Dynamic Price Competition: Theory and Evidence from Airline Markets

Ali Hortaçsu[1], Aniko Öry[2], Kevin R. Williams[3]

(1) University of Chicago & NBER, (2) Yale University, (3) Yale University & NBER

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Disclosures: We thank the anonymous airline for giving us access to the data used in this study. Under the agreement with the authors, the airline had "the right to delete any trade secret, proprietary, or Confidential Information" supplied by the airline. We agreed to take comments in good faith regarding statements that would lead a reader to identify the airline and damage the airline's reputation. All authors have no material financial relationships with entities related to this research.

Dynamic pricing is commonly used in markets with xed inventory and sales deadline

- Examples: Airlines, trains, hotels, cruises, entertainment tickets, retailing, etc.
- Capacity drives price dynamics:
  - The opportunity cost of selling changes with scarcity
    - Value of a seat today depends on the ability to sell it in the future
    - Excess inventory ! expect low prices
  - Demand may change over time
    - If high WTP consumers arrive in future, incentives to save seats

What are additional forces if firms compete?

1. Today's demand depends on the competitor's price

2. The opportunity cost of selling depends on the own and competitor inventories because they affect future prices

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   - E.g., if a firm has excess inventory, it might price high (not low) in order to get competitors to sell out early

   - E.g., fire sales by firm with less inventory to soften future competition

3. Open questions regarding dynamic price competition in perishable goods markets

   a) Equilibrium prices and profits lack "nice" properties; can we characterize equilibrium outcomes?

   b) Empirical welfare implications unknown

Contributions of the research project

1. We introduce a tractable oligopoly framework for dynamic price competition
   - Provide a differential equation characterization of equilibrium dynamics e.g. Gallego & van Ryzin (1994)
   - Provide insights on existence, uniqueness, competitive dynamics, e.g., the role of “minimum capacity” see Martinez-de-Albeniz & Talluri (2011) for perfect substitutes
2. We estimate the welfare effects of dynamic pricing in the airline industry
   - We find the opposite results compared to studies in the single-firm setting: DP increases output and profits, decreases welfare single-firm setting: e.g., Hendel and Nevo (2013), Castillo (2021), Williams (2022)
   - Heuristics similar to airline practices increase surplus relative to DP heuristics differ from, e.g., Calvano et al (2020), Brown and MacKay (2021), Asker et al. (2021)

Oligopoly model

- We consider a set $\mathcal{J} = \{1, \ldots, J\}$ of products and a set $\mathcal{F} := \{1, \ldots, F\}$ of firms
- Firm f owns products in $\mathcal{J}_f \subset \mathcal{J}$
- Initial capacity of each product j is $K_{j,0}$
- Firms must sell all units by time T, in periods $t = \Delta, 2\Delta, \ldots, T$
- In every period:
  - each firm f sets prices $\mathbf{p}_t^f := (p_{j,t})_{j \in \mathcal{J}_f}$
  - a consumer arrives with probability $\Delta \lambda_t \in (0, 1)$
  - consumer decides whether to buy a product or not and leave
- Firms observe history of all prices and inventories(j)]i0 g 0 GΩ0 g 0 GΩ0 g 0 GΩ0 g 0 GΩ0

Demand model

- Consumers are passive/short-lived ! demand function
  (with forward-looking buyers, firm competing with its future self e.g., Board &
  Skrzypacz (2016); Dilme & Li, (201934(r;Ω0 g 4IΩ0 00 g 0ofo)27(rw)28(a)28(rd-lo)-28(oking)-333(buy740ok05mw

Solution concept: Markov-perfect equilibrium

- We analyze Markov-perfect equilibria
- Payoff-relevant state: vector of inventory $\mathbf{K} := (K_j)_{j \in J}$ and time

Optimal control problem

- The continuation profit of a single firm with capacities $K_j > 0$ for $j \in K$

Properties of the single- rm case

Proposition 1

1. Value function $\Pi_{M;t}(\mathbf{K})$ is decreasing in time t and increasing in capacity
2. Opportunity costs $!_{j;t}(\mathbf{K})$ are decreasing in time t and capacity
3. The stochastic process $s_{j;t\wedge}(\mathbf{K}_t)$, := inf ft $\geq$ 0j$K_{j;t}$ jjK

Now, we consider the duopoly game. A new scarcity force.

- Back to a duopoly where each firm owns one product: $\mathcal{J} = \mathcal{F} = \{1, 2\}$
- Each firm f has its own continuation profit in state $(\mathbf{K}, t)$: $\Pi_{f,t}(\mathbf{K}, \Delta)$

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- Now, there are two scarcity effects for each firm f:

Differential equation characterization of equilibrium

Proposition 2 (Continuous-time limit)

Assume sufficient conditions on demand system. For every $\mathbf{K}$, there exists a $T_0(\mathbf{K}) > 0$, non-increasing in $\mathbf{K}$, so that the value function $\Pi_{f,t}(\mathbf{K}; \Delta)$ converges to a limit $\Pi_{f,t}(\mathbf{K})$ as $\Delta \to 0$ that solves the differential equation

$$\dot{\Pi}_{f,t}(\mathbf{K}) = -\;{}_t \quad s_f(\mathbf{p}(\Omega_t(\mathbf{K}); {}_t))\; p_f(\Omega_t(\mathbf{K}); {}_t) - \underbrace{(\Pi_{f,t}(\mathbf{K}) - \Pi_{f,t}(\mathbf{K} - \mathbf{e}_j))}_{\text{own-scarcity effect}}$$

$$- s_{f}(\mathbf{p}(\Omega_t(\mathbf{K}); {}_t)) \underbrace{\Pi_{f,t}(\mathbf{K}) - \Pi_{f,t}(\mathbf{K} - \mathbf{e}_{f})}_{\text{competitor-scarcity effect}}$$

where $f' \neq f$, with natural boundary conditions and $p(\Omega; \ )$ is an equilibrium of a stage game parameterized by $(\Omega; \ )$.

Allows us to empirically investigate DPs in oligopoly with large state spaces

The value function

- The Markov structure allows us to summarize the impact of today's price on future revenues into "scarcity effects."
- Given a pricing strategy $\mathbf{p}_t(\mathbf{K}) := (p_{1,t}(\mathbf{K}), p_{2,t}(\mathbf{K}))$, firm f's value function is

$$\Pi_{f,t}(\mathbf{K};\Delta) = \Delta_t \underbrace{s_{f,t}(\mathbf{p}_t(\mathbf{K})) \quad p_{f,t}(\mathbf{K}) + \Pi_{f,t+\Delta}(\mathbf{K}-\mathbf{e}_f;\Delta)}_{\text{revenue of own sale}} +$$

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where $f \neq f'$.

The stage game with equilibrium prices $p_t(k;\omega_t)$

- We can write for each firm $f \neq f'$

$$\Pi_{f,t+\Delta}(\mathbf{K};\Delta) - \Pi_{f,t}(\mathbf{K};\Delta) =$$

$$-\Delta_t \Big(\underbrace{s_{f,t}(\mathbf{p}_t(\mathbf{K}))\left(p_{f,t}(\mathbf{K}) - \omega^f_{f,t}(\mathbf{K})\right) - s_{f',t}(\mathbf{p}_t(\mathbf{K}))\,\omega^f_{f',t}(\mathbf{K})}_{\text{stage game payoff of firm } f} \Big).$$

  - "Own-scarcity effect"

$$\omega^f_{f,t}(\mathbf{K}) := \Pi_{f,t+\Delta}(\mathbf{K}) - \Pi_{f,t+\Delta}(\mathbf{K} -$$

Findings from simulations of this system of differential equations

- Profits are non-monotonic in the own capacity
- Profits are non-monotonic in competitor capacity
- Profits are neither concave nor convex in capacity: Both scarcity effects can be positive or negative
- But the dynamics of scarcity effects close to the deadline depends on which firm has the minimum capacity:
  - competition fiercest when firms have symmetric inventory (independent of symmetry in other dimensions)
  - largest price effects when the firm with min cap sells
- see paper for new markup rule

Data Overview

- Use third-party data provided to us by .0.0s(eap)27(gse)-333USy irline:I

Facts on Routes Studied

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Average outcomes across competitors

- No competitor sells consisently a larger fraction of its seats
- Price differences across carriers are small, but one carrier charges relatively lower prices earlier on and higher prices later on (on average)

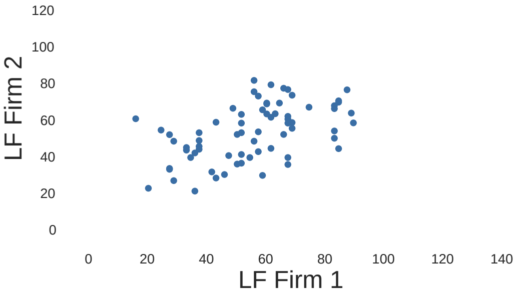

Figure: Average load factors for carriers in duopoly markets

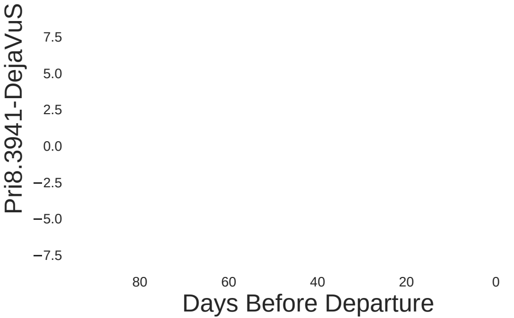

Figure: Difference in prices for markets in which each firm offers exactly one flight

Empirical Model of Demand|Nested Logit with 2 Nests

- Let j be a carrier-flight, d a departure date, t is day before departure, r a route

- Conditional on arrival, we specify consumer utilities as

$$u_{i,j,t,d,r} = \mathbf{x}_{j,t,d,r} \quad - \quad {}_t\, p_{j,t,d,r} + {}_{i,J} + (1 - \quad)\varepsilon_{i,j,t,d,r},$$

  where
  - ${}_{i,J} + (1 - \quad)\varepsilon_{i,j,t,d,r}$ follows a type-1 extreme value distribution, and ${}_{i,J}$ is an idiosyncratic preference for the inside goods;
  - We allow price sensitivity parameters ${}_t$ to vary with time
  - Nesting parameter captures flight substitutability

- Each arriving consumer solves their utility maximization problem such that consumer i chooses flight j if and only if $u_{i,j,t,d,r} \geq u_{i,j',d,t,r},\ \forall j' \in J_{t,d,r} \cup \{0\}.$

- Estimates robust to adding an unobservable , estimated with control function

Empirical Model of Demand|Poisson Arrival

- We assume daily arrivals are distributed Poisson, with rates ${}_{t,d,r}$ equal to

$$_{t,d,r} = \exp\left({}_{r}^{OD} + {}_{d}^{DD} + {}_{t,d}^{SD} + f\,(DFD)_t \right),$$

  where $f(\cdot)$ is a polynomial expansion

- Therefore, $q_{j,t,d,r} = \min\{C_{j,t,d,r},\ {}_{t,d,r} \cdot s_{j,t,d,r}(p;\ )\}$, which is censored Poisson

- We scale up arrivals using a factor (1-3.5) to account for unobserved searches, after accounting for the percentage of direct bookings/searches for a single carrier

Demand Estimates Over Time

40 20 0

Figure: Price Sensitivity Parameters

Figure: Arrival Rates

- Estimate nesting parameter = 0.5; avg. elasticity of -1.438
- Both the number of arriving customers and the average price sensitivity are increasing towards the deadline

Counterfactual Analysis: Dynamic Pricing

	Price	Firm 1 Rev.	Firm 2 Rev.	CS	Welfare	Q	LF	Sellouts
Benchmark	226.3	5571.5	5759.4	16698.2	28029.0	20.0	70.6	9.2
Uniform	250.8	4629.6	4925.7	19042.4	28597.6	19.2	69.7	7.9
% Di .	10.8	-16.9	-14.5	14.0	2.0	-3.8	-0.9	-1.3

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Counterfactual Results: Dynamic Pricing

Counterfactual Results: Heuristics

1. Lagged-price model
   - Firm assumes last observed price will continue until deadline
2. Deterministic model
   - Firms believe competitors will follow a fixed price path according to the minimum filed price

	Price	Firm 1 Rev.	Firm 2 Rev.	CS	Welfare	Q	LF	Sellouts
Benchmark	100.0	100.0	100.0	100.0	100.0	100.0	100.0	100.0
Lagged	104.6	104.1	105.3	103.3	103.9	100.0	100.1	101.0
Deterministic	98.0	99.4	100.8	108.2	104.9	103.9	101.4	109.2

- Heuristics result in higher CS and welfare

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Conclusion

- We introduce a framework to study dynamic price competition in perishable goods markets
- We show that competitor scarcity is a key driver of price dynamics and captures the incentive to soften competition in the future
- We apply our framework to airlines and find that DP expands output but decreases welfare in the routes studied
- Open questions remain regarding the use of dynamic versioning, loyalty, and the influence of forward-looking buyers