq d_A$ and some m. The transport cost parameter of the indifferent consumer is

$$\widetilde{t}\left(d_A, d_B, p_{Am}(x), p_{Bm}(x); x | \, x \leq d_A\right) := \frac{p_A(x) - p_B(x)}{d_B - d_A}, \text{ provided } \widetilde{t}(\cdot) \in \left[\underline{t}^m(k), \overline{t}^m(k)\right], \quad (9)$$

such that consumers with $t \geq \widetilde{t}(\cdot)$ buy at firm A. Consider first $m = 1$. Maximization of firms' expected profits yields the best-response functions

$$p_{A1}\left(d_A, d_B, p_{B1}(x); x, k | \, x \leq d_A\right) = \begin{cases} \frac{\overline{t}^1(k)(d_B - d_A) + p_{B1}(x)}{2} & \text{if} \quad p_{B1}(x) < \overline{t}^1(k)\,(d_B - d_A) \\ p_{B1}(x) & \text{if} \quad p_{B1}(x) \geq \overline{t}^1(k)\,(d_B - d_A) \end{cases} \quad (10)$$

and

$$p_{B1}\left(d_A, d_B, p_{A1}(x); x, k | \, x \leq d_A\right) =$$

$$\begin{cases} \frac{p_{A1}(x)}{2} & \text{if} \quad p_{A1}(x) \leq 2\overline{t}^1(k)\,(d_B - d_A) \\ p_{A1}(x) - \overline{t}^1(k)\,(d_B - d_A) & \text{if} \quad p_{A1}(x) > 2\overline{t}^1(k)\,(d_B - d_A)\,. \end{cases} \quad (11)$$

Given the best-response functions (10) and (11) we conclude that two types of equilibria are possible, where either firm A monopolizes segment m or where both firms serve consumers. Only the latter equilibrium exists where firms charge prices $p^d_{A1}(d_A, d_B; x, k) = 2\overline{t}\,(d_B - d_A) \,/\, \left(3 \times 2^k\right)$ and $p^d_{B1}(d_A, d_B; x, k) = \overline{t}\,(d_B - d_A) \,/\, \left(3 \times 2^k\right)$. Firm A serves consumers with $t \geq \overline{t}^1(k)/3$.

Consider now segments $m \geq 2$, where the best-response function of firm A is

$$p_{Am}\left(d_A, d_B, p_{Bm}(x); x, k | \, x \leq d_A\right) = p_{Bm}(x) + \underline{t}^m(k)\,(d_B - d_A)\,. \quad (12)$$

As $\overline{t}^m(k) - 2\underline{t}^m(k) \leq 0$ for any $m \geq 2$, there is no $p_{Bm}(x) \geq 0$ under which it is optimal for firm A to share the market with firm B. (12) yields $p^d_{Bm}(d_A, d_B; x, k) = 0$. Indeed, assume that in equilibrium $p^d_{Bm}(d_A, d_B; x, k) > 0$ holds. Firm B gets in equilibrium the profit of zero, because (12) implies that firm B serves no consumers. But firm B can increase its profit through slightly decreasing its price. Hence, $p^d_{Bm}(d_A, d_B; x, k) = 0$ must hold. Firm A charges the price $p^d_{Am}(d_A, d_B; x, k) = \underline{t}^m(k)\,(d_B - d_A)$ and serves all consumers on segment m on address x.

On the interval $x \leq d_A$ firms realize profits

$$\begin{aligned}\Pi_A\left(d_A, d_B; k | \, x \leq d_A\right) &= \int_0^{d_A} f_t \left[\left(\frac{2\bar{t}}{3 \times 2^k}\right)^2 (d_B - d_A) + \frac{\bar{t}\,(d_B - d_A)}{2^k} \sum_2^{2^k} \underline{t}^m(k)\right] dx \\ &= \frac{\bar{t}\,(d_B - d_A)\, d_A \left(9 \times 2^{2k} - 9 \times 2^k + 8\right)}{9 \times 2^{2k+1}}\end{aligned}$$

and

$$\Pi_B(d_A, d_B; k | \, x \leq d_A) = \frac{\bar{t}\,(d_B - d_A)\, d_A}{9 \times 2^{2k}}.$$

Using symmetry we conclude on firms' profits on the interval $x \geq d_B$:

$$\begin{aligned}\Pi_A(d_A, d_B; k | \, x &\geq d_B) = \frac{\bar{t}\,(d_B - d_A)\,(1 - d_B)}{9 \times 2^{2k}} \text{ and} \\ \Pi_B(d_A, d_B; k | \, x &\geq d_B) = \frac{\bar{t}\,(d_B - d_A)\,(1 - d_B)\left(9 \times 2^{2k} - 9 \times 2^k + 8\right)}{9 \times 2^{2k+1}}\end{aligned}$$

ii) Interval 2: $d_A < x \leq (d_A + d_B)/2$*.* Consider some $d_A < x \leq (d_A + d_B)/2$ and segment m. The transport cost parameter of the indifferent consumer is

$$\widetilde{t}\left(d_A, d_B, p_{Am}(x), p_{Bm}(x); x | \, d_A < x \leq \frac{d_A + d_B}{2}\right) := \frac{p_A(x) - p_B(x)}{d_A + d_B - 2x},$$

provided $\widetilde{t}(\cdot) \in \left[\underline{t}^m(k), \bar{t}^m(k)\right]$. Firm A serves consumers with $t \geq \widetilde{t}(\cdot)$. Consider first $m = 1$. Maximization of firms' profits yields the best-response functions

$$p_{A1}(d_A, d_B, p_{B1}(x); x, k | \, d_A < x \leq \frac{d_A + d_B}{2}) =$$

$$\begin{cases} \frac{\bar{t}^1(k)(d_A + d_B - 2x) + p_{B1}(x)}{2} & \text{if } \; p_{B1}(x) < \bar{t}^1(k)\,(d_A + d_B - 2x) \\ p_{B1}(x) & \text{if } \; p_{B1}(x) \geq \bar{t}^1(k)\,(d_A + d_B - 2x) \end{cases} \tag{13}$$

and

$$p_{B1}(d_A, d_B, p_{A1}(x); x, k | \, d_A < x \leq \frac{d_A + d_B}{2}) =$$

$$\begin{cases} \frac{p_{A1}(x)}{2} & \text{if } \; p_{A1}(x) \leq 2\bar{t}^1(k)\,(d_A + d_B - 2x) \\ p_{A1}(x) - \bar{t}^1(k)\,(d_A + d_B - 2x) & \text{if } \; p_{A1}(x) > 2\bar{t}^1(k)\,(d_A + d_B - 2x). \end{cases} \tag{14}$$

Given the best-response functions (13) and (14) we conclude that two types of equilibria are possible where either firm A serves all consumers on segment m or shares it with the rival. Only the latter equilibrium exists, where firms charge prices

$$\begin{aligned} p^d_{A1}(d_A, d_B; x, k) &= 2\bar{t}\,(d_A + d_B - 2x) \,/ \left(3 \times 2^k\right) \text{ and} \\ p^d_{B1}(d_A, d_B; x, k) &= \bar{t}\,(d_A + d_B - 2x) \,/ \left(3 \times 2^k\right). \end{aligned}$$

On $m = 1$ firm A serves consumers with $t \geq \bar{t} / \left(3 \times 2^k\right)$.

We now consider $m \geq 2$, where the best-response function of firm A takes the form

$$p_{Am}(\,d_A, d_B, p_{Bm}(x); x, k|\, d_A < x \leq \frac{d_A + d_B}{2}) = p_{Bm}(x,k) + \underline{t}^m(k)\,(d_A + d_B - 2x)\,,$$

such that firm A never finds it optimal to share segment m with firm B. Applying the logic described in part *i)* of the proof, we conclude that $p^d_{Bm}(d_A, d_B; x, k) = 0$ and $p^d_{Am}(d_A, d_B; x, k) = \underline{t}^m(k)\,(d_A + d_B - 2x)$. Firm A serves all consumers on any segment $m \geq 2$ on address x.

On the interval $d_A < x \leq (d_A + d_B)/2$ firms realize profits

$$\begin{aligned} &\Pi_A\left(d_A, d_B; k|\, d_A < x \leq \frac{d_A + d_B}{2}\right) \\ =& \int_{d_A}^{\frac{d_A+d_B}{2}} f_t \left[\left(\frac{2\bar{t}}{3 \times 2^k}\right)^2 (d_A + d_B - 2x) + \frac{\bar{t}\,(d_A + d_B - 2x)}{2^k} \sum_{2}^{2^k} \underline{t}^m(k)\right] dx \\ =& \frac{\bar{t}\,(d_B - d_A)^2\left(9 \times 2^{2k} - 9 \times 2^k + 8\right)}{9 \times 2^{2k+3}} \text{ and} \end{aligned}$$

$$\Pi_B\left(d_A, d_B; k|\, d_A < x \leq \frac{d_A + d_B}{2}\right) = \frac{\bar{t}\,(d_B - d_A)^2}{9 \times 2^{2k+2}}.$$

Using symmetry, we can conclude on firms' profits on the interval $(d_A + d_B)/2 < x \leq d_B$:

$$\begin{aligned} \Pi_A\left(d_A, d_B; k|\, \frac{d_A + d_B}{2} < x \leq d_B\right) &= \frac{\bar{t}\,(d_B - d_A)^2}{9 \times 2^{2k+2}} \text{ and} \\ \Pi_B\left(d_A, d_B; k|\, \frac{d_A + d_B}{2} < x \leq d_B\right) &= \frac{\bar{t}\,(d_B - d_A)^2\left(9 \times 2^{2k} - 9 \times 2^k + 8\right)}{9 \times 2^{2k+3}}. \end{aligned}$$

Summing up firms' profits on all the four intervals we get

$$\begin{aligned} \Pi^d_A(d_A, d_B; k) &= \frac{\bar{t}\,(d_B - d_A)\left[9 \times 2^k\left(2^k - 1\right)(3d_A + d_B) + 2\,(11 d_A + d_B) + 8\right]}{9 \times 2^{2k+3}} \text{ and} \\ \Pi^d_B(d_A, d_B; k) &= \frac{\bar{t}\,(d_B - d_A)\left[32 - 9 \times 2^k(2^k - 1)\,(3d_B + d_A - 4) - 2\,(11 d_B + d_A)\right]}{9 \times 2^{2k+3}}. \end{aligned}$$

Q.E.D.

Proof of Lemma 2. As firms are symmetric, we will only derive equilibrium on the two intervals on the turf of firm A and then conclude on the equilibrium on the turf of firm B.

i) Interval 1: $x \le d_A$. Consider some $x \le d_A$ and some $m \ge 1$. The transport cost parameter of the indifferent consumer is

$$\widetilde{t}\,(d_A, d_B, p_{Am}(x), p_{Bm}(x); x|\, x \le d_A) := \frac{p_A(x) - p_B(x)}{d_B - d_A}, \text{ provided } \widetilde{t}(\cdot) \in \left[\underline{t}^m(k), \overline{t}^m(k)\right].$$

The best-response function of firm A is

$$p_{Am}(\,d_A, d_B, p_{Bm}(x); x, k|\, x \le d_A) = p_{Bm}(x) + \underline{t}^m(k)\,(d_B - d_A)\,, \tag{15}$$

such that for any price of the rival firm A monopolizes segment m on address x. As $\overline{t}^m(k) - 2\underline{t}^m(k) \le 0$ for any $m \ge 2$, there is no $p_{Bm}(x) \ge 0$ under which it is optimal for firm A to share the market with firm B. (15) yields $p^h_{Bm}(d_A, d_B; x, k) = 0$. Indeed, assume that in equilibrium $p^h_{Bm}(d_A, d_B; x, k) > 0$ holds. Firm B gets in equilibrium the profit of zero, because (15) implies that firm B serves no consumers. But firm B can increase its profit through slightly decreasing its price. Hence, $p^h_{Bm}(d_A, d_B; x, k) = 0$ must hold. Firm A charges the price $p^h_{Am}(d_A, d_B; x, k) = \underline{t}^m(k)\,(d_B - d_A)$ and serves all consumers on segment m on address x. Hence, $\Pi_B(\,d_A, d_B; k|\, x \le d_A) = 0$ and the profit of firm A is computed as

$$\Pi_A(\,d_A, d_B; k|\, x \le d_A) = \sum_1^{2^k} \underline{t}^m(k) \int_0^{d_A} \left[\frac{(d_B - d_A)}{2^k}\right] dx = \frac{d_A\,(d_B - d_A)\left[\overline{t}\left(2^k - 1\right) + \underline{t}\left(2^k + 1\right)\right]}{2^{k+1}}. \tag{16}$$

ii) Interval 2: $d_A < x \le (d_A + d_B)/2$. Consider some $d_A < x \le (d_A + d_B)/2$ and some $m \ge 1$. The transport cost parameter of the indifferent consumer is

$$\widetilde{t}\left(\,d_A, d_B, p_{Am}(x), p_{Bm}(x); x|\, d_A < x \le \frac{d_A + d_B}{2}\right) := \frac{p_A(x) - p_B(x)}{d_A + d_B - 2x},$$

provided $\widetilde{t}(\cdot) \in \left[\underline{t}^m(k), \overline{t}^m(k)\right]$. Firm A serves consumers with $t \ge \widetilde{t}(\cdot)$. The best-response function of firm A is

$$p_{Am}(\,d_A, d_B, p_{Bm}(x); x, k|\, d_A < x \le \frac{d_A + d_B}{2}) = p_{Bm}(x) + \underline{t}^m(k)\,(d_A + d_B - 2x)\,.$$

Following the logic applied in part *i)* of the proof we conclude that

$$\begin{aligned} p_{Bm}^{h}(x,k) &= 0 \text{ and} \\ p_{Am}^{h}(d_A,d_B;x,k) &= \underline{t}^{m}(k)\left(d_A+d_B-2x\right). \end{aligned}$$

Hence, $\Pi_B(d_A,d_B;k|\, d_A < x \leq (d_A+d_B)/2) = 0$ and the profit of firm A is computed as

$$\begin{aligned} \Pi_A(d_A,d_B;k|\, d_A &< x \leq \frac{d_A+d_B}{2}) = \sum_{1}^{2^k} \underline{t}^{m}(k) \int_{d_A}^{(d_A+d_B)/2} \left[\frac{(d_A+d_B-2x)}{2^k}\right] dx \qquad (17) \\ &= \frac{(d_B-d_A)^2\left[\bar{t}\left(2^k-1\right)+\underline{t}\left(2^k+1\right)\right]}{2^{k+3}}. \end{aligned}$$

Summing up the profits (16) and (17) we get the profits of firm A as stated in the lemma. The profits of firm B are derived using symmetry. *Q.E.D.*

Proof of Lemma 3. We first derive first-best locations and prices. We will proceed in two steps. We will first derive first-best prices for any given locations and then will find first-best locations. Assume that firms are located at $d_A \leq d_B$. Social welfare is maximized when every consumer buys from the closer firm. Prices, which yield such a distribution of consumers between the firms are $p_{im}^{FB}(x), p_{jm}^{FB}(x) \geq 0$ such that

$$p_{im}^{FB}(x) \leq t\left|x-x_j\right| - t\left|x-x_i\right| + p_{jm}^{FB}(x) \text{ if } \left|x-x_i\right| \leq \left|x-x_j\right|. \qquad (18)$$

Given (18), the first-best locations, d_A^{FB} and d_B^{FB}, have to minimize the transport costs

$$\begin{aligned} &TC^{FB}(d_A,d_B;k) \qquad (19) \\ &= \frac{\left(\bar{t}+\underline{t}\right)}{2}\left[\int_0^{d_A}(d_A-x)\,dx + \int_{d_A}^{(d_A+d_B)/2}(x-d_A)dx + \int_{(d_A+d_B)/2}^{d_B}(d_B-x)\,dx + \int_{d_B}^{1}(x-d_B)\,dx\right], \end{aligned}$$

which yields the locations $d_A^{FB} = 1/4$ and $d_B^{FB} = 3/4$. Note that SOCs are fulfilled.

We now turn to the second-best locations. Here we have to distinguish between the cases of relatively homogeneous and differentiated consumers, because for any locations firms charge different prices in equilibrium depending on the case. We start with the case of relatively homogeneous consumers. Note that the equilibrium prices stated in Lemma 2 satisfy (18). Indeed, in equilibrium every consumer buys from the closer firm. Then second-best locations should also minimize (19), which yields $d_A^{SB,h} = 1/4$ and $d_B^{SB,h} = 3/4$.

We now consider the case of relatively differentiated consumers. According to Lemma 1, on its own turf each firm serves consumers with $t \geq \bar{t}/\left(3 \times 2^k\right)$, while consumers with $t < \bar{t}/\left(3 \times 2^k\right)$ switch to the rival. Then second-best locations have to minimize the transport costs

$$\begin{aligned}
TC^{SB,d}(d_A, d_B; k) &= \int_{\bar{t}/\left(3\times 2^k\right)}^{\bar{t}} \left[t f_t \int_0^{d_A} (d_A - x)\, dx \right] dt + \int_{\bar{t}/\left(3\times 2^k\right)}^{\bar{t}} \left[t f_t \int_{d_A}^{(d_A+d_B)/2} (x - d_A)\, dx \right] dt \\
&+ \int_0^{\bar{t}/\left(3\times 2^k\right)} \left[t f_t \int_{(d_A+d_B)/2}^{d_B} (x - d_A)\, dx \right] dt + \int_0^{\bar{t}/\left(3\times 2^k\right)} \left[t f_t \int_{d_B}^{1} (x - d_A)\, dx \right] dt \\
&+ \int_{\bar{t}/\left(3\times 2^k\right)}^{\bar{t}} \left[t f_t \int_{d_B}^{1} (x - d_B)\, dx \right] dt + \int_{\bar{t}/\left(3\times 2^k\right)}^{\bar{t}} \left[t f_t \int_{(d_A+d_B)/2}^{d_B} (d_B - x)\, dx \right] dt \\
&+ \int_0^{\bar{t}/\left(3\times 2^k\right)} \left[t f_t \int_{d_A}^{(d_A+d_B)/2} (d_B - x)\, dx \right] dt + \int_0^{\bar{t}/\left(3\times 2^k\right)} \left[t f_t \int_0^{d_A} (d_B - x)\, dx \right] dt \\
&= -\frac{\bar{t}}{2^{2k}} \left[\frac{(d_A - d_B)^2}{36} + \frac{(d_A - d_B)}{18} - 3 \times 2^{2k-3} \left((d_A)^2 + (d_B)^2 \right) \right] \\
&\quad -\frac{\bar{t}}{2^{2k}} \left(-2^{2k-2} + 2^{2k-1} d_B + 2^{2k-2} d_A d_B \right),
\end{aligned}$$

which yields

$$d_A^{SB}(k) = \frac{9 \times 2^{2k}}{36 \times 2^{2k} - 4} \text{ and } d_B^{SB}(k) = \frac{27 \times 2^{2k} - 4}{36 \times 2^{2k} - 4}.$$

SOCs are fulfilled. Note finally that $\lim_{k\to\infty} d_A^{SB}(k) = 1/4$ and $\lim_{k\to\infty} d_B^{SB}(k) = 3/4$. *Q.E.D.*

Proof of Proposition 1. *i)* Maximization of the profits

$$\begin{aligned}
\Pi_A^h(d_A, d_B; k) &= \frac{\underline{t}\left[\left(2^k+1\right) + l\left(2^k-1\right)\right](d_B + 3d_A)(d_B - d_A)}{2^{k+3}} \text{ and} \\
\Pi_B^h(d_A, d_B; k) &= \frac{\underline{t}\left[\left(2^k+1\right) + l\left(2^k-1\right)\right](4 - d_A - 3d_B)(d_B - d_A)}{2^{k+3}}
\end{aligned}$$

with respect to d_A and d_B yields the FOCs: $d_B - 3d_A = 0$ and $d_A - 3d_B + 2 = 0$, respectively. Solving them simultaneously we get $d_A^h = 1/4$ and $d_B^h = 3/4$, such that the profit of firm $i = \{A, B\}$ is

$$\Pi_i^h(k) = \frac{3\underline{t}\left[\left(2^k+1\right) + l\left(2^k-1\right)\right]}{2^{k+5}}. \tag{20}$$

Note that SOCs are fulfilled. To prove that these locations constitute indeed the equilibrium, we have to prove that firm A does not have an incentive to choose a location $d_A \geq d_B^h = 3/4$.

Due to symmetry, this would also imply that firm B does not have an incentive to choose $d_B \leq d_A^h = 1/4$. If firm A locates at $d_A \geq d_B^h$, then according to Lemma 2 it realizes the profit

$$\Pi_B(d_B, d_A; k) = \frac{\underline{t}\left[\left(2^k+1\right)+l\left(2^k-1\right)\right](4-d_B-3d_A)(d_A-d_B)}{2^{k+3}}. \tag{21}$$

Maximizing (21) with respect to d_A yields the FOC: $d_A\left(d_B^h\right) = \left(d_B^h+2\right)/3 = 11/12$. Firm A realizes the profit

$$\Pi_B\left(\frac{3}{4}, \frac{11}{12}; k\right) = \frac{\underline{t}\left[\left(2^k+1\right)+l\left(2^k-1\right)\right](4-d_B-3d_A)(d_A-d_B)}{2^{k+3}} = \frac{\underline{t}\left[\left(2^k+1\right)+l\left(2^k-1\right)\right]}{3\times 2^{k+5}}. \tag{22}$$

Comparing the profits (20) and (22) we conclude that

$$\Pi_i^h(k) - \Pi_B\left(\frac{3}{4}, \frac{11}{12}; k\right) = \frac{\underline{t}\left[\left(2^k+1\right)+l\left(2^k-1\right)\right]}{3\times 2^{k+2}} > 0 \text{ for any } k \geq 0,$$

hence, firm A does not have an incentive to deviate to $d_A \geq d_B^h$. We conclude that the locations $d_A^h = 1/4$ and $d_B^h = 3/4$ constitute indeed the equilibrium.

ii) Maximization of the profits

$$\begin{aligned}
\Pi_A^d(d_A, d_B; k) &= \frac{\bar{t}(d_B-d_A)\left[9\times 2^k\left(2^k-1\right)(3d_A+d_B)+2(11d_A+d_B)+8\right]}{9\times 2^{2k+3}} \text{ and} \\
\Pi_B^d(d_A, d_B; k) &= \frac{\bar{t}(d_B-d_A)\left[-9\times 2^k(2^k-1)(3d_B+d_A-4)-2(11d_B+d_A)+32\right]}{9\times 2^{2k+3}}
\end{aligned}$$

with respect to d_A and d_B yields the FOCs

$$\begin{aligned}
d_A(d_B; k) &= \frac{9\times 2^k d_B\left(2^k-1\right)+10d_B-4}{27\times 2^{2k}-27\times 2^k+22} \text{ and} \\
d_B(d_A; k) &= \frac{9\times 2^k\left(2^k-1\right)(d_A+2)+10d_A+16}{27\times 2^{2k}-27\times 2^k+22},
\end{aligned}$$

respectively. Solving FOCs simultaneously we get the locations

$$\begin{aligned}
d_A^d(k) &= \frac{9\times 2^{2k}-9\times 2^k+6}{36\times 2^{2k}-36\times 2^k+32} \text{ and} \\
d_B^d(k) &= \frac{27\times 2^{2k}-27\times 2^k+26}{36\times 2^{2k}-36\times 2^k+32},
\end{aligned} \tag{23}$$

such that firm $i = \{A, B\}$ realizes the profit

$$\Pi_i^d(k) = \frac{\bar{t}\left(9 \times 2^{2k} - 9 \times 2^k + 10\right)^2 \left(27 \times 2^{2k} - 27 \times 2^k + 22\right)}{9 \times 2^{2k+5}\left(9 \times 2^{2k} - 9 \times 2^k + 8\right)^2}.$$

Note that the SOCs are also fulfilled. To prove that the locations $d_A^d(k)$ and $d_B^d(k)$ constitute indeed the equilibrium, we have to show that firm A does not have an incentive to locate at $d_A \geq d_B^d(k)$. As firms are symmetric, firm B then does not have an incentive to locate at $d_B \leq d_A^d(k)$ either. If firm A chooses $d_A \geq d_B^d(k)$, then it realizes the profit

$$\begin{aligned} & \Pi_B^d(d_B^d(k), d_A; k) \\ = \; & \frac{\bar{t}\left(d_A - d_B^d(k)\right)\left[-9 \times 2^k(2^k - 1)\left(3d_A + d_B^d(k) - 4\right) - 2\left(11d_A + d_B^d(k)\right) + 32\right]}{9 \times 2^{2k+3}}. \end{aligned} \tag{24}$$

Maximization of (24) with respect to d_A yields

$$\begin{aligned} d_A\left(d_B^d(k); k\right) &= \frac{9 \times 2^k\left(2^k - 1\right)\left(d_B^d(k) + 2\right) + 10d_B^d(k) + 16}{27 \times 2^{2k} - 27 \times 2^k + 22} \\ &= \frac{2547 \times 2^{2k} - 1782 \times 2^{3k} + 891 \times 2^{4k} - 1656 \times 2^k + 772}{(36 \times 2^{2k} - 36 \times 2^k + 32)(27 \times 2^{2k} - 27 \times 2^k + 22)}, \end{aligned}$$

such that firm A realizes the profit

$$\Pi_B(d_B^d(k), d_A\left(d_B^d(k); k\right); k) = \frac{\bar{t}\left(9 \times 2^{2k} - 9 \times 2^k + 10\right)^4}{9 \times 2^{2k+5}(9 \times 2^{2k} - 9 \times 2^k + 8)^2(27 \times 2^{2k} - 27 \times 2^k + 22)}.$$

Comparison of the profits $\Pi_i^d(k)$ and $\Pi_B(d_B^d(k), d_A\left(d_B^d(k); k\right); k)$ yields

$$\begin{aligned} & \Pi_i^d(k) - \Pi_B(d_B^d(k), d_A\left(d_B^d(k); k\right); k) \\ = \; & \frac{\left(3 \times 2^{2k} - 3 \times 2^k + 2\right)\left(9 \times 2^{2k} - 9 \times 2^k + 10\right)^2}{3 \times 2^{2k+2}\left(27 \times 2^{2k} - 27 \times 2^k + 22\right)\left(9 \times 2^{2k} - 9 \times 2^k + 8\right)} > 0 \text{ for any } k, \end{aligned}$$

hence, firm A does not have an incentive to locate at $d_A \geq d_B^d(k)$. We conclude that the locations $d_A^d(k)$ and $d_B^d(k)$ in (23) constitute indeed the equilibrium. *Q.E.D.*

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