

## THE WELFARE EFFECTS OF DYNAMIC PRICING: EVIDENCE FROM AIRLINE MARKETS

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Airfares fluctuate due to demand shocks and intertemporal variation in willingness to pay. I estimate a model of dynamic airline pricing accounting for both sources of price adjustments using flight-level data. I use the model estimates to evaluate the welfare effects of dynamic airline pricing. Relative to uniform pricing, dynamic pricing benefits early-arriving, leisure consumers at the expense of late-arriving, business travelers. Although dynamic pricing ensures seat availability for business travelers, these consumers are then charged higher prices. When aggregated over markets, welfare is higher under dynamic pricing than under uniform pricing. The direction of the welfare effect at the market level depends on whether dynamic price adjustments are mainly driven by demand shocks or by changes in the overall demand elasticity.

**KEYWORDS:** Dynamic pricing, revenue management, stochastic demand, intertemporal price discrimination, airlines.

### 1. INTRODUCTION

THE AIRLINE INDUSTRY IS WELL KNOWN FOR EMPLOYING complex intertemporal pricing strategies that in principle could be welfare-improving or welfare-reducing. Fare adjustments may arise in part because aggregate demand shocks change the opportunity cost of selling a seat. Airlines raise fares to avoid selling out flights in advance, or fares may fall from one day to the next, after a sequence of low demand realizations. These price adjustments are welfare-improving as they increase capacity utilization. However, fare adjustments may also reflect changes in the aggregate demand elasticity. If late shoppers are business travelers, airlines will raise prices over time to capture these consumers' high willingness to pay through intertemporal price discrimination. This allows airlines to extract more surplus, but it could also lower welfare if seats remain empty more frequently. Existing theoretical frameworks on the welfare effects of price discrimination, including Aguirre, Cowan, and Vickers (2010) and Bergemann, Brooks, and Morris (2015), do not consider sequential markets with limited capacity. However, these works establish that the welfare predictions are ambiguous—depending on demand elasticities and information structure—in the static setting; therefore, it is likely also true when considering dynamic prices. This suggests it is an empirical question whether dynamic airline pricing is on net welfare-increasing.

In this paper, I estimate the welfare effects of dynamic pricing in the airline industry, and in doing so, examine the sources of price adjustments over time. I develop a dynamic pricing model that combines features of stochastic demand and revenue management

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models from operations research with estimation techniques widely used in empirical economics research. I estimate this model using data that track daily prices and seat availabilities for over 12,000 flights in U.S. monopoly markets. I find that if intertemporal price adjustments were not possible, dynamic allocation efficiency is reduced because prices do not respond to demand shocks. Allowing fares to respond to both the changing composition of demand and demand shock realizations expands output and results in a significant reallocation of capacity across time. Leisure consumers benefit, and business consumers are made significantly worse off.

I begin by describing airline pricing practices (Section 2) and documenting stylized facts (Section 3) to motivate my empirical approach. I show that fare patterns are consistent with both standard dynamic pricing models with aggregate demand uncertainty and models of intertemporal price discrimination. I document that these pricing patterns also occur in competitive markets and when considering tickets of different qualities (the pricing of economy versus basic economy, and economy versus first class). This indicates that the forces and trade-offs explored in this paper are relevant for these important extensions. The frequency of price adjustments as well as the presence and depth of advance purchase discount opportunities vary across markets. This motivates an empirical design that includes route-specific parameters.

In Section 4, I develop a structural model that combines features of dynamic pricing and stochastic demand models commonly used in operations research, including Gallego and Van Ryzin (1994), Zhao and Zheng (2000), Talluri and Van Ryzin (2004), and Su (2007), with elements of the discrete, unobserved-heterogeneity utility specification of Berry, Carnall, and Spiller (2006). Discrete heterogeneity demand models are commonly used in airline studies—for example, in Berry and Jia (2010), where demand comprises “business” and “leisure” travelers. Although I tailor the model to reflect institutional features of airline markets, the methodology can be useful for analyzing any perishable goods market with a deadline.

The model contains three key ingredients: (i) a monopolist has fixed capacity and finite time to sell; (ii) the firm faces a stochastic arrival of consumers; and (iii) the mix of consumers is allowed to change over time. The model timing is discrete. Each day before departure, the number of business and leisure arrivals is distributed according to independent Poisson distributions with time- and day-of-week-dependent arrival rates. Consumers know their preferences and solve static utility maximization problems. On the supply side, the monopolist solves a finite-horizon, stochastic dynamic programming problem. Within a period, the firm chooses a price, consumer demand is realized, and the capacity constraint is updated. The process repeats until the perishability date or until the plane is full.

This paper proposes explicitly modeling the pricing decision of the firm to address the well-known issue of missing “no purchase” data, or the number of arrivals who opted not to purchase (Vulcano, van Ryzin, and Chaar (2010)). The identification assumption is that preferences for flights evolve in the same predictable way, but demand shocks can vary (Section 5). This results in variation in seats sold toward the deadline, and the firm’s response to these shocks informs the magnitude of stochastic demand. The route-specific estimates establish that a significant shift in the composition of arriving customers occurs over time and that demand shocks are a meaningful driver of the variation in sales (Section 6). Variation in demand across days of the week matches travel patterns documented with data provided by the Transportation Security Administration (TSA).

I use the model estimates to quantify the welfare effects of dynamic airline pricing and to examine the drivers of dynamic price adjustments (Section 7). I show that relative to

uniform pricing, dynamic pricing expands output (by 2.7 percent), primarily through lower fares offered to leisure travelers. Dynamic pricing allows for increased price targeting such that late-arriving business travelers face significantly higher fares. The reduction in business consumer surplus is sufficiently strong that total consumer welfare is 6.3 percent lower under dynamic pricing compared to uniform pricing. Increased revenues more than offset this decline, and I estimate total welfare to be one percent higher under dynamic pricing compared to uniform pricing.

Dynamic pricing increases welfare in most—but not all—of the monopoly markets studied. I show that the direction of the overall welfare effect depends on which sources of price adjustments drive revenues. Welfare declines under dynamic pricing when price changes are mainly in response to changes in willingness to pay and not in response to demand shocks. Intertemporal price discrimination explains the strong upward trajectory in prices and accounts for two thirds of the revenue gains of dynamic pricing over uniform pricing. The remaining one third comes from responses to demand shocks that occur greater than 21 days before departure, when aggregate price responsiveness is stable but overall demand uncertainty is at its highest. If airlines did not react to demand shocks, price adjustments would occur one third as frequently in the markets studied.

### 1.1. Related Literature

This paper contributes to growing literatures in economics, marketing, and operations research that study intertemporal pricing dynamics. Intertemporal price discrimination can be found in many markets, including video games (Nair (2007)), Broadway theater (Leslie (2004)), storable goods (Hendel and Nevo (2006, 2013)), and concerts (Courty and Pagliero (2012)).<sup>1</sup> Importantly, this paper focuses on third-degree intertemporal price discrimination resulting from time-varying arrivals of different consumer types, instead of second-degree intertemporal price discrimination as a result of screening (Stokey (1979), Bulow (1982), Conlisk, Gerstner, and Sobel (1984), Sobel (1991), Su (2007), Board and Skrzypacz (2016), Öry (2016), Gershkov, Moldovanu, and Strack (2018), Dilmé and Li (2019)). This large theoretical literature focuses on forward-looking buyer behavior, but abstracts from a changing composition of arriving customers over time. McAfee and Te Velde (2006) argued that a change in the elasticity of demand is required to rationalize airfare pricing patterns.

This paper advances consumer demand models that have been extensively used in operations research (Gallego and Van Ryzin (1994), Zhao and Zheng (2000), Talluri and Van Ryzin (2004), McAfee and Te Velde (2006)).<sup>2</sup> I extend baseline Poisson demand models to include discrete random coefficients with time-varying arrivals and empirically estimate both arrivals and preferences. I impose assumptions on demand that can affect welfare estimates, via estimates of willingness to pay (Hendel and Nevo (2006)) or from sorting and the timing of market participation (Sweeting (2012)). For example, Nair (2007) showed that abstracting from forward-looking consumers can lead to profit losses when demand becomes more elastic over time. However, the incentive to wait to purchase decreases if demand becomes more inelastic over time and/or if capacity is constrained.<sup>3</sup>

<sup>1</sup>Lambrecht et al. (2012) provided an overview of empirical work on price discrimination more broadly.

<sup>2</sup>Elmaghraby and Keskinocak (2003) and Talluri and Van Ryzin (2005) provided an overview of revenue management work in operations.

<sup>3</sup>See Soysal and Krishnamurthi (2012) for an example where capacity is constrained. Aguirregabiria (1999) also considered a model with markdowns and studied how pricing varies with remaining inventory.

Gale and Holmes (1993) and Dana (1998) considered capacity-constrained environments and established why firms may offer advance purchase discounts (prices increase over time). Dana (1998) emphasized that aggregate uncertainty increases can increase capacity costs over time and hence, prices, which further decreases the incentive to wait to purchase.

This paper also complements recent airline studies, including Escobari (2012), Alderighi, Nicolini, and Piga (2015), and Puller, Sengupta, and Wiggins (2015). In closely related work, Lazarev (2013) estimated the welfare effects of intertemporal price discrimination in airline markets by modeling how changes in willingness to pay over time affect the firm's choice of the distribution of fares to offer, prior to the realization of demand shocks. In this project, I investigate the firm's responses to demand shocks over time (the "revenue management" problem); however, I abstract away from the set of fares chosen (see Section 2). Chen (2018) extended the methodology presented here to investigate competitive dynamics. Aryal, Murry, and Williams (2018) utilized survey data to examine dynamic pricing in international airline markets where seats have different qualities.

Finally, concurrent works provide new insights on the effects of dynamic pricing in other industries. D'Haultfœuille et al. (2018) quantified the welfare effects of revenue management in the French railway system. Cho et al. (2018) extended the framework presented here to allow for cancellations and quantified the welfare effects of dynamic pricing in the hotel industry. Pan (2019) extended this framework to costly price adjustments.

## 2. INDUSTRY SETTING AND PRICING PRACTICES

In this section, I provide a short overview on airline pricing practices to motivate my empirical approach. Additional details on industry practices can be found in McGill and Van Ryzin (1999) and Gallego and Topaloglu (2019).

Flight prices depend on (1) plane capacity, (2) filed fares, and (3) revenue management decisions. Filed fares (input 2) are the pre-set price levels at which the airline is willing to sell tickets for a flight, and inventory allocation (input 3) is the number of tickets allocated to each fare level. Each of these decisions is made by separate departments, holding the other departments' choices fixed. This paper focuses on modeling dynamic prices arising from (3).

A carrier's network-planning department determines which markets are served, and assigns capacity and flight frequencies. These decisions typically occur well in advance of the departure date. Although I do observe aircraft substitutions in the collected data, I find that they are not correlated with flight loads.<sup>4</sup> It is more likely that these gauge adjustments occur for operational reasons. This motivates my assumption that initial capacity is exogenous.

The pricing department determines filed fares, or prices and associated ticket restrictions, that consumers may face. A fare class (or booking class) is a single- or double-letter code to denote broad ticket characteristics—for example, deeply discounted economy

<sup>4</sup>I observe that 3.0% of flights experience a change in aircraft in the sixty days before departure. Seventy-nine percent of occurrences happen within the last two days before departure. These changes do not seem to be associated with flight loads. I cannot reject the null hypothesis that flights which see an upgauge (increase in capacity) have flight loads higher than the average load factor for that route and vice versa. In the former case,  $p = 0.999$ ; in the latter case,  $p = 0.197$ . Flights which see an upgauge actually have lower load factors than the route average.

versus full-fare economy. When the additional ticket restrictions are incorporated, this results in what is called a fare basis code (the fare class, price, and restrictions). A common ticket restriction is an advance-purchase (AP) requirement, or a restriction that requires consumers to purchase by a deadline. These are commonly observed at 3, 7, 10, 14, 31, and 30 days before departure. I incorporate this feature in the empirical model by having firms choose among a discrete set of time-varying fares. Finally, the revenue management department dynamically determines fare availability, among the fare classes set by the pricing department. This process involves setting the number of seats available for purchase for each fare class over time. Allocations are determined using techniques developed in operations research, including the well-known ESMR-b heuristic, in order to make them tractable (Belobaba (1987, 1989, 1992), Belobaba and Weatherford (1996)). Phillips (2005) provided an overview of these approaches. Importantly, the allocation decision takes fares and forecasts as inputs, which are also the inputs I consider in my model. Although I do not model inventory allocations explicitly, I note that the average number of seats booked per day is less than one. This means customers are unlikely to face intra-day price dispersion due to fare classes closing.<sup>5</sup>

### 3. DATA

For this study, I collect data from travel management companies, travel meta-search engines, and airline websites.<sup>6</sup> I merge daily one-way fares, censored fare class allocations, and recovered bookings information by comparing airline seat maps across consecutive days.<sup>7</sup> I show in Appendix C of the Supplemental Material (Williams (2022)) that the measurement error in using seat maps to proxy bookings may be small.

In the following subsections, I discuss route selection (Section 3.1) and document a set of new descriptive facts on dynamic pricing in the airline industry (Section 3.2).

#### 3.1. Route Selection

I use the publicly available Department of Transportation DB1B tables to select non-stop markets to study. The DB1B tables contain a 10-percent sample of domestic U.S. ticket purchases and are at the quarterly level. I define a market in the DB1B as an origin-destination (OD), quarter, year, and filter based on the following criteria:

- (i) there is only one carrier operating nonstop;
- (ii) there is no nearby alternative airport serving the same destination;
- (iii) total quarterly traffic is greater than 600 passengers;
- (iv) total quarterly traffic is less than 45,000 passengers;
- (v) at least 35 percent of traffic is nonstop;
- (vi) at least 35 percent of traffic is not connecting.

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<sup>5</sup>Many RM systems are designed such that several fares are available at any given point in time, which is called nesting (Phillips (2005)). I assume that consumers purchase the lowest available economy-class fare.

<sup>6</sup>The data come from Alaska Airlines, BCD Travel, ExpertFlyer, Fare Compare, JetBlue Airways, United Airlines, and Yaptia. The airline websites provide seat availabilities, seat maps, and fares; ExpertFlyer reports filed fares, seat availabilities, and seat maps; BCD Travel reports seat availabilities; Fare Compare reports filed fares, and Yaptia tracks daily fares. Data were collected in 2012 and again in 2019.

<sup>7</sup>For example, G5 means the active G-class fare has five available seats; however, airlines censor these data at seven or none, depending on the carrier.

Criteria (i) and (ii) narrow the focus to monopoly markets in terms of nonstop flight options. Criteria (iii) and (iv) remove infrequently-served markets, and the upper limit on traffic keeps data collection manageable. When I implement these criteria, the resulting number makes up roughly 14 percent of OD traffic in the United States. In addition, quarterly revenues for these markets are roughly \$2.3 billion. Criterion (v) addresses the potential for alternative flight options, including connecting flights for each OD. Criterion (vi) addresses how fares are assigned to observed changes in remaining capacity. Criteria (v) and (vi) filter markets to select homogeneous itineraries, primarily composed of non-connecting, nonstop trips. The collected data feature markets where these statistics average above 75 percent. Note that criteria (v) and (vi) are negatively correlated because ODs with very high nonstop traffic percentages tend to be short distance flights to hubs with passengers connecting to other destinations.

I collect data on fifty nonstop OD pairs which satisfy the selection criteria above. In addition, to compare the descriptive evidence, I select six duopoly markets with nonstop service.<sup>8</sup> In Supplemental Material Appendix B, I present additional route selection information, market-level statistics, and comparisons with the entire DB1B sample. All of the routes studied either originate or end at Boston, MA; Portland, OR; or Seattle, WA. Most of the sample covers markets served by Alaska Air Lines (JetBlue and Delta are the other carriers studied).

JetBlue does not oversell flights.<sup>9</sup> I use this feature of the data to simplify the pricing problem presented in the next section. Because many of the markets studied feature coach-only flights, I am able to capture all sales and control for one aspect of versioning (first class versus economy class). Finally, the sample focuses on airlines that allow consumers to select seats before departure. Many carriers now charge fees to choose seats when traveling on restrictive coach tickets.<sup>10</sup>

In contrast with Jetblue, Alaska and Delta offer first class in several of the markets studied—first class appears in 58 percent of the sample, with the average cabin size being twelve seats of the plane. I provide some descriptive analysis of first-class pricing (see Supplemental Material Appendix A), but I do not pursue versioning in the model. Although Alaska does allow for overselling, the carrier has an average denied-boarding rate (overselling) among the major airlines.<sup>11</sup>

### 3.2. Descriptive Evidence

#### 3.2.1. Summary Statistics

The sample contains over 12,000 flights, each tracked for the last sixty days before departure. The sample contains 738,625 observations, as well as over five million connecting fares. Data collection occurred over two six-month periods (March 2012–August 2012, March 2019–August 2019).

<sup>8</sup>Two markets, (Boston, MA—Kansas City, MO) and (Boston, MA—Seattle, WA) were both monopoly and duopoly markets. The former market originally had nonstop service offered by Delta and Frontier. Frontier exited early on in the sample and Delta became the only carrier flying nonstop. The latter market was very briefly served by just Alaska, prior to the entry of JetBlue.

<sup>9</sup>In the legal section of the JetBlue website, under “Passenger Service Plan”: “JetBlue does not overbook flights. However some situations, such as flight cancellations and reaccommodation, might create a similar situation.”

<sup>10</sup>The JetBlue data were collected before the introduction of Blue Basic seats, which feature a fee to select seats. This is also true for Delta. Alaska’s restrictive coach tickets are called Saver fares. These fares do allow for limited seat selection in the coach cabin. I observe availability of these seats in 98 percent of seat maps.

<sup>11</sup>Source: Air Travel Consumer Report, accessed February 2020.

TABLE I  
SUMMARY STATISTICS FOR THE DATA SAMPLE.

Variable	Mean	Std. Dev.	Median	5th Pctile.	95th Pctile.
One-way fare (\$)	232.60	139.33	190.18	89.00	504.00
Load factor	88.76	13.52	93.42	59.21	100.00
Daily booking rate	0.68	1.94	0.00	0.00	4.00
Daily fare change (\$)	3.43	31.25	0.00	0.00	46.00
Unique fares (per itin.)	6.97	2.16	7.00	4.00	11.00

*Note:* Summary statistics for 12,119 flights tracked between 3/2/2012–8/24/2012 and 3/21/2019–8/31/2019. Each flight is tracked for sixty days before departure. The total number of observations is 738,625. Load factor is reported between zero and 100 the day of departure. The daily booking rate and daily fare change compares consecutive days.

I present summary statistics in Table I. The average one-way fare in the sample is \$233. Load factor is the number of occupied seats divided by capacity on the day of departure. Average load factor is 89 percent, ranging from 70 percent to 98 percent, by market. I observe that 15.7 percent of flights sell out. There is considerable variation in load factor within a market. The coefficient of variation (CV) of within-market load factors ranges between 0.04 and 0.27. CVs are higher well in advance of the departure date; the reduction over time is consistent with price adjustments to fill unsold seats. The  $R^2$  of a regression of load factor on origin-destination-flight number and departure date fixed effects is 0.56, which suggests the presence of flight-level demand shocks. I estimate the average booking rate to be 0.68, with the 5th and 95th percentiles of zero and four seats per flight, respectively. Sixty-one percent of seat maps do not change across consecutive days. On average, each itinerary reaches seven unique fares and experiences 10.4 fare changes. This implies that fares fluctuate up and down, usually a few times, and that the number of realized prices is relatively small. For the markets studied, the median number of daily departures is one, and the mean is two. Finally, I examine individual seat map changes and estimate the number of passengers per booking to be 1.37. This motivates the unit demand assumption in the model.<sup>12</sup>

There are a few differences across collected samples. Relative to the data collected in 2012, the 2019 data contain substantially lower fares (−\$170); the booking rate and daily price increase are slightly lower (−0.2; −\$0.3); slightly fewer fares are offered per flight (−0.5); and load factors are lower (−7%). These differences cannot be attributed to a single factor, as the carriers and markets differ across the samples. In Section 7, I highlight how the welfare estimates vary across markets.

### 3.2.2. Dynamic Prices

In Figure 1(a), I plot mean fares and load factors by day before departure. The overall trend in prices is strongly positive, with fares nearly doubling in sixty days. The noticeable jumps occur when crossing advance-purchase (AP) restrictions. The booking curve for flights in the sample is smooth over time and starts to level off around 80

<sup>12</sup>Each row in the data has at most six seats, and I assume whenever more than two seats in a row become occupied, this is a party traveling together. This occurs in less than 8 percent of bookings. For rows in which two seats become occupied, I check if the seats are adjacent. Seats with passengers or space in-between are assumed to be two single-passenger bookings. This removes 18 percent of the two-passenger bookings. Thus, as a potential lower bound, I find that 55 percent of passengers, or 75 percent of bookings, are single-passenger bookings.

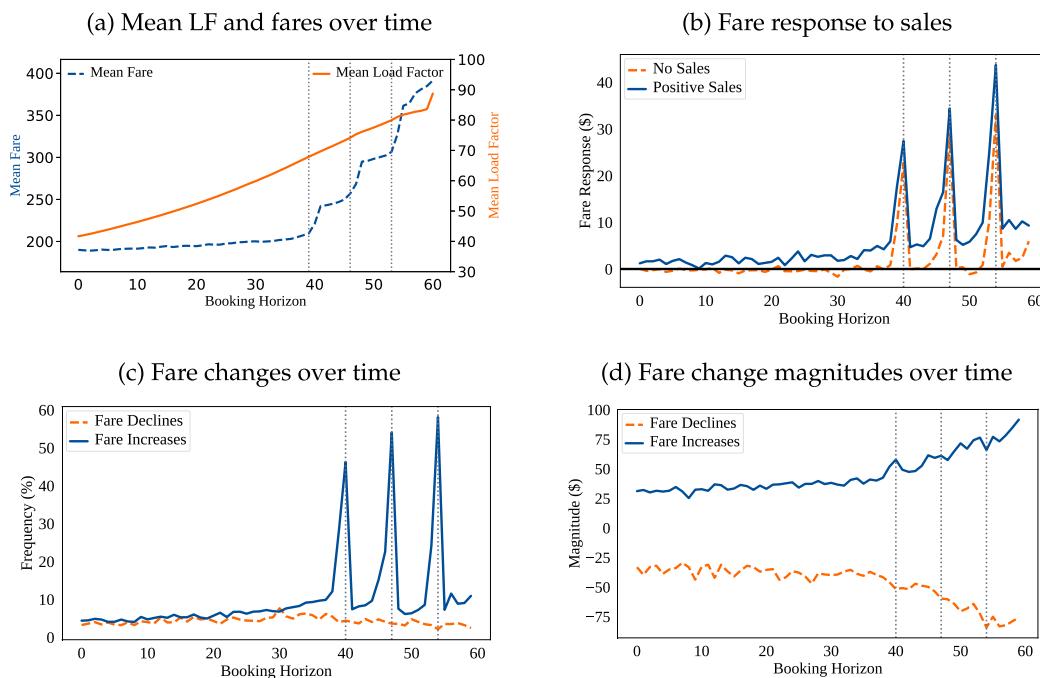


FIGURE 1.—Average fares, load factors, and fare response to sales. Notes: (a) Average fare and load factor by day before departure. The vertical lines correspond to advance-purchase discount periods (fare fences). (b) Average fare changes as a response to sales by day before departure. The vertical lines correspond to advance-purchase discount periods (fare fences). The horizontal line indicates no fare response. The top panel shows the percentage of itineraries that see fares increase or decrease by day before departure. The lower panel plots the magnitude of the fare declines and increases by day before departure. The vertical lines correspond to advance-purchase discount periods (fare fences).

percent a few days before departure. There is a spike in load factor, of around 5 percent, the day of departure. Although this spike could be due to measurement error (consumers who were not assigned seats in advance are assigned seats at check-in), I also find that there is a sharp decline in economy seat availability at this time. This suggests that last-minute bookings do occur (see Supplemental Material Appendix A for more details).

In Figure 1(b), I establish an important link between bookings and price adjustments. The graph separates out two scenarios: (1) a flight experiences positive sales in the previous period; and (2) there are no sales in the previous period. Fares respond to demand shocks as predicted by standard dynamic pricing models: When bookings occur, prices tend to rise; when bookings do not occur, prices stay the same, or fall. However, close to the departure date and regardless of bookings, prices increase. This suggests late-arriving consumers are less price-sensitive and airlines engage in intertemporal price discrimination.

In Figure 1(c), I plot the frequency of fare increases and decreases over time. The numbers of fare hikes and fare declines are roughly even, except when advance-purchase (AP) discounts expire. The use of AP discounts is not universal—for example, less than 60 percent of flights experience a price increase at the 7-day AP requirement. Figure 1(d) shows that fare change magnitudes increase over time.

The pricing patterns documented here also occur in competitive markets and when considering tickets of different qualities, that is, first class and basic economy. I highlight two findings here; additional analysis appears in Supplemental Material Appendix A. First, the magnitude of systematic fare increases is lower, and the number of systematic fare decreases is higher, in competitive markets. This may suggest that the role of intertemporal price discrimination is reduced in competitive markets.<sup>13</sup> Second, all ticket qualities respond to AP restrictions; the gap between economy and basic economy grows over time, and the availability of basic economy fares decreases. Therefore, economy cabin fares rise over time for two reasons: economy fares become more expensive and restrictive economy tickets are no longer offered.

I also note that there is considerable variation in pricing patterns across markets. In Figure 7 and Figure 8 in Supplemental Material Appendix A, I plot average fares and the average percentage change in fares over time for each route separately. Price levels, the timing of AP restrictions, and the depth of AP discounts vary by route. This motivates allowing for route-specific parameters in the model.

#### 4. AN EMPIRICAL MODEL OF DYNAMIC AIRLINE PRICING

##### 4.1. *Model Overview*

A monopolist airline offers a flight for sale in a series of sequential markets. More precisely, I will define the markets for a flight on a particular departure date, and I will abstract away from potential correlations in demands across departure dates and other flight options, including connecting flights and other nonstop itineraries. The sales process for every market evolves over a finite and discrete time horizon  $t \in \{0, \dots, T\}$ . Period 0 corresponds to the first sales period, and period  $T$  corresponds to the flight departure date. Initial capacity for the flight is exogenous, and the firm is not allowed to oversell. Unsold capacity on the day of the flight ( $t = T$ ) is scraped with zero value. The only costs modeled are the opportunity costs of remaining capacity, and all other costs are normalized to zero.

Each period  $t$ , the airline first offers a single price for the flight, and then consumers arrive according to a stochastic process specified in the next subsection. Each arriving consumer is either a business traveler or a leisure traveler; business travelers are less price sensitive than leisure travelers, and the proportion of each type is allowed to change over time. Note that the terms “business” and “leisure” are used simply to describe a consumer type; they do not identify consumers based on a travel need. Upon entering the market, all uncertainty about travel preferences is resolved.<sup>14</sup> Arriving consumers either purchase a ticket or exit the market. If demand exceeds remaining capacity, tickets are randomly rationed. Consumers who are not selected receive the outside option. This ensures that the capacity constraint is not violated. Consumers do not cancel bookings, so remaining

<sup>13</sup>This finding complements the work of Siegert and Ulbricht (2020), who used fare data to show that competition is correlated with a flattening of prices over time. Dana and Williams (2021) showed in a theoretical model that strong competitive effects work to equalize prices across periods and that inventory controls can facilitate intertemporal price discrimination in oligopoly. If the role of intertemporal price discrimination is reduced in competitive markets, this may suggest the efficiency aspect of dynamic pricing may be higher compared to the markets studied in this paper.

<sup>14</sup>This approach differs from earlier theoretical work such as Gale and Holmes (1993), as well as some empirical work such as Lazarev (2013), in which existing consumer uncertainty can be resolved by delaying purchase. This assumption is motivated by the fact that I do not find significant bunching in bookings before the expiration of AP fares (see Supplemental Material Appendix D).

capacity is monotonically decreasing.<sup>15</sup> This process repeats each sales period. The firm is forward looking and solves the dynamic program.

#### 4.2. Demand

Each day before the flight leaves,  $t = 0, 1, \dots, T$ , a stochastic process brings a discrete number of new consumers to the market.  $\tilde{M}_t$  denotes the arrival draw. The demand model is based on the two-consumer type discrete choice model of Berry, Carnall, and Spiller (2006), which is frequently applied to airline data. Consumer  $i$  is a business traveler with probability  $\gamma_t$  or a leisure traveler with probability  $1 - \gamma_t$ . Consumer  $i$  has preferences  $(\beta_i, \alpha_i)$  over product characteristics ( $x_{jt} \in \mathbb{R}^K$ ) and price ( $p_{jt} > 0$ ), respectively.

I assume utility is linear in product characteristics and price. If consumer  $i$  purchases a ticket on flight  $j$ , she receives utility  $u_{ijt} = x_{jt}\beta_i - \alpha_i p_{jt} + \varepsilon_{ijt}$ . If she does not fly, she receives normalized utility  $u_{i0t} = \varepsilon_{i0t}$ . Each arriving consumer solves a straightforward maximization problem: consumer  $i$  selects flight  $j$  if and only if  $u_{ijt} \geq u_{i0t}$ .

Define  $y_t = (\alpha_i, \beta_i, \varepsilon_{ijt}, \varepsilon_{i0t})_{i \in 1, \dots, \tilde{M}_t}$  to be the vector of consumer preferences. Suppressing the notation on product characteristics for the rest of this section, demand for flight  $j$  at  $t$  is defined as  $Q_{jt}(p, y_t) := \sum_{i=0}^{\tilde{M}_t} 1[u_{ijt} \geq u_{i0t}] \in \{0, \dots, \tilde{M}_t\}$ , where  $1(\cdot)$  denotes the indicator function. Demand is integer valued; however, it may be the case that there are more consumers who want to travel than there are seats remaining. That is,  $Q_{jt}(p, y) > c_{jt}$ , where  $c_{jt}$  is the number of seats remaining at  $t$ . Since the firm is not allowed to oversell, in these instances, I assume that remaining capacity is rationed by random selection. Specifically, consumers arrive and choose to fly or not. The capacity constraint is then checked. If demand exceeds remaining capacity,  $c_{jt}$  consumers are randomly selected from the set of consumers who chose to travel, and the rest receive their outside options. Although this assumption may appear restrictive, the daily booking rate is less than one.

Without the ability to oversell and incorporating the rationing rule, expected sales are formed by integrating over the distribution of  $y_t$ ,

$$Q_{jt}^e(p; c) = \int_{y_t} \min(Q_{jt}(p, y_t), c) dF_t(y_t).$$

I incorporate a number of parametric assumptions. First, following McFadden (1973), I assume that the idiosyncratic preferences of consumers are independently and identically distributed according to a Type-1 Extreme Value (T1EV) distribution. This assumption implies that the individual choice probabilities are equal to

$$\pi_{jt}^i(p_{jt}) = \frac{\exp(x_{jt}\beta_i - \alpha_i p_{jt})}{1 + \exp(x_{jt}\beta_i - \alpha_i p_{jt})}.$$

Let  $B$  denote the business type and  $L$  denote the leisure type. Recall that the probability of a consumer being type  $B$  is  $\gamma_t$ . Then,  $\gamma_t \pi_{jt}^B$  defines the purchase probability that a consumer is of the business type and wants to purchase a ticket;  $(1 - \gamma_t) \pi_{jt}^L$  is similarly defined. Hence, integrating over consumer types, product shares is equal to  $\pi_{jt}(p_{jt}) =$

<sup>15</sup>The average number of cancellations per flight in the data is less than two.

$\gamma_t \pi_{jt}^B(p_{jt}) + (1 - \gamma_t) \pi_{jt}^L(p_{jt})$ . Next, I assume that consumers arrive according to a Poisson distribution,  $\tilde{M}_t \sim \text{Poisson}_t(\mu_t)$ . The arrival rates,  $\mu_t$ , are also allowed to change over time. Hence, daily demands will depend on both the arrival process as well as preferences of consumers entering the market. Conditional on price, it follows that demand is also Poisson,  $Q_{jt} \sim \text{Poisson}_t(\mu_t \pi_{jt})$ . The probability that  $q$  seats are demanded on flight  $j$  at time  $t$  is equal to

$$\Pr_t(Q_{jt} = q; p_{jt}) = \frac{(\mu_t \pi_{jt})^q \exp(-\mu_t \pi_{jt})}{q!}.$$

With these probabilities defined and noting that demand is censored at remaining capacity, expected sales is equal to<sup>16</sup>

$$\begin{aligned} Q_{jt}^e(p_{jt}; c_{jt}) &= \sum_{q=0}^{c_{jt}-1} \Pr_t(Q_{jt} = q; p_{jt}) q + \sum_{q=c_{jt}}^{\infty} \Pr_t(Q_{jt} = q; p_{jt}) c_{jt} \\ &= \sum_{q=0}^{c_{jt}-1} \frac{(\mu_t \pi_{jt})^q \exp(-\mu_t \pi_{jt})}{q!} q \\ &\quad + \sum_{q=c_{jt}}^{\infty} \frac{(\mu_t \pi_{jt})^q \exp(-\mu_t \pi_{jt})}{q!} c_{jt}. \end{aligned}$$

#### 4.3. Monopoly Pricing Problem

The monopolist maximizes expected revenues of flight  $j$  (subscript suppressed) over a series of sequential markets. Each day before departure, the firm chooses to offer a single price before the arrival of customers. Using the institutional features discussed in Section 2, I assume the firm chooses a price from a discrete set, denoted  $A(t)$ . The set may change over time due to advance-purchase restrictions.<sup>17</sup>

The pricing decision is based on the states of the flight: seats remaining; time left to sell; flight characteristics; and idiosyncratic shocks  $\omega_t \in \mathbb{R}^{A(t)}$ , which are assumed to be independently and identically distributed following a Type-1 Extreme Value (T1EV) distribution, with scale parameter  $\sigma > 0$ . These shocks are assumed to be additively separable to the remainder of the per-period payoff function, which are expected revenues,  $R_t^e(p_t; c_t) = p_t \cdot Q_t^e(p_t; c_t)$ .

The firm's problem can be written as a dynamic discrete choice model. Let  $V_t(c_t, \omega_t)$  be the value function given the state  $(t, c_t, \omega_t)$ . Denoting  $\delta$  as the discount factor, the

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<sup>16</sup>This is can be equivalently written as

$$Q_{jt}^e(p_t; c_{jt}) = \sum_{q=0}^{c_{jt}-1} \frac{(\mu_t \pi_{jt})^q \exp(-\mu_t \pi_{jt})}{q!} q + \left(1 - \sum_{q=0}^{c_{jt}-1} \frac{(\mu_t \pi_{jt})^q \exp(-\mu_t \pi_{jt})}{q!}\right) c_{jt}.$$

<sup>17</sup>In principle, the model can be extended to an environment where the monopolist offers multiple flights ( $J$ ). Two assumptions that can be used so that the model closely follows the exposition here are: (1) consumers do not know remaining capacities when solving the utility maximization problem, (2) when capacity is rationed, consumers not selected receive the outside option. It follows that conditional on price,  $Q_{jt}$  is independent of  $Q_{j't}$  for  $j' \neq j$  and that  $Q_{jt} \sim \text{Poisson}_t(\mu_t \pi_{jt})$ . The complexity of the dynamic program increases by  $\dim[A(\cdot)]^{(J-1)}$  relative to the complexity of the single-flight problem.

dynamic program (DP) of the firm is

$$V_t(c_t, \omega_t) = \max_{p \in A(t)} \left( R_t^e(p; c_t) + \omega_{tp} \right. \\ \left. + \delta \int_{\omega_{t+1}, c_{t+1} | \omega_t, p, c_t} V_{t+1}(c_{t+1}, \omega_{t+1}) dH_t(\omega_{t+1}, c_{t+1} | \omega_t, p, c_t) \right).$$

Because the firm cannot oversell, capacity transitions as  $c_{t+1} = c_t - \min\{Q_t, c_t\}$ , where  $Q_t$  is the realized demand draw. The firm faces two boundary conditions. The first is that once the airline hits the capacity constraint, it can no longer sell seats for that flight. The second is that unsold seats are scrapped with zero value.

I follow Rust (1987) and assume that conditional independence is satisfied. This means that the transition probabilities are equal to  $h_t(\omega_{t+1}, c_{t+1} | \omega_t, p_t, c_t) = g(\omega_{t+1})f_t(c_{t+1} | p_t, c_t)$ . The capacity transitions  $f_t(\cdot)$  can be derived from the probability distribution of sales described in the previous section. I return to this momentarily.

By assuming the unobservable is distributed T1EV, along with conditional independence, the conditional value function is equal to

$$\text{EV}_t(p_t, c_t) = \int_{c_{t+1}} \left[ \sigma \ln \left( \sum_{p_{t+1} \in A(t+1)} \exp \left( \frac{R_{t+1}^e(c_{t+1}, p_{t+1}) + \text{EV}_{t+1}(p_{t+1}, c_{t+1})}{\sigma} \right) \right) \right] \\ \times f_t(c_{t+1} | c_t, p_t) + \sigma \phi,$$

where  $\phi$  is Euler's constant. The conditional choice probabilities also have a closed form and are computed as

$$\text{CCP}_t(p_t; c_t) = \frac{\exp\{(R_t^e(p_t, c_t) + \text{EV}_t(p_t, c_t))/\sigma\}}{\sum_{p'_t \in A(t)} \exp\{(R_t^e(p'_t, c_t) + \text{EV}_t(p'_t, c_t))/\sigma\}}.$$

Before continuing, I discuss the connection between the notation  $\Pr_t(Q_{jt} = q; p_{ji})$  and  $f_t(c_{t+1} | c_t, p_t)$ . Consider a two-period model with a single seat. In the first period, expected revenues are simply  $\Pr_1(Q_1 \geq 1; p_1) \cdot 1 \cdot p_1$  because at most one seat can be sold. The demand probabilities exactly inform the capacity transition probabilities under conditional independence, that is,  $f_1(c_2 | 1, p_1) = [\Pr_1(Q_1 \geq 1; p_1), \Pr_1(Q_1 = 0; p_1)]$ . With probability  $\Pr_1(Q_1 \geq 1; p_1)$ , the seat sells today and nothing is available for sale tomorrow, and with probability  $\Pr_1(Q_1 = 0; p_1)$ , the seat is not sold today and is available for purchase tomorrow. The optimal price that affects these probabilities depends on the arrival process and product shares. Time is a deterministic state. Note, in the general model, any transition probability where  $c_{t+1} > c_t$  is equal to zero because capacity is monotonically decreasing.

I utilize a dynamic discrete choice model because fares are chosen from a pre-determined set—as discussed in Section 2, fares are assigned by the pricing department. The supply model can be interpreted as modeling the decisions of revenue management, conditional on the choices made by other airline departments. In particular, the model takes the initial capacity and observed fares as given. Given the set of fares, identification assumes that the pricing choice is optimal. This is perhaps not unreasonable given the sophisticated pricing models used by airlines (McGill and Van Ryzin

(1999)). However, airlines operate complex networks and the pricing decision for a single flight may be impacted by forces not accounted for in the model—for example, a persistent, unobserved shock to the network could overstate the role of capacity in the model.

Another potential limitation of the model is that consumers are assumed to make a one-shot decision upon entering the market, and market participation is exogenous. This can impact estimated demand elasticities (Hendel and Nevo (2006)). If increasing prices are also used to shape consumer expectations, my estimates may overstate the proportion of business travelers and understate their price sensitivity. In addition, if consumers learn about their preferences toward the deadline, this will cause opportunity costs to rise over time (Dana (1998)), which may act to reinforce this potential overstatement.

## 5. ESTIMATION

I assign the discount factor to be 1. Arrival rates,  $\mu_t^d$ , vary by day before departure ( $t$ ) and departure date ( $d$ ) in the following way. Over the booking horizon, I let arrival rates vary corresponding to observed advance-purchase discount intervals, which are then scaled according to the day of the week of the departure date,

$$\mu_t^d = \begin{cases} \mu^{\text{dow}} \cdot \mu_1, & \text{greater than twenty-one days before departure (21+);} \\ \mu^{\text{dow}} \cdot \mu_2, & \text{fourteen to twenty-one days before departure (20–14);} \\ \mu^{\text{dow}} \cdot \mu_3, & \text{seven to fourteen days before departure (13–7); and} \\ \mu^{\text{dow}} \cdot \mu_4, & \text{within seven days before departure (6–0).} \end{cases}$$

Here,  $\mu^{\text{dow}}$  is a day-of-the-week shifter for each departure date. Mondays are normalized to 1, and parameters are estimated for Tuesday through Sunday. In total, there are ten arrival rate parameters per route.

I introduce flexibility in the composition of consumer types by assuming

$$\Pr_t(\text{Business}) = \gamma_t = \frac{\exp(\gamma_0 + \gamma_1 t + \gamma_2 t^2)}{1 + \exp(\gamma_0 + \gamma_1 t + \gamma_2 t^2)}, \quad \forall t = 0, \dots, T.$$

This parametric specification allows for non-monotonicity in consumer types over time, while keeping the function bounded between zero and 1. Each route has three consumer-type parameters.

Finally, I assume consumer utility is of the form

$$u_{ijt} = \beta^{\text{dow}_j} - \alpha_i p_{jt} + \varepsilon_{ijt},$$

where  $\beta^{\text{dow}_j}$  is a day-of-the-week preference for the departure date. There are nine preference parameters per route.

To reduce computational burden, I construct a single pricing menu for each route by reducing the dimensionality of observed prices. The average number of unique fares observed per flight is less than seven; however, I observe price differences across departure dates within a route, sometimes by a single dollar. To avoid constructing likelihoods for each flight individually, I first cluster all observed prices for a given route using k-means with a minimum in-sample fit threshold of 99 percent. This results in pricing choice sets that range in size from five to eleven. I then map each observed

fare to its clustered fare, creating pricing menus that only vary by route and day before departure. Because lower-priced fares are typically not offered close to the departure date, this procedure preserves advance-purchase discounts, albeit with clustered fares.

Given a set of flights ( $F$ ) each tracked for ( $T$ ) periods, the log-likelihood for the data is given by

$$\max_{(\beta, \alpha, \gamma_t, \mu_t, \sigma)} \sum_F \sum_T \log(\text{CCP}_t(p_t; c_t)) + \log(f_t(c_{t+1}|c_t, p_t)).$$

I maximize this objective separately for each route. To increase sample sizes, I group together the directional traffic of the city pairs, which means demand does not vary by direction. In Supplemental Material Appendix B, I show that directional prices are similar. For any candidate parameter vector, I calculate the censored-Poisson demand functions, expected revenues, and transition probabilities. I then solve for the value functions using the recursive structure of the firm's problem, which defines the conditional choice probabilities (CCP).<sup>18</sup>

### 5.1. Identification

The key identification challenge of the paper is to separately identify the demand parameters from the arrival process. This challenge was pointed out in Talluri and Van Ryzin (2004), for example. The issue arises because without proprietary search data to pin down the arrival process, an increase in arrivals could instead be inferred as inelastic demand. For example, the sale of two seats could have occurred because two consumers arrived and both purchased, or because twenty consumers arrived and a tenth purchased. This is sometimes called the lack of “no purchase” data.

This paper proposes incorporating the supply-side model in order to separately identify the demand parameters and the arrival process. In particular, I assume that the firm optimally prices given seats remaining, time left to sell, and the unobservables. Preferences are assumed to evolve in the same predictable way, but demand shocks can vary for each flight toward the deadline. This results in variation in seats sold over time, and the firm's response to these shocks informs the magnitude of stochastic demand. That is, by solving the firm's problem, I recover the opportunity cost of capacity, and along with the pricing decision, I back out the overall demand elasticity. By tracing out price adjustments from variation in seats remaining given time to sell and variation over time given a constant capacity constraint, I separate the incentives to adjust prices in response to demand shocks versus the overall demand elasticity.

In Figure 1(b), I provide graphical evidence of the identification argument. Given stochastic demand, we would expect prices to rise when demand exceeds expectations and fall after a sequence of low demand realizations. This is shown in the figure as the solid (blue) line is above zero, and the dashed (orange) line is at or below zero. However, Figure 1(b) shows that prices sharply rise close to the departure date and regardless of bookings. This sharp rise in prices, regardless of the scarcity of seats, suggests a change in demand elasticity. That is, consumers who shop late are less price sensitive than those who shop early.

<sup>18</sup>Estimation uses analytical gradients computed via the module JAX using GPUs (set to 64-bit) and the solver Knitro. I select the Sequential Quadratic Programming (SQP) algorithm. I first use parallel multi-start, selecting 200 random initial starting values, using relaxed parameter bounds. I verify the obtained solutions using a second estimation script with tighter bounds centered around the first solution.

TABLE II  
DEMAND RESULTS SUMMARY TABLE.

Parameter	Mean	Std. Dev.	Median	25th Pctile.	75th Pctile.
DoW preferences	5.77	4.67	4.72	3.27	6.99
Leisure price sensitivity	-3.48	3.46	-2.37	-3.57	-1.71
Business price sensitivity	-1.61	1.72	-1.24	-1.72	-0.74
Prob(Business)	0.26	0.28	0.15	0.03	0.38
DoW arrival rates	2.02	2.36	1.35	0.93	2.01

*Note:* Summary of demand estimates. See Table IV–Table VI for all parameter estimates. DoW preference statistics are computed using all  $\beta_r^d$  parameters. Leisure and Business price sensitivity statistics are computed using all  $\alpha_{L,r}$  and  $\alpha_{B,r}$  parameters. Probability of business uses the predicted values of the Logit specification at the  $\gamma_{t,r}$  level. DoW arrival rates are computed using all  $\mu_{t,d}^d$  parameters.

## 6. EMPIRICAL RESULTS

I present complete parameter estimates in Table IV–Table VI in the Appendix.<sup>19</sup> Each table reports results for a set of markets and has three sections. The first section, “Logit Demand,” reports day-of-the-week preferences, price sensitivities, and the parameters governing the probability on consumer types over time ( $\gamma_t$ ). The second section, “Poisson Rates”, reports mean arrival rates for each of the specified time intervals for Monday departures. The rows labeled “DoW Effect” contain the multiplicative factor for Tuesday through Sunday departures. Finally, the last row, “Firm Shock”, reports estimates of the scaling parameter. I summarize the demand estimates in Table II.

I estimate that almost all preference parameters are statistically significant at conventional levels.<sup>20</sup> The parameter estimates suggest that, on average, leisure consumers are over twice as price sensitive as business consumers, and business consumers are willing to pay up to 125 percent more in order to secure a seat.<sup>21</sup> I estimate meaningful differences in demand across departure dates due to day-of-the-week effects. In Figure 2(a), I plot the average willingness to pay for the days of the week, relative to the minimum estimated day-of-the-week preference. The histogram is over routes. I estimate that willingness to pay is highest for flights departing on Sunday, Friday, Thursday, Monday (in that order; highest to lowest). Saturday, Tuesday, and Wednesday are estimated to be the most off-peak days. These values closely match day-of-the-week patterns found using security checkpoint data from the Transportation Security Administration (TSA).<sup>22</sup>

Fitted values of the probability that a customer is of the business type ( $\gamma_t$ ) are shown in Figure 2(b). The plots depict the average (across routes) business share over time, as well as the interquartile range and the fifth and ninety-fifth percentiles over routes. Most routes exhibit increasing  $\gamma_t$  processes over time. On average, 10 percent of early

<sup>19</sup>I do not estimate demand in competitive routes or routes with infrequent service. The excluded routes are: Boston, MA—Seattle, WA; Boston, MA—Portland, OR; Portland, OR—Sacramento, CA; Portland, OR—Lihue, HI; and Portland, OR—Palm Springs, CA. In addition, Omaha, NE—Seattle, WA is excluded from the analysis due to numerical stability issues and resource constraints.

<sup>20</sup>The exception being Oklahoma City, OK—Seattle, WA. All random starts converge to the same maximum; however, several parameters are estimated to be insignificant.

<sup>21</sup>The mean ratio of price sensitivity across markets is 3.34; the median is 2.25.

<sup>22</sup>In 2019, the busiest to least busy travel days in the United States were Friday (2.44 mil.), Sunday (2.38 mil.), Thursday (2.37 mil.), Monday (2.36 mil.), Wednesday (2.15 mil.), Tuesday (2.06 mil.), and Saturday (2.01 mil.), respectively (daily average). Compiled from <https://www.tsa.gov/foia/readingroom>.

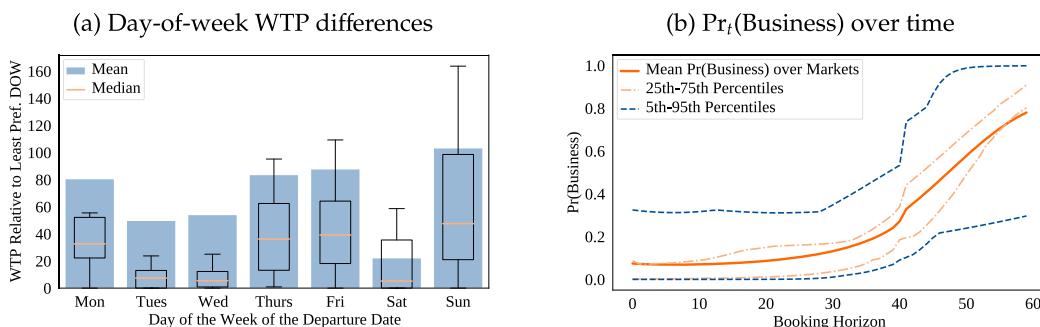


FIGURE 2.—Day-of-week preferences and consumer types over time. Note: (a) Average willingness to pay for the days of the week, relative to the minimum estimated day-of-week effect for each market. The plot shows an average over markets. (b) Fitted values of the arrival process of business versus leisure customers across the booking horizon. The y-axis is  $\text{Pr}(\text{Business})$ , so  $1 - \text{Pr}_t(\text{Business})$  defines  $\text{Pr}_t(\text{Leisure})$ .

arrivals are the type labeled “business” and close to 80 percent of late arrivals are the type labeled “business.” In early periods, prices are relatively flat and I estimate the average  $\gamma_t$  to be flat. Starting at 21 days before departure, I estimate a significant change in the business customer share. This corresponds with the time at which fares start raising rapidly.

In Figure 12 in Supplemental Material Appendix A, I show there is substantial heterogeneity in the fitted values for  $\gamma_t$  across routes. The heterogeneity reflects the differences in pricing dynamics across markets (see Figure 7 and Figure 8 in Supplemental Material Appendix A). In general, the shape of the curves correlates with the use of AP restrictions: a larger price increase at the 21-day AP requirement generally creates a steeper profile. The share of business arrivals well before the departure date is typically between zero and twenty percent and increases to between sixty to eighty percent the day of departure.

The parametric assumption on consumer types is flexible, as it captures S-shape, almost linear, and convex arrival paths. It can also be restrictive. One market is estimated to shift from one Poisson demand distribution to another (leisure to business) corresponding to the 21-day AP requirement.

All arrival rates are estimated to be statistically significant.<sup>23</sup> There are three levels of heterogeneity in these estimates. First, across markets, the average number of arrivals ranges from around one to up to ten. Second, in some markets, the arrival rates increase over time, whereas in most of the estimates, the rates remain low. Finally, there is variation in which days of the week experience the largest market sizes across routes. Monday and Sunday are estimated to have the largest market sizes in forty percent of routes, followed by Thursday and Friday. I estimate that 24.6 percent of arrivals are business travelers. As a point of comparison, Lazarev (2013) estimated twenty percent of consumers are business travelers.

Overall, the demand estimates establish that a meaningful shift occurs in willingness to pay over time. Demand elasticities range from  $-9.38$  to  $-1.46$ , depending on the route and time until departure. I estimate the average price elasticity to be  $-3.31$ .

<sup>23</sup>The exception being Oklahoma City, OK—Seattle, WA, where both the DoW preferences and blocked arrival rates are found to be insignificant.

### 6.1. Model Fit and Discussion

The model fits the data well. In Figure 3(a), I present within-sample model fit by plotting data and model fares over time. Model fares are shown under the choice set restrictions in the estimated model as well as with the restrictions removed—the firm has access to the entire choice set in each period. The figure depicts the mean values as well as the fifth and ninety-fifth percentiles. Model fares closely follow observed fares, with an average difference of \$7.50. Differences do vary by day before departure—differences are less than \$11 for the first half of the sample, but the gap increases around AP requirements. The reason is that the model produces a smoother fare profile that results in fare hikes slightly before the 7-day and 14-day AP requirements. The fifth and ninety-fifth percentiles of fares are also aligned, except for close to the departure date, where the top five percent of data fares are higher than what the model assigns. The dashed line, corresponding to model fares where the firm utilizes the entire choice set, also closely follows the data except close to the deadline, where the unrestricted model assigns lower prices. One view on this finding is that the utilization of fare restrictions acts as a reputation mechanism that allows firms to commit to high prices close to the date of travel, even for flights with excess capacity.

Price adjustments occur because of the time-varying composition of customers and in response to demand shocks. In Figure 3(b), I highlight how remaining capacity affects pricing within a period for a sample route. Plotted are the firm's policy functions. Each line corresponds to a different time period. With fewer seats remaining (moving toward the origin on the  $x$ -axis), fares increase. The plot also demonstrates that for a given amount of seats remaining, opportunity costs are increasing in time left to sell. For example, the price of having forty seats remaining sixty days out is higher than forty seats remaining thirty days out. However, close to departure, fares are higher regardless of remaining capacity due to demand being more inelastic. Also, consistent with Dana (1998), aggregate demand uncertainty results in unused capacity that raises opportunity costs over time.

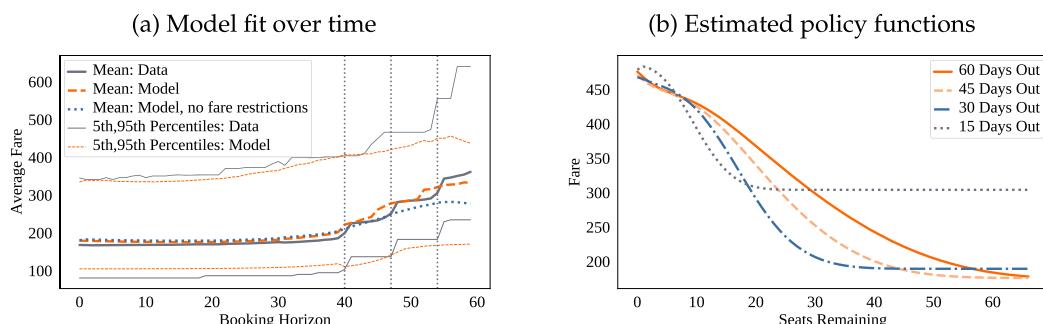


FIGURE 3.—Model fit and optimal pricing. Note: Comparison of mean data fares and mean model fares across the booking horizon. Two versions of model fares are plotted. The solid black line defines per-period price choice sets using fare restrictions in the data. The dashed gray line allows firms to choose from all prices each period.

## 7. THE WELFARE EFFECTS OF DYNAMIC AIRLINE PRICING

In this section, I estimate the welfare effects of dynamic pricing through a series of counterfactual exercises. In Section 7.1, I study uniform pricing, where the firm is not able to respond to demand shocks nor changes in the overall demand elasticity. I also study intertemporal price discrimination (IPD), where the firm is not able to respond to demand shocks, but prices may adjust over time. In Section 7.2, I examine the sources of price adjustments and show how both forces explain airline pricing patterns.

To set up all counterfactuals, I use the empirical distribution of remaining capacity sixty days before departure as the initial capacity condition.<sup>24</sup> All counterfactuals utilize the important boundary conditions of the initial problem: (1) the firm cannot oversell, and capacity transitions as  $c_{t+1} = c_t - \min\{Q_t(p, y_t), c_t\}$ ; (2) unused capacity is scrapped with zero value. I simulate 100,000 flights per route using the distribution of initial observed capacities. I then combine the results over routes. Route-level heterogeneity is then explored.

For all counterfactual analysis, I make two changes to the estimated model. First, I allow firms to use the unrestricted choice set,  $A(t) = \bigcup_{t=0}^T A(t)$ , in each period, in order to streamline the counterfactuals; for example, under uniform pricing, the firm may wish to charge a low fare that is not available close to departure. Second, I remove the firm shocks ( $\omega$ ) in order to single out the effects of the demand elasticity and scarcity (rather than the role of unobservable errors) in determining the pricing decision. For example, under uniform pricing, the firm would receive a single error vector, whereas in the dynamic counterfactual, the firm receives per-period error shocks.

### 7.1. Uniform Pricing and a Model of Intertemporal Price Discrimination

With uniform pricing, the firm sets a single price for each flight by integrating over future demands in the initial period. The revenue maximization problem under uniform pricing is

$$\max_p \mathbb{E}_y \left[ \sum_{t=0}^T p \min\{Q_t(p, y_t), c_t\} \right]$$

such that  $c_{t+1} = c_t - \min\{Q_t(p, y_t), c_t\}$ ,  $c_0$  given.

With a constant price, the firm cannot respond to both demand shocks and changes in the overall willingness to pay of arriving consumers.

In the model of intertemporal price discrimination, I assume the firm sets a sequence of prices before sales begin, at  $t = 0$ . Price changes over time reflect changes in willingness to pay—intertemporal price discrimination as third-degree price discrimination (as opposed to screening with second-degree price discrimination). The revenue maximization

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<sup>24</sup>Note that it may be profitable for firms to adjust capacity if the unmodeled fixed costs are such that the counterfactual pricing systems support a different gauge of aircraft. This is explored further in Supplemental Material Appendix E, where I consider dynamic pricing under a large range of initial capacities. I do not bound the fixed costs, but I do show that capacity would need to be significantly higher for demand shocks to not affect airline prices.

problem is therefore

$$\max_{p_0, \dots, p_T} \mathbb{E}_y \left[ \sum_{t=0}^T p_t \min\{Q_t(p_t, y_t), c_t\} \right]$$

such that  $c_{t+1} = c_t - \min\{Q_t(p_t, y_t), c_t\}$ ,  $c_0$  given.

Since prices cannot depend on the remaining capacity, they cannot react to changes in the opportunity cost of a seat.<sup>25</sup>

The counterfactuals are nested such that as the pricing strategy becomes more flexible, expected revenues are necessarily increasing. This is because under dynamic pricing, prices are defined by  $p^*(c_t, t)$ , whereas in the model of intertemporal price discrimination, prices are time dependent,  $p^*(t)$ . Finally, under uniform pricing, prices do not vary with both seats and time remaining,  $p^*$ . Therefore, expected revenues are increasing in pricing flexibility, that is,

$$\underbrace{\sum_{t=0}^T R_t^e(p^*; c_t)}_{\text{Uniform Pricing}} \leq \underbrace{\sum_{t=0}^T R_t^e(p^*(t); c_t)}_{\text{IPD}} \leq \underbrace{\sum_{t=0}^T R_t^e(p^*(t, c_t); c_t)}_{\text{Dynamic Pricing}}$$

Note that if capacity were sufficiently large, then the outcomes of the IPD and dynamic pricing models would coincide. The extent to which they differ suggests that responding to demand shocks is particularly important in the airline context.

Note that aggregate demand uncertainty affects prices in all scenarios, but in distinct ways. With dynamic pricing, prices are state dependent and the firm reacts directly to demand shock realizations. However, with uniform pricing and in the model of IPD, the pricing decision reflects the integral of all future demands (for given prices) before any uncertainty is resolved. The magnitude of demand uncertainty affects both the overall price level, and also the incentive to set different prices over time, irrespective of changes in the demand elasticity. Therefore, in order to completely separate the effects of demand uncertainty changes in willingness to pay on intertemporal price adjustments, I consider an alternative model of intertemporal price discrimination in Section 7.2.

The firm's objective function the model of IPD is a large dimensional problem—an exhaustive search involves evaluating the objective over  $\dim(A)^T$  possible price vectors. At a minimum, the problem contains approximately  $8.6e41$  possibilities. To reduce the dimensionality of the problem, I add the restriction that the firm can adjust fares when the advance purchase requirements typically expire (days 3, 7, 14, and 21). This results in five prices per flight.

In Table III, I present the welfare estimates for the baseline dynamic pricing model and the two counterfactuals. All values are in levels, except for load factor and sell outs, which are reported as percentages. I present a visual summary of the intertemporal dynamics in Figure 4.

I find that average fares are over ten percent lower under uniform pricing compared to the other pricing models. However, this does not lead to an increase in output—load

<sup>25</sup>Note that because demand becomes more inelastic over time, there is little to no role for Coasian forces (consumer waiting for fare declines). In Supplemental Material Appendix D, I provide a bound on the waiting costs so that no consumer would choose to wait to buy under dynamic pricing.

TABLE III  
WELFARE EFFECTS OF DYNAMIC AIRLINE PRICING.

	Fare	Load Factor	Sell Outs	Revenue	$CS_L$	$CS_B$	CS	Welfare
Dynamic	243.3	87.6	18.7	10.7	2.2	6.5	8.7	19.5
IPD	243.6	83.6	22.2	10.4	2.1	6.4	8.4	18.9
Uniform	219.9	84.9	29.4	9.9	2.0	7.4	9.3	19.2

*Note:* Fare: mean fare for flight observations with positive seats remaining; Load factor (LF): average at departure time; Sell Outs: percentage of flights with zero seats remaining in the last period; Revenue: mean flight revenue; Consumer surplus ( $CS_L$ ,  $CS_B$ ): surplus per flight; Welfare: daily mean revenues plus consumer surplus, excluding fixed costs. All dollar values reported in thousands of dollars. Results come from simulating 100,000 flights per route given the empirical distribution of remaining capacity sixty days before departure.

factors are 2.7 percent higher under dynamic pricing. This occurs because uniform pricing creates an incentive for the firm to save an inefficient number of seats for later arrivals, and dynamic pricing allows the firm to materialize the option value of being able to respond to demand shocks. I show in Figure 4(a) that uniform pricing results in average fares that are relatively high early on, but that are on average relatively low close to the departure date. Depending on the magnitude of demand shocks, the uniform price may be too high or too low. For flights with low realized demand, prices remain too high under uniform pricing.

The primary driver of market expansion under dynamic pricing is that by being able to respond to demand shocks, leisure consumers are offered lower fares. This is shown

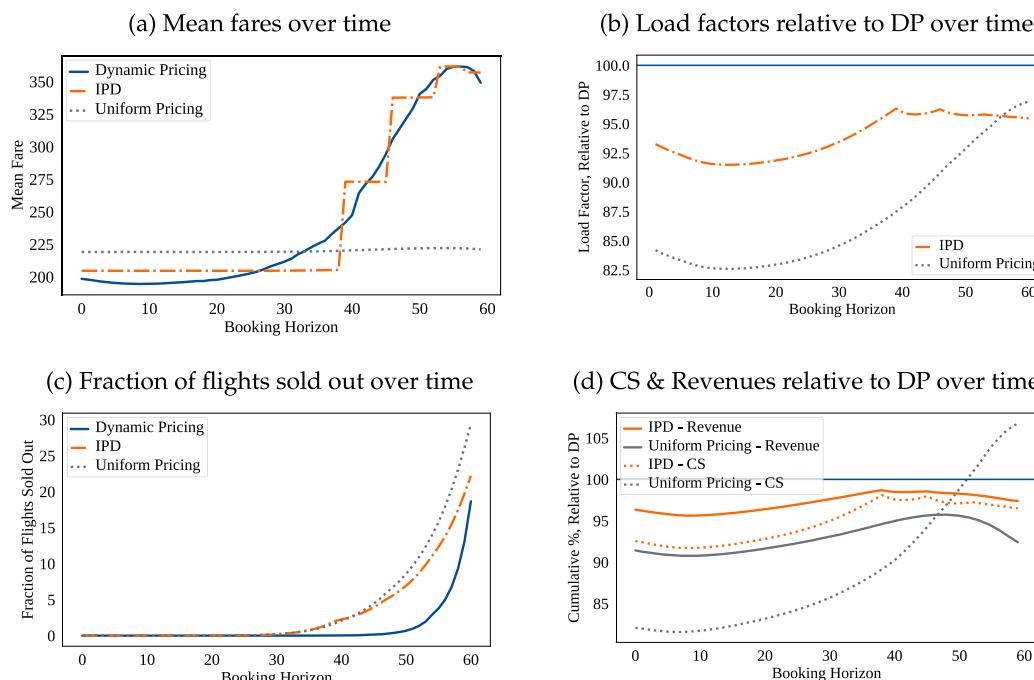


FIGURE 4.—Counterfactual results over time. Notes: (a) Average fares over time for flights that have not sold out. (b) Average load factors over time, relative to dynamic pricing. (c) The fraction of flights that are sold out over time. (d) Consumer surplus and revenues over time, relative to dynamic pricing.

in Figure 4(b), which depicts load factors relative to dynamic pricing over time. Output remains highest under dynamic pricing. Although the relative booking rate increases under both uniform pricing and in the model of IPD (the lines move closer to 100%), both curves level off. Without the ability to respond to demand shocks, flights with high demand shocks are more likely to sell out in advance. Figure 4(c) highlights this result, which shows the fraction of flights sold out over time. Uniform pricing not only results in more sell outs, but sell outs also occur much earlier because the firm does not adjust to changes in opportunity costs. Sell outs are 3.5 percent higher under IPD and 10.7 percent higher under uniform pricing.

Dynamic pricing leads to substantial changes in how capacity is allocated across consumer types (and time). In general, leisure consumers benefit under more flexible pricing systems because they result in lower relative prices early on. I estimate leisure consumer surplus would decline by 12.4 percent under uniform pricing due to higher relative prices. Dynamic pricing allows for increased price targeting among business consumers. For flights with low demand realizations, business consumers face higher prices due to intertemporal price discrimination. For flights with high demand realizations, business consumers face even higher fares, but may obtain seats with higher probabilities if leisure travelers do not purchase under these high fares. Higher fares reduce business consumer surplus by 13.3 percent under dynamic pricing compared to uniform pricing. Aggregating over consumer types, I estimate that dynamic pricing results in 6.3 percent lower total consumer surplus compared to uniform pricing. Thus, dynamic pricing increases output but it does not lead to an increase in consumer surplus.

Dynamic pricing leads to substantially higher revenues than those under uniform pricing (7.6 percent higher). This primarily comes from the ability to extract surplus from the changing composition of demand. In particular, there is a large transfer of business consumer surplus to the firm. Output expands because the firm can respond to demand shocks, but since the firm can also react to changing demand composition over time, the firm is able to extract more surplus. Because the counterfactuals are nested, I calculate

$$\frac{\text{Revenue under IPD} - \text{Revenue under Uniform Pricing}}{\text{Revenue under Dynamic Pricing} - \text{Revenue under Uniform Pricing}} \quad (7.1)$$

to measure the importance of intertemporal price discrimination versus the importance of responding to demand shocks in explaining the revenue increase. Using this decomposition, I find that 65.7 percent of the revenue gains associated with dynamic pricing over uniform pricing come from intertemporal price discrimination. The remaining 34.3 percent comes from the ability to respond to demand shocks.

I estimate the overall welfare effect of dynamic pricing to be a one percent increase in surplus compared to uniform pricing. That is, the increase in revenues under dynamic pricing is greater than the aggregate consumer surplus decline. There is a stark reallocation of capacity. Dynamic pricing leads to a 7.2 percent increase in tickets purchased by leisure consumers and a 5.8 percent decrease in the number of tickets purchased by business travelers.

Dynamic airline pricing increases welfare in aggregate, but not for each market individually. Figure 5 graphically shows the welfare effects of dynamic pricing for each market separately; each dot denotes the total welfare of dynamic pricing over the welfare of uniform pricing on the vertical axis. On the horizontal axis, I plot the calculation in Equation

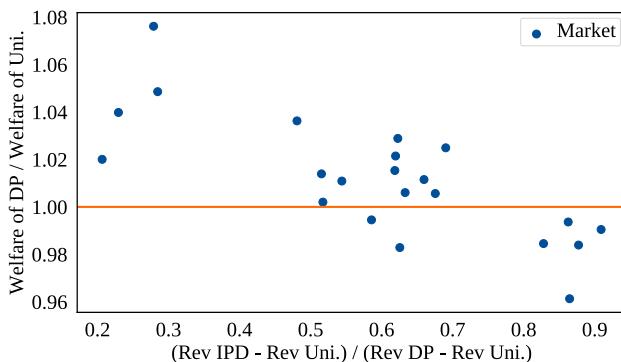


FIGURE 5.—Welfare effects of dynamic pricing due to IPD. Note: Each dot represents counterfactual results for a single market. The vertical axis is welfare under dynamic pricing over the welfare under uniform pricing. The horizontal axis computes the percentage of revenue gains from uniform pricing to dynamic pricing attributed to intertemporal price discrimination. Figure 13 in Supplemental Material Appendix A presents an alternative figure with market labels and reports the frequency of sell outs for each market.

(7.1). I find that dynamic pricing lowers welfare in seven of the markets studied and increases welfare in fifteen of the markets studied. As Figure 5 shows, the direction of the overall welfare effect depends on which sources of price adjustments drive revenues. Welfare declines under dynamic pricing when price changes are mainly in response to changes in willingness to pay and not in response to demand shocks. Examining route characteristics, I find that dynamic pricing generally increases welfare when the variance in consumer arrivals is high, consumer types are more similar, initial capacity is low, and variation in day of the week preferences is high.

## 7.2. The Sources of Price Adjustments in Airline Markets

In this section, I examine the importance of the two reasons for price adjustments with dynamic pricing: changes in the willingness to pay and changes in the opportunity cost of a seat. I consider a model of static pricing where the cost of capacity is (close to) zero.<sup>26</sup> This implies that price adjustments occur only in response to changes in demand. The revenue maximization problem in this counterfactual is simply the baseline pricing model with the discount factor set equal to zero; that is,  $\max_{p_t} \mathbb{E}_{y_t} [p_t \min\{Q_t(p_t, y_t), c_t\}]$ .

The static pricing model results in substantially lower fares because there is no opportunity cost of capacity. Prices still rise significantly over time due to changes in willingness to pay, conditional on the firm having seats remaining. Figure 6(a) shows that both models produce qualitatively similar patterns. Fares nearly double in sixty days and the slopes are similar. There is a level shift because the opportunity cost of capacity is close to zero under static pricing, lowering prices. This establishes that the primary source for increasing prices in airline markets is intertemporal price discrimination. Although average fares are nearly 30 percent lower under static pricing, output increases by only 3.5 percent and the

<sup>26</sup>Because the model is not in continuous time, more than a single seat may be demanded in a single period. This would raise prices (opportunity costs are positive); however, the estimated arrival rates are sufficiently low that this does not significantly impact the results. Results are very similar to a model where the firm does not take into account its capacity constraint when pricing.

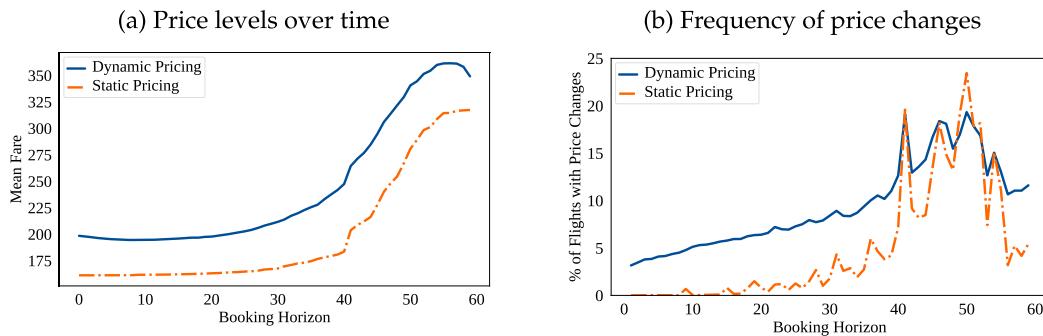


FIGURE 6.—Decomposition of the source of price adjustments. Note: (a) Average fares over time under dynamic pricing and static pricing. (b) The percentage of flights that experience price changes from  $t$  to  $t + 1$  under dynamic pricing and static pricing.

number of seats sold to business travelers decreases by 41.9 percent (leisure sales increase by 17.8 percent).

In Figure 6(b), I plot the percentage of flights that experience price adjustments over time. Comparing the two lines provides insights on the sources of price adjustments. Under static pricing, the first significant price hike occurs twenty-one days before departure, or when there is a significant change in the composition of arriving consumers according to the model estimates. These price adjustments occur regardless of whether the firm internalizes scarcity. Under dynamic pricing, there are substantially more price adjustments at all other times. This occurs well in advance of departure date (over five times more price adjustments), even though preferences are not changing. There are also over three times as many price adjustments close to the perishability date. Both of these findings are consistent with the raw data and show that the early price adjustments are primarily in response to demand shock realizations that allow the firm to better reoptimize remaining inventory for future (and increasingly price-insensitive) arrivals.

## 8. CONCLUSION

This paper investigates two major determinants of airfare fluctuations, demand shocks and intertemporal variation in willingness to pay. The main contribution of this paper is to jointly study these pricing forces to quantify their welfare implications. I do so by examining U.S. monopoly markets using flight-level data. I show that dynamic airline pricing expands output, increases revenues, and lowers total consumer surplus relative to uniform pricing. Leisure consumers benefit from dynamic pricing. Although business consumers are ensured seats, they are also targeted with high prices. In aggregate, I find welfare is higher under dynamic pricing than under uniform pricing. The results at the route level highlight that the welfare effects of dynamic pricing are ambiguous. In markets where price adjustments are primarily in response to changes in willingness to pay, the intertemporal price discrimination force dominates, and welfare decreases under dynamic pricing.

## APPENDIX

See Tables IV–VI.

TABLE IV  
PARAMETER ESTIMATES.

Variable	AUSBOS	BILSEA	BOIPDX	BOSJAX	BOSMCI	BOSSAN	BZNPDX	CHSSEA	
<i>Logit Demand</i>									
DoW Prefs	$\beta^0$	6.769	3.642	4.529	6.404	7.536	9.365	3.412	4.911
		0.197	0.300	0.131	0.170	0.046	0.349	0.314	0.193
	$\beta^1$	6.275	3.246	3.993	5.165	7.231	8.597	2.579	2.374
		0.166	0.285	0.122	0.173	0.050	0.286	0.276	0.318
	$\beta^2$	6.126	3.110	4.088	5.343	7.432	8.609	2.803	3.371
		0.172	0.286	0.129	0.169	0.051	0.317	0.290	0.237
	$\beta^3$	6.414	3.291	4.780	6.662	7.400	9.679	3.696	4.120
		0.200	0.299	0.139	0.164	0.052	0.359	0.300	0.230
	$\beta^4$	6.031	3.365	4.922	6.515	7.550	9.270	3.777	5.692
		0.245	0.308	0.140	0.193	0.052	0.339	0.311	0.191
	$\beta^5$	6.169	3.388	3.737	6.090	8.397	9.634	2.470	-10.958
		0.181	0.302	0.120	0.219	0.050	0.346	0.291	0.001
	$\beta^6$	6.367	3.874	4.928	7.033	7.906	10.141	4.219	6.996
		0.255	0.324	0.143	0.228	0.048	0.382	0.294	0.214
Leis. Price Sens.	$\alpha_L$	-4.087	-1.647	-3.268	-3.285	-3.994	-2.409	-2.056	-1.661
		0.099	0.094	0.078	0.067	0.022	0.103	0.125	0.054
Bus. Price Sens.	$\alpha_B$	-1.721	-0.722	-1.498	-2.157	-1.636	-1.707	-0.693	-0.968
		0.044	0.055	0.044	0.040	0.011	0.061	0.062	0.040
Pr(Bus.) Cons.	$\gamma_0$	-1.561	-4.194	-6.661	-3.369	-0.452	-0.705	-18.985	-5.982
		0.152	0.234	0.152	0.110	0.004	0.197	2.263	0.463
Pr(Bus.) Linear	$\gamma_1$	-0.020	0.005	0.119	0.103	-0.026	-0.018	0.614	0.061
		0.003	0.007	0.005	0.007	7.0E-04	0.008	0.093	0.021
Pr(Bus.) Quad.	$\gamma_2$	0.001	0.002	3.5E-04	-3.7E-04	5.2E-04	0.002	-0.004	0.001
		6.6E-05	8.7E-05	5.4E-05	9.2E-05	1.5E-05	1.3E-04	8.7E-04	2.8E-04
<i>Poisson Rates</i>									
>21 Days	$\mu_1$	3.531	1.451	0.804	1.338	1.344	1.178	1.193	2.094
		0.463	0.070	0.010	0.037	0.008	0.034	0.062	0.068
14 to 21 days	$\mu_2$	2.948	1.661	1.349	1.028	1.484	0.939	0.831	1.580
		0.292	0.108	0.023	0.033	0.012	0.036	0.056	0.067
7 to 14 days	$\mu_3$	2.279	1.418	1.237	0.745	1.287	0.770	0.533	1.140
		0.169	0.103	0.023	0.025	0.008	0.038	0.047	0.053
<7 days	$\mu_4$	0.809	1.798	1.218	0.442	0.986	0.406	0.851	1.303
		0.070	0.143	0.025	0.019	0.010	0.029	0.096	0.056
DoW Effect	$\mu^1$	1.089	0.977	0.901	1.347	1.141	0.995	1.062	2.559
		0.033	0.076	0.030	0.044	0.008	0.048	0.068	0.530
	$\mu^2$	1.039	1.144	1.024	1.252	1.190	1.173	1.036	1.602
		0.032	0.060	0.014	0.035	0.007	0.044	0.055	0.101
	$\mu^3$	1.181	1.207	0.997	1.032	1.209	1.124	0.822	1.205
		0.035	0.063	0.012	0.031	0.007	0.044	0.038	0.052
	$\mu^4$	1.425	1.174	0.905	1.051	1.128	1.232	0.871	0.956
		0.043	0.066	0.013	0.045	0.006	0.043	0.050	0.043
	$\mu^5$	1.024	0.936	0.801	0.981	0.451	0.824	0.891	8.493
		0.029	0.067	0.029	0.064	0.003	0.036	0.045	0.001
	$\mu^6$	1.366	0.932	0.826	0.973	0.941	1.160	0.695	0.691
		0.050	0.048	0.011	0.050	0.006	0.060	0.041	0.048
<i>Firm Shock</i>									
	$\sigma$	0.670	0.370	0.118	0.499	0.311	0.862	0.182	1.068
		0.030	0.039	0.005	0.014	0.001	0.025	0.012	0.035
LogLike		-47,557	-79,749	-266,052	-101,409	-60,597	-61,387	-53,669	-35,926
Number of Flights		238	423	1626	478	304	317	333	173
Number of Dep. Dates		119	106	106	120	108	120	106	87
Number of Obs.		13,645	25,180	96,774	26,673	22,652	18,294	19,848	10,198

Note: Standard errors in parentheses. Prices are scaled to \$100.

TABLE V  
PARAMETER ESTIMATES.

Variable		CMHSEA	FATPDX	GEGPDX	GTFSEA	HLNSEA	ICTSEA	MSOPDX
<i>Logit Demand</i>								
DoW Prefs	$\beta^0$	3.715	3.270	21.913	12.182	6.107	1.386	5.627
		0.343	0.255	0.604	1.497	0.327	0.234	0.446
	$\beta^1$	3.319	3.017	21.325	12.105	5.667	1.768	5.043
		0.302	0.216	0.601	1.491	0.312	0.215	0.412
	$\beta^2$	3.406	2.761	21.605	12.132	5.517	2.057	4.971
		0.305	0.204	0.603	1.500	0.304	0.187	0.409
	$\beta^3$	3.849	3.032	22.216	12.175	6.077	2.463	5.433
		0.362	0.239	0.601	1.496	0.331	0.209	0.418
	$\beta^4$	3.780	3.212	22.152	12.247	6.350	1.845	5.166
		0.349	0.253	0.605	1.502	0.359	0.249	0.410
	$\beta^5$	3.295	3.186	21.178	12.111	5.416	2.407	4.838
		0.325	0.238	0.601	1.491	0.297	0.295	0.404
	$\beta^6$	3.951	3.323	22.225	12.261	6.593	0.837	5.430
		0.389	0.261	0.604	1.498	0.362	0.316	0.445
Leis. Price Sens.	$\alpha_L$	-1.288	-2.215	-17.718	-6.131	-3.321	-1.146	-3.266
		0.079	0.097	0.488	0.729	0.165	0.043	0.227
Bus. Price Sens.	$\alpha_B$	-0.552	-0.837	-8.825	-2.755	-1.691	-0.240	-1.538
		0.047	0.049	0.235	0.348	0.087	0.021	0.151
Pr(Bus.) Cons.	$\gamma_0$	-6.175	-4.325	-2.734	-2.276	-12.088	-2.553	-1.742
		0.378	0.309	0.089	0.438	2.080	0.128	0.162
Pr(Bus.) Linear	$\gamma_1$	0.115	0.022	-0.015	-0.360	-4.022	0.024	-0.029
		0.015	0.011	0.007	0.181	2.406	0.005	0.006
Pr(Bus.) Quad.	$\gamma_2$	2.2E-04	0.001	0.002	0.010	0.107	7.2E-05	0.002
		1.4E-04	1.2E-04	1.4E-04	0.005	0.061	4.8E-05	1.8E-04
<i>Poisson Rates</i>								
>21 Days	$\mu_1$	2.712	1.624	1.019	0.833	0.930	3.128	0.930
		0.143	0.065	0.015	0.029	0.020	0.320	0.025
14 to 21 days	$\mu_2$	3.278	2.606	0.614	0.588	0.492	3.448	0.690
		0.186	0.165	0.021	0.064	0.031	0.372	0.039
7 to 14 days	$\mu_3$	1.831	2.513	0.482	0.572	0.376	3.821	0.535
		0.189	0.142	0.021	0.049	0.021	0.410	0.037
<7 days	$\mu_4$	2.501	2.861	0.277	0.946	0.234	6.489	0.366
		0.290	0.158	0.013	0.089	0.014	0.727	0.060
DoW Effect	$\mu^1$	0.990	0.777	0.895	0.869	0.882	0.678	0.942
		0.053	0.039	0.020	0.059	0.041	0.071	0.047
	$\mu^2$	0.925	0.838	0.876	1.120	0.946	0.643	1.050
		0.055	0.038	0.021	0.038	0.047	0.052	0.034
	$\mu^3$	0.979	0.928	0.890	1.168	0.928	0.528	0.987
		0.051	0.024	0.025	0.037	0.044	0.040	0.039
	$\mu^4$	1.006	0.970	0.917	1.218	1.009	0.765	1.140
		0.056	0.024	0.023	0.047	0.050	0.096	0.042
	$\mu^5$	0.928	0.820	0.769	0.915	0.943	0.519	0.929
		0.086	0.021	0.018	0.052	0.047	0.131	0.050
	$\mu^6$	1.054	1.114	0.825	0.982	0.883	1.624	1.202
		0.061	0.024	0.025	0.082	0.035	0.188	0.048
<i>Firm Shock</i>								
	$\sigma$	0.678	0.228	0.260	0.194	0.197	0.264	0.086
		0.073	0.020	0.004	0.018	0.012	0.016	0.010
LogLike		-40,301	-78,041	-304,409	-57,210	-29,791	-39,109	-26,969
Number of Flights		210	424	1718	412	212	212	208
Number of Dep. Dates		106	106	106	106	106	106	106
Number of Obs.		12,398	25,248	102,292	24,532	12,644	12,606	12,390

Note: Standard errors in parentheses. Prices are scaled to \$100.

TABLE VI  
PARAMETER ESTIMATES.

Variable		OKCSEA	PDXRNO	PDXSBA	PDXSTS	SBASEA	SEASTS	SEASUN
<i>Logit Demand</i>								
DoW Prefs	$\beta^0$	-0.834 0.501	6.991 0.203	3.173 0.370	4.479 0.183	3.698 0.436	4.591 0.333	9.845 1.071
	$\beta^1$	-0.590 0.429	6.045 0.204	2.463 0.280	2.917 0.235	2.799 0.356	3.099 0.354	9.279 1.086
	$\beta^2$	-0.567 0.441	6.051 0.206	2.484 0.276	2.416 0.226	2.930 0.364	3.206 0.352	9.498 1.101
	$\beta^3$	-0.403 0.463	6.888 0.195	2.942 0.352	4.313 0.184	3.638 0.437	4.421 0.326	8.822 0.993
	$\beta^4$	-0.579 0.549	7.394 0.216	3.265 0.378	4.504 0.183	3.864 0.455	4.665 0.347	9.967 1.064
	$\beta^5$	-0.449 0.458	6.256 0.195	2.647 0.314	3.359 0.228	3.458 0.410	2.772 0.411	8.767 1.007
	$\beta^6$	-0.697 0.479	9.448 0.277	3.857 0.444	4.555 0.193	4.429 0.553	5.608 0.388	10.033 0.995
Leis. Price Sens.	$\alpha_L$	-0.715 0.037	-3.658 0.102	-1.603 0.098	-2.333 0.077	-1.850 0.147	-1.873 0.096	-7.118 0.760
Bus. Price Sens.	$\alpha_B$	-0.029 0.029	-2.037 0.065	-0.741 0.066	-0.860 0.050	-0.747 0.073	-0.979 0.067	-2.551 0.254
Pr(Bus.) Cons.	$\gamma_0$	-3.454 0.219	-3.739 0.441	-3.370 0.401	-6.307 0.473	-7.502 0.368	-7.091 0.833	-1.334 0.078
Pr(Bus.) Linear	$\gamma_1$	0.044 0.004	-0.114 0.019	0.008 0.011	0.058 0.015	0.160 0.017	0.020 0.019	-0.025 0.005
Pr(Bus.) Quad.	$\gamma_2$	-3.0E-04 4.7E-05	0.004 2.2E-04	0.001 1.7E-04	0.001 1.9E-04	-1.6E-04 1.8E-04	0.002 3.9E-04	6.0E-04 1.1E-04
<i>Poisson Rates</i>								
>21 Days	$\mu_1$	11.419 8.256	1.137 0.026	1.790 0.133	1.603 0.044	2.418 0.126	1.234 0.050	0.991 0.032
14 to 21 days	$\mu_2$	13.810 9.989	1.151 0.030	1.862 0.173	1.662 0.073	3.172 0.245	1.353 0.069	0.832 0.047
7 to 14 days	$\mu_3$	13.188 9.446	0.951 0.032	1.795 0.179	1.015 0.056	2.521 0.217	0.995 0.061	0.821 0.050
<7 days	$\mu_4$	18.045 12.784	1.106 0.052	2.305 0.241	1.248 0.083	2.895 0.346	1.036 0.068	0.895 0.157
DoW Effect	$\mu^1$	0.763 0.159	0.879 0.031	0.944 0.052	0.881 0.086	0.905 0.054	1.353 0.094	1.100 0.047
	$\mu^2$	0.730 0.156	0.907 0.032	0.918 0.061	1.075 0.144	0.972 0.062	1.348 0.086	1.009 0.047
	$\mu^3$	0.687 0.163	0.918 0.029	0.994 0.042	0.852 0.035	1.039 0.036	1.051 0.052	1.149 0.046
	$\mu^4$	0.860 0.207	0.940 0.038	0.953 0.036	0.917 0.040	0.976 0.038	1.101 0.053	1.011 0.044
	$\mu^5$	0.640 0.147	0.835 0.028	0.868 0.046	0.730 0.061	0.867 0.042	1.437 0.154	0.847 0.063
	$\mu^6$	0.932 0.205	0.645 0.024	0.867 0.053	1.137 0.040	0.884 0.104	0.999 0.055	0.722 0.132
<i>Firm Shock</i>								
	$\sigma$	0.262 0.013	0.430 0.015	0.309 0.036	0.395 0.024	0.464 0.065	0.623 0.052	0.194 0.015
LogLike		-36,660	-143,894	-38,303	-66,833	-43,454	-58,125	-26,587
Number of Flights		212	721	212	384	212	306	168
Number of Dep. Dates		106	106	106	106	106	106	85
Number of Obs.		12,405	42,989	12,623	22,833	12,582	18,182	9994

Note: Standard errors in parentheses. Prices are scaled to \$100.

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