A Model of Dynamic Limit Pricing with an Application to the Airline Industry

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We develop a dynamic limit pricing model where an incumbent repeatedly signals information relevant to a potential entrant's expected profitability. The model is tractable, with a unique equilibrium under refinement, and dynamics contribute to large equilibrium price changes. We show that the model can explain why incumbent airlines cut prices dramatically on routes threatened with entry by Southwest, presenting new reduced-form evidence and a calibration that predicts a pattern of price changes across markets similar to the one observed in the data. We use our calibrated model to quantify the welfare effects of asymmetric information and subsidies designed to encourage Southwest's entry.

I. Introduction

Economists have long been interested in models where incumbents try to deter entry (Kaldor [1935] and Bain [1949] provide early examples, and

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chaps. 8 and 9 of Tirole [1988] are devoted to models of strategic investment). However, even though survey evidence suggests that managers engage in deterrence (Smiley 1988), little empirical evidence exists showing that any particular model can explain observed firm behavior. This may be partly due to the fact that it is unclear what the stylized two-period models that dominate the theoretical literature predict should happen when firms interact repeatedly, as happens, for example, when a potential entrant can wait for several years before entering. In this paper, we extend one particular model of entry deterrence, the classic Milgrom and Roberts (1982) model of limit pricing with asymmetric information, to a dynamic setting, and we show that it provides a plausible explanation for why, in the 1990s and 2000s, incumbent airlines often responded to the threat of entry by Southwest by lowering their prices and then keeping them low before entry actually occurred.[1] This empirical pattern is part of the phenomenon commonly known as the "Southwest Effect," a term coined by Bennett and Craun (1993) in a Department of Transportation study that showed that many contemporary pricing trends in the industry could be attributed to the presence of Southwest on airline routes or at their end point airports.

In the two-period Milgrom and Roberts (1982) model, an incumbent faces a potential entrant that is uninformed about some relevant aspect of the market, such as the incumbent's marginal cost. In equilibrium, the incumbent may deter entry by choosing a low price to credibly signal that its marginal costs are so low that the potential entrant's postentry profits would likely not cover its entry costs. However, it is unclear whether the incumbent would keep setting low prices if entry were repeatedly threatened. In contrast to the view that dynamic games of asymmetric information are intractable when using standard equilibrium concepts (Doraszelski and Pakes 2007; Fershtman and Pakes 2012), we develop a tractable model where we allow the incumbent's private information to be positively serially correlated, but not perfectly persistent, over time. The model has a unique Markov perfect Bayesian equilibrium (MPBE) under a refinement when the incumbent's payoffs satisfy several conditions. When the incumbent's marginal cost evolves exogenously, the required conditions can be shown to always hold under quite weak and easy-to-check conditions on the primitives of the model. The unique equilibrium involves the incumbent using fully separating price strategies, which allows us to devise a computationally simple strategy for solving and

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[1] The term "dynamic limit pricing" has sometimes been used to refer to incumbents keeping prices low to limit the growth of entrants (Gaskins 1971). Instead, we present a model where an incumbent faces a long-lived potential entrant and may lower prices for many periods to keep entry from happening.

calibrating the model. The introduction of dynamics can substantially increase the magnitude of the equilibrium price cuts, so that prices may fall significantly even when the incumbent's information can have only a small effect on the probability of entry.

As documented by Goolsbee and Syverson (2008), incumbent airlines lower prices by as much as 20% on airport-pair routes when Southwest serves both end point airports without (yet) serving the route itself, and these price cuts can have substantial welfare effects. For example, Morrison (2001) estimates that Southwest's presence as a potential competitor lowered expenditure on airfares by $3.3 billion in 1998. While this is a natural setting in which to consider limit pricing, as these price reductions are the largest documented in response to a threat of entry in any industry (Bergman 2002), we are not aware of anyone testing a model of limit pricing or any other strategic investment model in this context.

We present two forms of evidence in favor of our model. The first type of evidence comes from analyzing markets where there is a dominant incumbent carrier before Southwest enters, which matches the assumed market structure in our model. We show that in these markets there is a nonmonotonic relationship between the magnitude of observed price declines and a measure of how likely Southwest is to enter these markets, where the measure is defined in a way that it should not be affected by how the incumbent changes its pricing when entry is threatened. The price declines are largest in markets with intermediate probabilities of entry. Under some fairly standard assumptions, our limit pricing model predicts exactly this type of nonmonotonic relationship. We show that several explanations for the shape of this relationship that do not involve limit pricing (e.g., strategic increases in capacity, declining load factors, or competition with connecting service on Southwest) are not consistent with the data.

Second, we calibrate a parameterized version of our model. We estimate demand and marginal-cost parameters using data from quarters where limit pricing should not be taking place, and we estimate the distribution of Southwest's entry costs using information on how the probability of entry varies across markets and over time. This is computationally feasible because entry decisions in equilibrium will be the same as under complete information. We use no information on how much prices fall when entry is threatened. However, when we introduce asymmetric information, the model predicts a magnitude of price cuts and a marked nonmonotonic relationship between price cuts and the probability of entry that are similar to those observed in the data. We use the calibrated model to quantify the welfare effects of limit pricing. Even though we consider only 109 medium-sized and smaller markets, we find substantial welfare effects: in present-value terms, limit pricing increases consumer surplus by almost $600 million and total welfare by over $500 million (in 2009 dollars). We also examine the welfare effects of a policy that provides Southwest with small financial subsidies when it provides nonstop service, motivated by the fact that service subsidies are quite common in the industry (Ryerson 2016). We predict that even small subsidies can substantially increase welfare, and at low cost to the government. A large proportion of the gains comes from the smallest markets, where, under asymmetric information, subsidies can cause dominant incumbents to significantly lower prices even when entry is a low-probability event.

Our focus in the text is on relatively simple models where the incumbent has full information about the potential entrant, the potential entrant is uninformed about the incumbent's exogenously evolving marginal cost and exogenous serial correlation in the incumbent's marginal cost, and signaling incentives provide the only source of dynamics. Appendix F (apps. A–F are available online) shows that we can also solve models where marginal costs depend on carriers' sticky-capacity investments, and the incumbent may also learn about the probability of entry over time. These extensions are interesting in their own right (e.g., we are not aware of entry-deterrence models with two-way learning being explored in the literature), and as well as generating large limit-price reductions in equilibrium, these models also help explain some features of the data. For example, two-way learning can help to explain why the magnitude of price cuts tends to increase over time in some markets. In the model with endogenous-capacity investments, we show that even though the incumbent could try to deter entry by building additional, observable capacity, it chooses not to do so, engaging in limit pricing instead.[2] Consistent with this prediction, in our data we do not observe incumbents significantly changing capacity when entry is threatened. We set up this extended model to show how asymmetric information about connecting traffic, which makes up the majority of traffic on the routes in our empirical sample, can lead to limit pricing. This is consistent with the existing airline literature that has pointed out that connecting traffic makes it difficult to accurately measure a carrier's marginal cost on many routes (Edlin and Farrell 2004; Elzinga and Mills 2005).

Our work draws on and is related to two broad literatures aside from the ones that have studied market power in airlines and the Southwest Effect (we discuss these literatures in sec. III). Limit pricing is an old idea, but early models (e.g., Modigliani 1958; Kamien and Schwartz 1971) assumed that low prices would lead a potential entrant to expect low post-entry prices without explaining why. Milgrom and Roberts (1982) provided an equilibrium explanation based on asymmetric information between the

[2] Spence (1977) compares price levels in a model where an incumbent limit prices (through an assumed price commitment) and a model where an incumbent can deter entry by investing in capacity.

incumbent and the potential entrant, with Matthews and Mirman (1983) and Harrington (1986) exploring different extensions of the Milgrom and Roberts (1982) framework. In characterizing what happens in a dynamic, finite-horizon version of Milgrom and Roberts (1982), we recursively apply the results of Mailath (1987), Ramey (1996), and Mailath and von Thadden (2013) in one-shot signaling models. Roddie (2012a, 2012b) also takes a recursive approach to solving a dynamic game of asymmetric information, focusing on the example of a quantity-setting game between two incumbents, one of whom has a privately known marginal cost that evolves exogenously. As in these papers, we formally assume a finite-horizon structure, where we can use backwards induction to show existence and uniqueness properties. We allow the number of periods to increase to infinity to deliver a model where we can compute equilibria in an efficient manner. We differ from Roddie in considering an entry-deterrence game, in using different high-level conditions on incumbent payoffs to show the existence and uniqueness of our equilibrium, and—in the exogenous marginal cost version of our model—in showing how these conditions will be satisfied under a small number of easy-to-check conditions on the static primitives of the model. Kaya (2009) and—in a limit pricing context—Toxvaerd (2017) consider repeated signaling models where the sender's type is fixed over time. This structure can lead to signaling only in the early periods of a game, whereas with an evolving type our model has repeated signaling in equilibrium. A model where the incumbent's type is fixed would have difficulty explaining two aspects of our empirical application. First, incumbents not only cut prices when Southwest first appears as a potential entrant but also keep prices low even if Southwest does not initially enter. Second and more fundamentally, if the incumbent's type is fixed, then Southwest should be able to infer the incumbent's type from how it set prices before Southwest became a potential entrant, leaving it unclear what cutting prices once Southwest threatens entry would achieve.

A second directly related literature has tried to provide empirical evidence of strategic investment. A common approach has looked for evidence of different investment strategies among firms (e.g., Lieberman 1987) or effects of incumbent investment on subsequent entry (e.g., Chevalier 1995) without specifying the exact mechanism involved. Masson and Shaanan (1982, 1986) provide empirical evidence for limit pricing using annual data on a large number of industries. While the empirical approach is very different, this conclusion is consistent with our results, although Strassmann (1990) did not find evidence of limit pricing when applying the Masson and Shaanan approach to 92 heavily traveled airline routes. Ellison and Ellison (2011) introduced the idea of interpreting nonmonotonicities between the probability of entry and an investment decision of an incumbent as evidence of entry deterrence. Our reduced-form analysis is based on a similar approach, and we complement it by providing additional evidence through our calibration.[3]

Snider (2009) and Williams (2012) provide structural evidence in favor of hub carriers predating by increasing their capacities. Our evidence suggests that incumbents did not use capacity investment as a strategy to try to deter a much stronger potential entrant, Southwest. Both of these papers use infinite-horizon dynamic structural models with complete information (up to independent and identically distributed payoff shocks) in the tradition of Ericson and Pakes (1995). One feature of these models is that there are often multiple equilibria. We differ from this literature by considering a dynamic model with asymmetric information and explicitly establishing conditions and a refinement under which the MPBE that we look at is unique. Fershtman and Pakes (2012) consider an alternative way of incorporating persistent asymmetric information in a dynamic game, using an alternative concept of experience-based equilibrium (EBE), where players have beliefs about the payoffs from different actions, not the types of other players. When the structure of equilibrium beliefs is unknown ex ante, this EBE approach may have computational advantages. However, in our model we can show uniqueness of an MPBE where the entrant's beliefs will always be correct on the equilibrium path.[4] This allows us to provide a natural dynamic extension of one of the classic two-period models of theoretical industrial organization.

The rest of the paper is organized as follows. Section II lays out our model of dynamic limit pricing when marginal costs are exogenous, characterizes the equilibrium, and examines the predictions of the model. Section III introduces our empirical application and describes our data. Section IV provides the reduced-form evidence in support of our limit pricing model. Section V presents our calibration of the model and quantifies the welfare effects of limit pricing and the welfare effects of counterfactual subsidies that would encourage Southwest to enter. Section VI outlines several extensions to the basic model. Section VII concludes. While the text is intended to be self-contained, the appendixes contain proofs, computational details, robustness checks, and the details of the extensions. In each section, we indicate which appendix the reader should consult for further details.

[3] Seamans (2013) uses the Ellison and Ellison approach to argue that the pricing of incumbent cable television systems is consistent with the Milgrom and Roberts (1982) model based on cross-sectional variation in how incumbent prices vary with the distance to the nearest potential telephone company entrant. In our analysis, we directly look at whether price changes vary nonmonotonically with the probability of entry once Southwest becomes a potential entrant.

[4] Fershtman and Pakes (2012) consider an infinite-horizon, discrete-state, and discrete-action model where players may have limited recall or information is sometimes publicly released. Our structure involves continuous actions and continuous states, and we use a finite-horizon structure to prove the properties of our game. Borkovsky et al. (2014) contains a more detailed comparison of the EBE approach and the one used here.

II. Model

In this section, we develop the most tractable version of our model, where the incumbent's marginal cost is private information and evolves exogenously. Section II.A shows the existence and uniqueness of a fully separating MPBE under some simple conditions on static payoff functions for a given market. Section II.B illustrates the properties of the model, and in particular the nonmonotonic relationship between the probability of entry and how much the incumbent lowers its prices, when we make specific assumptions about demand and costs. Section II.C briefly discusses limitations and extensions of the model.

A. A Dynamic Limit Pricing Model with Exogenous Marginal Costs

1. Overview

We consider a finite-horizon dynamic game played in a single market, with periods $t = 1, \ldots, T$, although, as we explain below, we will make use of the limiting infinite-horizon version of the model when performing computations. The discount factor is $0 < \beta < 1$. Consumer demand is static (i.e., it does not depend on past prices or availability), common knowledge, and time invariant. There are two firms. An incumbent firm, I, is always in the market. Its marginal cost, $c_{I,t}$, lies on a compact interval and evolves over time according to a first-order Markov process. A long-lived potential entrant, E, with known and fixed marginal cost c_E, has to decide whether to enter the market each period. Entry requires payment of a sunk entry cost, κ_t, which is private information to E. If E enters, it is an active competitor in the next period. Before entry, I's marginal cost is private information. However, E can observe I's current-period price, $p_{I,t}$, chosen from an interval $[\underline{p}, \overline{p}]$, and all previous prices before it decides whether to enter in t. Therefore, I can potentially choose its price to influence E's entry decision. Once E has entered, we assume that it will stay in the market for the rest of the game, that I's marginal cost will be observable, and that both firms will choose prices simultaneously each period in a static Nash equilibrium. Our focus will therefore be on equilibrium strategies before entry occurs.

2. Cost Assumptions

The incumbent's marginal cost $c_{I,t}$ lies on a compact interval $[\underline{c_I}, \overline{c_I}]$ and evolves exogenously according to a first-order Markov process $\psi_I : c_{I,t-1} \to c_{I,t}$ with full support; that is, $c_{I,t-1}$ can evolve to any point on the support in the next period. Therefore, E will view any value of $c_{I,t}$ on the support as being possible even if equilibrium play and what it has observed prior to

t gives it a precise prior about the value of $c_{I,t}$. The conditional probability density function is denoted $\psi_I(c_{I,t}|c_{I,t-1})$. We make the following assumptions.

ASSUMPTION 1 (Marginal cost transitions).

1. $\psi_I(c_{I,t}|c_{I,t-1})$ is continuous and differentiable (with appropriate one-sided derivatives at the boundaries).
2. $\psi_I(c_{I,t}|c_{I,t-1})$ is strictly increasing; that is, a higher type in one period implies that higher types in the following period are more likely. Specifically, we will require that for all $c_{I,t-1}$ there is some c' such that $(\partial\psi_I(c_{I,t}|c_{I,t-1})/\partial c_{I,t-1})|_{c_{I,t}=c'} = 0$ and $\partial\psi_I(c_{I,t}|c_{I,t-1})/\partial c_{I,t-1} < 0$ for all $c_{I,t} < c'$ and $\partial\psi_I(c_{I,t}|c_{I,t-1})/\partial c_{I,t-1} > 0$ for all $c_{I,t} > c'$. Obviously it will also be the case that $\int_{\underline{c_I}}^{\overline{c_I}}(\partial\psi_I(c_{I,t}|c_{I,t-1})/\partial c_{I,t-1})\, dc_{I,t} = 0$.

To enter in period t, E has to pay a private-information sunk entry cost, κ_t, which is an independent and identically distributed draw from a commonly known time-invariant distribution $G(\kappa)$ (density $g(\kappa)$) with support $[\underline{\kappa} = 0, \bar{\kappa}]$.

ASSUMPTION 2 (Entry cost distribution).

1. $G(\cdot)$ is continuous and differentiable, and the density $g(\kappa) > 0$ for all $\kappa \in [0, \bar{\kappa}]$.
2. $\bar{\kappa}$ is large enough so that, whatever the beliefs of the potential entrant, there is always some probability that it does not enter because the entry cost is too high.

3. Preentry-Stage Game

The potential entrant does not observe $c_{I,t}$ prior to entering, but E does observe the whole history of the game to that point. The timing of the game in each preentry period is as follows:

1. I sets a price $p_{I,t}$ and receives flow profit

$$\pi_I^M(p_{I,t}, c_{I,t}) = q^M(p_{I,t})(p_{I,t} - c_{I,t}), \tag{1}$$

where $q^M(p_{I,t})$ is the demand function of a monopolist. Define

$$p_I^{\text{static monopoly}}(c_I) \equiv \arg\max_{p_I} q^M(p_I)(p_I - c_I). \tag{2}$$

The incumbent can choose a price from the compact interval $[\underline{p}, \overline{p}]$, although all of our theoretical results would hold when the monopolist sets a quantity. The choice of strategic variable in the duopoly game that follows entry may matter, as will be explained below.

2. E observes $p_{I,t}$ and κ_t and then decides whether to enter (paying κ_t if it does so). If it enters, it is active at the start of the following period.
3. I's marginal cost evolves according to ψ_I.

Assumption 3 (Monopoly payoffs).

1. $q^M(p_I)$, the demand function of a monopolist, is strictly monotonically decreasing in p_I, continuous, and differentiable.
2. $\pi_I^M(p_I, c_I)$ has a unique optimum in price, and for any $p_I \in [\underline{p}, \bar{p}]$ where $\partial^2\pi_I^M(p_I, c_I)/\partial p_I^2 > 0$, $\exists\ k > 0$ such that $|\partial\pi_I^M(p_I, c_I)/\partial p_I| > k$ for all c_I.
3. $\bar{p} \geq p_I^{\text{static monopoly}}(\overline{c_I})$, and $\underline{p}$ is low enough such that no firm would choose it (for any t) even if this would prevent E from entering, whereas any higher price would induce E to enter with certainty.[5]

The second condition is consistent with strict quasi-concavity of the profit function, and it is satisfied for most forms of demand, including the parameterized nested logit model used in our computations.

4. Postentry-Stage Game

We assume that once E enters, marginal costs, which continue to evolve as before, are observed by both firms so that there is no scope for further signaling. The duopolists choose their strategic variables, $a_{I,t}$ and $a_{E,t}$, which could be prices or quantities, simultaneously.

Assumption 4 (Duopoly payoffs and output).

1. Firms use unique static Nash equilibrium strategies in each period following entry. Static per-period equilibrium profits are $\pi_I^D(c_{I,t})$ and $\pi_E^D(c_{I,t})$, and outputs are $q_I^D(c_{I,t})$ and $q_E^D(c_{I,t})$.
2. $\pi_I^D(c_I)$, $\pi_E^D(c_I) \geq 0$ for all c_I.
3. $\pi_I^D(c_I)$ and $\pi_E^D(c_I)$ are continuous and differentiable in their arguments, and $\pi_I^D(c_I)$ ($\pi_E^D(c_I)$) is monotonically decreasing (increasing) in c_I.
4. $\pi_I^D(c_I) < \pi_I^M(p_I^{\text{static monopoly}}(c_I), c_I)$ for all c_I.
5. $q_I^D(c_I) - q^M(p_I^{\text{static monopoly}}(c_I)) - (\partial\pi_I^D(c_I)/\partial a_E)(\partial a_E^*/\partial c_I) < 0$ for all c_I, where a_E^* is the equilibrium price or quantity choice of the entrant in the duopoly game.

The second condition rationalizes why neither firm will exit once entry has occurred. Given that we are assuming that the postentry game has

[5] For some parameters (although not for the ones that we estimate in our calibration), this could require $\underline{p} < 0$. The purpose of this restriction is to ensure that the action space is large enough to allow all types to separate.

complete information and a finite horizon and that the firms have single products and constant marginal costs, uniqueness of the pricing equilibrium will be guaranteed under many standard demand formulations, such as linear, logit, and nested logit (e.g., Mizuno 2003). The fifth condition implies that a decrease in marginal cost is more valuable to a monopolist than a duopolist, and it is important in showing a single-crossing condition on the payoffs of an incumbent monopolist. Note that because $q^M(p_I)$ is decreasing in p_I, if this condition holds when a monopolist incumbent sets $p_I^{\text{static monopoly}}$, then it will also hold for lower limit prices, a fact that is used in our proof. The condition is easier to satisfy when the duopolists compete in prices (strategic complements), as $(\partial \pi_I^D(c_I)/\partial a_E)(\partial a_E^*/\partial c_I) > 0$ in this case, and when c_E is low relative to $\underline{c_I}$ (i.e., the potential entrant is always relatively efficient).[6] This makes sense in our empirical setting, as Southwest is viewed as having had significantly lower costs than legacy carriers during our sample period, and our estimates of the carriers' marginal costs are in line with this view.

5. Equilibrium: Existence, Uniqueness, and Characterization

By assumption, there is a unique subgame perfect Nash equilibrium in the postentry complete-information duopoly game. Our equilibrium concept for the preentry period is MPBE (Toxvaerd 2008; Roddie 2012a). In the finite-horizon model, the specification of an MPBE requires, for each period:

- a period-specific pricing rule for I as a function of its marginal cost, $\varsigma_{I,t}(c_{I,t})$;
- a period-specific entry rule for E as a function of its beliefs about I's marginal cost and its own entry cost draw; and
- a specification of E's beliefs about I's marginal costs given all possible histories of the game.

To form an MPBE, E's entry rule must be optimal given its beliefs and its expected postentry payoffs, and its beliefs should be consistent with I's pricing strategy and the application of (the continuous random variable version of) Bayes's rule on the equilibrium path. The pricing rule for I must be optimal given what E will infer from I's price and how E will

[6] In his presentation of the two-period Milgrom and Roberts (1982) model, Tirole (1988) assumes that a static monopolist should produce more than a duopolist with the same marginal cost. However, this condition will not hold in all models, such as one with homogeneous products and simultaneous Bertrand competition when the entrant has the higher marginal cost but it is below the incumbent's monopoly price.

decide to enter. The Markovian restriction is that history matters only through how it affects E's beliefs about I's current marginal costs. These beliefs are payoff relevant because they affect E's expected future profits and its entry decision. To eliminate possible pooling equilibria, we use the D1 refinement (Cho and Sobel 1990; Ramey 1996), which restricts the inferences that a receiver can make if it observes off-the-equilibrium-path actions, to eliminate pooling or partial pooling equilibria. Specifically, D1 requires the receiver to place zero posterior weight on a signaler having a type θ_1 if there is another type, θ_2, who would have a strictly greater incentive to deviate from the putative equilibrium for any set of post-signal beliefs that would give θ_1 an incentive to deviate.

The following theorem contains our main theoretical result for this model.

Theorem 1. Consider the following strategies and beliefs:

In the last period, $t = T$, a monopolist incumbent will set $p_{I,T} = p^{\text{static monopoly}}(c_{I,T})$, and the potential entrant will not enter whatever price the incumbent sets.

In all preentry periods $t < T$:

i. E's entry strategy will be to enter if and only if its entry cost κ_t is lower than a threshold $\kappa_t^*(\hat{c}_{I,t})$, where $\hat{c}_{I,t}$ is E's point belief about I's marginal cost and

$$\kappa_t^*(\hat{c}_{I,t}) = \beta(\mathbb{E}_t[\phi_{t+1}^E|\hat{c}_{I,t}] - \mathbb{E}_t[V_{t+1}^E|\hat{c}_{I,t}]), \tag{3}$$

where $\mathbb{E}_t[V_{t+1}^E|\hat{c}_{I,t}]$ is E's expected value at time t of being a potential entrant in period $t + 1$ (i.e., if it does not enter now), given equilibrium behavior at $t + 1$, and $\mathbb{E}_t[\phi_{t+1}^E|\hat{c}_{I,t}]$ is its expected value of being a duopolist in period $t + 1$ (which assumes that it has entered prior to $t + 1$).[7] The threshold $\kappa_t^*(\hat{c}_{I,t})$ is strictly increasing in $\hat{c}_{I,t}$.

ii. I's pricing strategy, $\varsigma_{I,t}(c_{I,t})$, will be the (unique) solution to a differential equation

$$\frac{\partial p_{I,t}^*}{\partial c_{I,t}} = \frac{\beta g(\kappa_t^*(c_{I,t}))(\partial \kappa_t^*(c_{I,t})/\partial c_{I,t})\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\}}{q^M(p_{I,t}) + (\partial q^M(p_{I,t})/\partial p_{I,t})(p_{I,t} - c_{I,t})} \tag{4}$$

and an upper boundary condition $p_{I,t}^*(\overline{c_I}) = p^{\text{static monopoly}}(\overline{c_I})$. The expectation $\mathbb{E}_t[V_{t+1}^I|c_{I,t}]$ is I's expected value of being a monopolist at the start of period $t + 1$ given current (t period) costs and equilibrium behavior at $t + 1$. The incumbent's expected value of being

[7] We define values at the beginning of each stage. For more details, see the discussion in app. A.

a duopolist in period $t+1$ is given by $\mathbb{E}_t[\phi^E_{t+1}|c_{I,t}]$. The function $\varsigma_{I,t}(c_{I,t})$ is strictly increasing in $c_{I,t}$, so it is fully separating and invertible.

iii. E's beliefs: observing a price $p_{I,t}$, E believes that I's marginal cost is $\varsigma_{I,t}^{-1}(p_{I,t})$ if $p_{I,t}$ is in the range of $\varsigma_{I,t}(c_{I,t})$. For off-path beliefs, if $p_{I,t} > \varsigma_{I,t}(\overline{c_I})$, then E believes that $c_{I,t}$ equals $\overline{c_I}$. If $p_{I,t} < \varsigma_{I,t}(\underline{c_I})$, then E believes that $c_{I,t}$ equals $\underline{c_I}$.

This equilibrium exists, and these strategies form the unique MPBE strategies and equilibrium-path beliefs consistent with a recursive application of the D1 refinement.

Proof. See appendix A. QED

The existence and uniqueness results are established recursively, beginning with the last period of the model, where there is no signaling.[8] We can then characterize the unique equilibrium in $T-1$, prove several properties of the firms' value functions implied by these strategies, and use these properties to show the existence and uniqueness of the equilibrium at $T-2$ and so on. We use well-known results from the literature on one-shot signaling models (in particular, Ramey 1996; Mailath and von Thadden 2013) to characterize the incumbent's unique equilibrium strategy in each period. To do this, we show that the incumbent's expected payoff function satisfies conditions of type monotonicity (a price cut is more costly for an incumbent with higher marginal costs), belief monotonicity (the incumbent always benefits when the entrant believes that he has lower marginal costs and so is less likely to enter), and a single-crossing condition (a lower-cost incumbent is always willing to cut the current price slightly more to differentiate itself from a higher-cost type). The more novel part of our results is that we show that these conditions will be satisfied throughout a multiperiod dynamic game under the simple conditions on static payoffs and entry costs given in assumptions 1–4. The fully separating equilibrium pricing strategy corresponds to the so-called Riley equilibrium (Riley 1979), where the incentive compatibility constraints consistent with full separation are satisfied at minimum cost to I in each period.

The fact that the incumbent's equilibrium strategy is fully separating, together with our assumption that there is complete information after entry so that there is no scope for E to time its entry to affect postentry competition, implies that on the equilibrium path, E's entry strategy (and choices) will be the same as in a model with complete information throughout the game. This property is very convenient because it means that we can solve for E's strategy without solving for I's limit pricing strategy.

We can use equation (4) to understand what the incumbent's limit pricing schedule will look like. From (4) and the boundary condition,

[8] Note that our recursive approach means that when we apply the D1 refinement, we are assuming that an off-the-equilibrium-path action in a period before t cannot affect how an off-the-equilibrium-path action in t is interpreted (Roddie 2012a).

the incumbent's limit price will be lower than its static monopoly price (except in the final period) for all c_I below $\bar{c}$. We will call this reduction in price "price shading" in what follows. To understand what will affect the magnitude of shading, it is useful to study a slightly rewritten version of (4) for the first period of a $T = 2$ version of the model, when there is only one chance for E to enter:

$$\frac{\partial p_{I,1}^{*}}{\partial c_{I,1}} = \frac{\beta(\partial \Pr(E \text{ enters in period } 1)/\partial c_{I,1})\{\mathbb{E}_{t=1}[\pi_I^M(p_I^{\text{static monopoly}}(c_{I,2}), c_{I,2})|c_{I,1}] - \mathbb{E}_{t=1}[\pi_I^D(c_{I,2})|c_{I,1}]\}}{q^M(p_{I,1}) + (\partial q^M(p_{I,1})/\partial p_{I,1})(p_{I,1} - c_{I,1})}. \quad (5)$$

Holding the discount factor fixed, the pricing function will become steeper, implying greater shading when, all else equal, (i) there is a greater difference between I's static monopoly and duopoly profits (i.e., when the entrant will tend to be more competitive); (ii) E's entry decision, which will be to enter if the entry cost is less than $\kappa_1^* = \mathbb{E}_{t=1}[\pi_E^D(c_{I,2})|c_{I,1}]$, is more sensitive to the incumbent's current marginal cost (this will be the case when I's marginal cost is more serially correlated and when the entry cost distribution has more mass around κ_1^*); and (iii) the profit that the incumbent loses when it lowers its price is small, which will depend on the curvature of the static profit function. As the static profit function will be flat at the static monopoly price, quite large price decreases may be incentive compatible as long as the curvature is not too great.

In the multiperiod model, the difference in expected next-period profits is replaced by $\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]$, where V^I and ϕ^I are the incumbent's continuation values as a monopolist and as a duopolist, respectively. As we now illustrate, the difference in continuation values can be much greater than the difference in static, one-period profits, because entry that is deterred in the current period may allow the incumbent to enjoy a number of periods of monopoly in the future. This can lead to substantial shading even if $c_{I,t}$ has only modest effects on the probability of entry.

B. Numerical Illustration and Cross-Market Comparisons

The previous analysis has focused on a single market. Our empirical analysis will focus on cross-market comparisons, where exogenous variation in market characteristics, such as market size, will lead to variation in how likely Southwest is to enter when it becomes a potential entrant. To illustrate both the magnitude of shading that the model can generate and these cross-market relationships, we introduce the assumptions that we will make in the calibration.

Assumption 5 (Calibration assumptions).

1. A firm's demand is determined by multiplying market size (M) by the firm's market share, which is determined as a function of prices by a static nested logit demand model.

2. I's marginal cost evolves according to an AR(1) process with truncated normal innovations

$$c_{I,t} = \rho^{AR} c_{I,t-1} + (1 - \rho^{AR}) \frac{\underline{c_I} + \overline{c_I}}{2} + \varepsilon_{I,t}, \tag{6}$$

where $\rho^{AR} > 0$, $\varepsilon_{I,t} \sim TRN(0, \sigma_c^2, \underline{c_I} - c_{I,t-1}, \overline{c_I} - c_{I,t-1})$ and the last two arguments give the lower and upper truncation points, and σ_c^2 is the variance of the untruncated distribution.

3. E's entry costs have a truncated normal distribution, with a lower truncation point at zero and an upper truncation point that exceeds the maximum possible discounted variable profits of the potential entrant.

The assumption that market size enters demand—and therefore profit functions—multiplicatively implies that in our model it has no effect on optimal monopoly or duopoly prices except through signaling incentives. Signaling incentives will vary because market size will affect the probability of entry, as for a given entry cost, entry will be more attractive in larger markets. An extended model discussed in section VI will allow market size to also affect pricing through capacity choices.

Figure 1 is constructed using the demand parameters that we estimate to perform the calibration (sec. V). Consistent with earlier airline estimates, they imply that an incumbent monopolist has substantial market power and that the incumbent and Southwest (our E) are quite close substitutes once entry has occurred. To construct the figure, we also assume that $c_E = \$150$, the range of c_I is \$170–\$270, $\rho^{AR} = 0.97$, and $\sigma_c = \$35$. The entry cost distribution has mean \$20 million and standard deviation \$2 million. The discount factor is 0.98, so that periods can be interpreted as quarters. While the finite structure of the model in section II.A allows us to show existence and uniqueness, it also implies that strategies will change from period to period, which complicates illustration. We will therefore solve for stationary strategies in the limiting infinite-horizon version of the model. Appendix B.1 explains the computational procedure.

Figure 1*a* shows I's (signaling) pricing strategy in the dynamic model for a market size of $M = 20{,}000$ for $\rho^{AR} = 0.97$ (our baseline case) and $\rho^{AR} = 0.7$. The difference between the incumbent's strategy and the static monopoly price indicates the degree of shading. As the incumbent's current marginal cost is less informative about E's postentry profits when $\rho^{AR} = 0.7$, there is less shading, but in both cases the threat of entry causes the incumbent to significantly lower its price when $c_I < \overline{c_I}$. We can illustrate that shading yields a higher expected payoff than the static monopoly price by considering an example: for $\rho^{AR} = 0.97$ and $c_I = \$220$, the incumbent shades its price by \$59. As shown in figure 1*b*, this lower price reduces the incumbent's current profit by \$37,785 compared with the

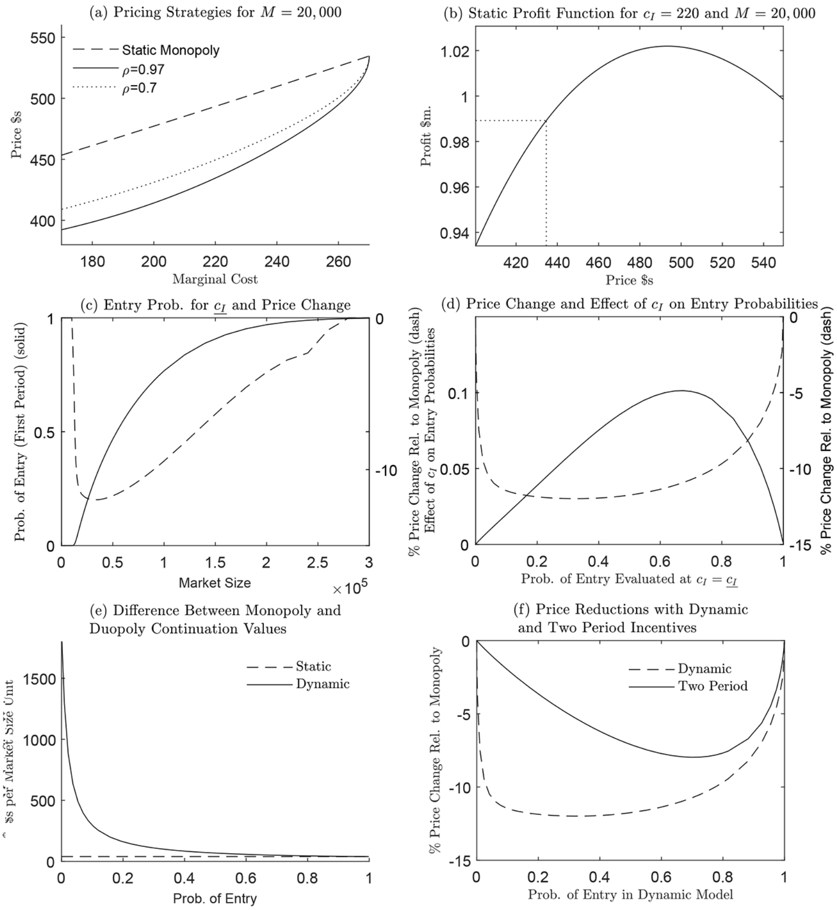

FIG. 1.—Relationship between market size, entry probabilities, and shading in the dynamic limit pricing model.

static optimal price of \$493. On the other hand, the difference in the incumbent's expected monopoly and duopoly continuation values is \$5.1 million, and charging the limit price reduces the entry probability from 0.143 to 0.131. As $(0.143 - 0.131) \times 5.1 > 0.038$, choosing the limit price increases the incumbent's payoff.

Figure 1*c* shows how the equilibrium entry probability (measured at $c_I = \underline{c_I}$) and the average price change due to signaling (expressed as percent of the static monopoly price) when we vary market size from 1,000 to 300,000 people. There is a monotonic and increasing relationship between market size and the probability of entry and a nonmonotonic relationship between market size and the degree of shading. The assumption that entry costs are normally distributed implies that, all else equal, *E*'s entry decision will be most sensitive to I's marginal cost when the probability of entry takes on intermediate rather than extreme values. The implied nonmonotonicity between the probability of entry (which here is varying because of market size) and the degree of shading is the relationship that we will observe in the data and our calibration.

One might have expected that I's marginal cost would need to have a large absolute effect on the probability of entry to generate significant shading. Figure 1*d* shows that this is not necessarily the case in the dynamic model by plotting the relationship between the entry probability at $c_I = \underline{c_I}$ (X-axis) as we vary market size, the difference in the entry probabilities for $c_I = \overline{c_I}$ and $c_I = \underline{c_I}$ (left Y-axis), and the degree of shading (right Y-axis). The degree of shading can be large when the effect that c_I has on the entry probabilities is quite small. For example, for $M = 20{,}000$, the incumbent's cost can reduce the entry probability only from 0.143 to 0.119, but there is an average 11.6% reduction in the incumbent's price. The degree of shading is maximized at 12.0% of the static profit-maximizing price when the entry probability for $c_I = \underline{c_I}$ is 0.291.

Figure 1*e* and 1*f* help to explain why the dynamic model can generate significantly more shading than the two-period model. Figure 1*e* compares the average difference in the continuation values per unit of market size (i.e., $(\mathbb{E}_t[V^I_{t+1}|c_{I,t}] - \mathbb{E}_t[\phi^I_{t+1}|c_{I,t}])/M$ averaged over $c_{I,t}$) in the first period of a two-period model and the dynamic model, as a function of the entry probability. Under assumption 5, the difference in continuation values per market size unit in the two-period model is independent of market size. In the dynamic model, the difference in continuation values depends on the probability of entry in future periods. When the probability of entry in future periods is very high, the difference between dynamic continuation values is essentially just the difference between one-period profits. However, at very low entry probabilities, the difference can be up to $50(= 1/(1 - 0.98))$ times greater, and as a result, incentives to signal are strengthened. Figure 1*f* compares, for given entry probabilities, equilibrium shading when the incumbent considers only payoffs in the next period, as it would in a two-period model, and when it considers dynamic continuation values.[9] Consistent with our discussion above, there is much less shading in equilibrium in the two-period model, unless entry probabilities are high. This difference is important for our empirical application because we observe large price cuts in markets where entry does not occur for quite long periods of time.

[9] To be precise, in both cases we use the entry probabilities implied by the infinite-horizon dynamic model and compute the incumbent's pricing strategy using either (4) (dynamic model) or (5) (two-period model). We use this approach because there is no natural way to rescale the entry cost distributions to generate comparable probabilities of entry.

C. *Extensions and Limitations*

The model presented above is simple, and we wish to emphasize that it is possible to relax many of the assumptions. Our results would not change if E received information that allowed it to infer $c_{I,t}$ after it had taken its period-t entry decision. This is relevant for our empirical setting, where the Department of Transportation releases data that might help firms to understand their rivals' costs with a one- or two-quarter lag. Gedge, Roberts, and Sweeting (2014) show that all of the results hold when the potential entrant's marginal cost varies over time as long as it is publicly observed. We can also extend the model to allow for the incumbent's marginal cost to be partly endogenous, through being dependent on its capacity investment, and for the incumbent to be learning about the parameters of the entrant's entry cost distribution, as we show in appendix F. However, in these cases we have not been able to show that simple conditions on the static primitives of the model are sufficient to guarantee existence and uniqueness of an equilibrium. Instead, we have to numerically verify conditions on value functions in each period of the game. We could also introduce the possibility that one of the firms may exit during the duopoly game that follows entry, although we have chosen not to focus on this more complicated case, as in our sample of routes there is only one case where Southwest enters and then exits, and the incumbent is still active 2 years after Southwest enters on over 80% of routes. We may also be able to relax the assumption of complete information in the postentry game: Sweeting, Tao, and Yao (2019), building on Mailath (1989), illustrate how multisided signaling in an oligopoly pricing game can significantly affect prices. However, the oligopoly signaling game is more challenging to solve than the one considered here.

Other features of the model appear more essential. In particular, tractability requires that the signaler has only one piece of private information per period.[10] This is a limitation, as in many environments it is plausible that an incumbent has private information about both its costs and the level of demand. Some people have also suggested that the implications of our model are not intuitive. For example, when the degree of serial correlation is high, our model predicts that I will shade price significantly in every period, even though past prices will provide E with a quite tight prior over I's current marginal cost. Our result reflects a standard feature of fully separating equilibria in signaling models: the equilibrium distortion introduced by signaling does not depend on the receiver's prior but only on the range of values of the private-information variable that are possible, and here our assumption that marginal costs can transition to

[10] When we allow for both pricing and capacity investments, we specify a timing structure, which means that capacity cannot be used as a signal.

any value on $[\underline{c}, \bar{c}]$ is important. As a result, there is a discontinuity in the equilibrium between the case where the receiver's prior has zero variance, in which case signaling may not be possible, and the case where the prior has a small but positive variance, where signaling can have a large effect on prices. One interpretation of this feature is that signaling is implausibly powerful in a model such as ours, but one might also argue that the discontinuity reflects the fact that it is the complete-information model that embodies the extreme assumption, generating predictions that are quite different from more plausible models where some asymmetry of information exists.

III. Empirical Application and Data

We now examine whether our model can explain why dominant incumbent airlines lower prices when faced with the threat of entry by Southwest. In this section, we introduce the empirical setting and describe the data, with additional details given in appendix C.

A. Empirical Application: Background

Several studies (e.g., Morrison and Winston 1987) show that airline ticket prices tend to be lower when there are more potential competitors (defined as carriers serving one or both end points but not yet serving the route), but "the most dramatic effects from potential competition arise in the case of Southwest Airlines . . . the dominant low-cost carrier" (Kwoka and Shumilkina 2010, 772). Morrison (2001) and Goolsbee and Syverson (2008) estimate that potential competition from Southwest lowers incumbent prices by as much as 33% and 19%–28%, respectively, consistent with observations in the media (e.g., Zuckerman 1999). These are the largest-estimated price effects of potential competition in any industry (Bergman 2002), but the literature has provided no clear explanation for why incumbents lower prices when Southwest is a potential competitor but has not yet entered. Goolsbee and Syverson (2008) tentatively favor a deterrence explanation on the basis that, in their sample, observed price declines are smaller on routes where Southwest preannounces its entry, although the difference with their remaining routes is not statistically significant. Because incumbents do not tend to increase their capacities when entry is threatened, Goolsbee and Syverson (2008) suggest that carriers may lower prices to increase customer loyalty, lowering Southwest's expected market share if it enters (Goolsbee and Syverson 2008, 1629). While we also find that capacities do not change, our preferred explanation involves incumbents signaling to Southwest.

Deterrence explanations are consistent with the comments of legacy carrier executives about the importance of preventing Southwest from entering routes, especially at their hub airports, which is where Bennett and Craun (1993) originally identified the Southwest Effect.[11] They are also consistent with the comments of Southwest's managers that indicate that their entry decisions on at least some routes are sensitive to new information about incumbent prices and expected route profitability.[12] We present new evidence that favors a deterrence explanation, focusing on routes with a single dominant incumbent when entry is threatened, which are almost all routes from one of the dominant incumbent's hubs, as these routes come closest to the market structure assumed in models of strategic investment, including ours. We show that the data are particularly consistent with a limit pricing/signaling explanation, where incumbents use prices to signal information about the profitability of the route to Southwest. Most of our analysis will focus on the average price charged by a carrier, but results in appendixes C.4 and D.2.3 will show that we observe similar price changes across the price distribution, which theory predicts should happen if a limit pricing incumbent can price discriminate between different classes of customer (Pires and Jorge 2012).

A critical feature of our story is that the incumbent must have some private information that will affect how tough it will be as a competitor. For an airline, the marginal cost of selling a seat to a local passenger depends on the demand for seats on the same flight from connecting passengers (i.e., those traveling as part of longer itineraries). Edlin and Farrell (2004) and Elzinga and Mills (2005) document the difficulties of estimating marginal costs on routes where connecting traffic is important, even with access to a carrier's internal data. Almost all of the routes in our dominant incumbent sample are routes from hubs where connecting traffic is especially important. We provide a model where the incumbent's private information is about the level of connecting demand and its marginal costs depend on this demand and endogenously chosen capacities in appendix F.[13]

[11] For example, when Southwest entered Philadelphia in 2004, then US Airways CEO David Siegel told employees, "Southwest is coming for one reason: they are coming to kill us. They beat us on the West Coast, and they beat us in Baltimore. If they beat us in Philadelphia, they're going to kill us" (*Business Travel News* 2004).

[12] For example: "It's all based on customer demand. We're always evaluating markets to see if they are overpriced and underserved" (quote from Southwest spokesperson Brandy King, cited in Swett 2002). Also: "Southwest does not have any hard and fast criteria dictating when it enters a market. The method is a cautious, reactive approach designed to take advantage of opportunities as they arrive" (quote from Brook Sorem, Southwest's manager of schedule planning, reported in *World Airport Week* 1998). Herb Kelleher, longtime chairman and CEO of Southwest, also admitted to having at least six different strategic plans for how Southwest might develop in the northeastern United States after its initial entry into Providence, Rhode Island (McCartney 1996). Consistent with entry decisions becoming more sensitive to time-varying information, Boguslaski, Ito, and Lee (2004) show that fixed market characteristics explained fewer of Southwest's entry decisions over the 1990s.

[13] Of course, connecting traffic is likely to be correlated across routes, and we have not tried to design a model where Southwest (or any other potential entrant) can make inferences from pricing behavior on multiple routes.

B. Data

Most of our data are drawn from the US Department of Transportation's Origin-Destination Survey of Airline Passenger Traffic (data bank 1; DB1), a quarterly 10% sample of domestic tickets, and its T100 database that reports monthly carrier-segment-level information on flights, capacity, and the number of passengers carried on the segment (which may include connecting passengers). We aggregate the T100 data to the quarterly level to match the structure of the DB1 data, and we include flights operated by and trips on regional affiliates operating for the primary carrier. From DB1, we drop itineraries with prices greater than $2,000 and less than $25 (for one-way trips, we use half these amounts) and those involving more than one connection in either direction. Our data cover the period from 1993:1 to 2010:4 (72 quarters).

Following Goolsbee and Syverson (2008), we define a market as a nondirectional airport pair with quarters as periods. We consider only pairs where on average at least 50 DB1 passengers are recorded as making return trips each period, possibly using connecting service, and in everything that follows a one-way trip is counted as half of a round trip. We also exclude pairs where the round-trip distance is less than 300 miles. We define Southwest as having entered a route once it has at least 65 flights per quarter recorded in T100 and carries 150 direct passengers on the route in DB1, and we consider it to be a potential entrant once it serves at least one route nonstop out of each of the end point airports.[14]

Based on our potential entrant definition, there are 1,542 markets where Southwest becomes a potential entrant after the first quarter of our data and before 2009:4. We choose this cutoff so that we can look at whether Southwest enters in the following year. Southwest enters 337 of these markets during the period of our data. We will call these 1,542 markets our "full sample." However, we will focus most of our analysis on a subset of markets where one carrier is a dominant incumbent before Southwest enters. As we want to identify sustained dominance in a market, we use the following rules to identify a dominant carrier (where we treat a carrier on a route before and after a merger as the same carrier, even if the merger changes the carrier's name):

1. To be considered "active" in a route quarter, a carrier must have at least 150 DB1 direct (i.e., not connecting) passengers.
2. Once the carrier becomes active in a market, it is considered dominant in the market if three conditions are met: (i) it must be active in at least 70% of quarters before Southwest enters, (ii) in 80% of those quarters it must account for 80% of direct traffic and at least

[14] The results are not sensitive to our 65-flight threshold, as there are less than 2% of route quarters where Southwest has more than one flight but fewer than 100 flights per quarter.

50% of total traffic, and (iii) during the time that Southwest is a potential entrant, Southwest must carry fewer than an average of 50 DB1 passengers per quarter. These thresholds are also chosen so that there are few observations close to them.

We identify 109 markets, listed in appendix C.1, with a dominant incumbent before Southwest enters. However, Southwest enters some of these routes in the same quarter that it becomes a potential entrant, and for others Southwest is already a potential entrant when the incumbent meets our definition of dominance. As a result, there are 65 markets where we observe a dominant incumbent both before Southwest is a potential entrant and after it is a potential entrant but before it actually entered. It is price changes on these routes that can identify how the entry threat changes the dominant incumbent's behavior, although we include all 109 routes in our "dominant incumbent" sample regressions to more precisely identify the coefficients on the time effects and other controls.

Table 1 provides some summary statistics that allow for a comparison of routes in the different samples. While all sets of routes have heterogeneous characteristics, dominant incumbent markets tend to be shorter, with end point airports that are more likely to be primary airports in large cities.

TABLE 1
COMPARISON OF MARKETS IN THE FULL SAMPLE AND DOMINANT INCUMBENT SAMPLES

	Full Sample		Dominant Incumbent Samples: 109 Markets		Dominant Incumbent Samples: 65 Markets	
	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Mean end point population (millions)	2.509	1.918	2.834	1.923	3.218	2.112
Round-trip distance (miles)	2,525.11	1,352.57	1,257.57	743.08	1,344.5	798.75
Constructed market size measure	33,005	46,389	65,637	68,589	52,325	62,642
Origin or destination is a:						
Primary airport in multiairport MSA	.186	.389	.321	.469	.262	.443
Secondary airport in multiairport MSA	.316	.465	.321	.469	.369	.486
Airport in big city	.643	.479	.844	.364	.877	.331
Leisure destination	.108	.311	.110	.314	.092	.292
Slot-controlled airport	.039	.193	.064	.246	.108	.312
Number of markets	1,542		109		65	

NOTE.—We define leisure destinations (primarily cities in Florida; Las Vegas; Charleston, SC; and New Orleans) and big cities (top 30 metropolitan statistical areas [MSAs] excluding leisure destinations) following Gerardi and Shapiro (2009). We define New York's John F. Kennedy, LaGuardia, and Newark; Washington's Reagan; and Chicago's O'Hare airports as slot controlled, although slot controls are no longer in place at O'Hare. We identify metropolitan areas with more than one major airport using Wikipedia (http://en.wikipedia.org/wiki/List_of_cities_with_more_than_one_airport) and identify the primary airport as the one with the most passenger traffic in 2012.

They are also larger by a measure of market size that we construct using an estimated generalized gravity model (see app. C.2) so that we capture how traffic varies systematically with both distance and the total number of passengers using the end point airports, in ways that more common population-based measures of market size do not. As we will use the market size variable as an exogenous determinant of the probability of Southwest's entry into a market, we base our explanatory variables on passenger flows in 1993:1, the first quarter of our sample, when we estimate the gravity equation and predict market sizes for subsequent quarters. All of the markets in our dominant firm sample are shorter than the longest routes that Southwest flies nonstop (such as Las Vegas–Providence), so its entry should be feasible.

Our analysis will focus on how incumbent prices change when Southwest threatens entry. For each market, we split the sample quarters into three groups:

- Phase 1: before Southwest is a potential entrant on the route.
- Phase 2: when Southwest is a potential entrant on the route but has not (yet) entered.
- Phase 3: after Southwest has entered.

Table 2 reports, for our dominant incumbent markets, summary statistics for prices, capacities, and passenger flows for each of these phases. The dominant carrier's average capacity and passenger numbers are higher for phase 3 observations because Southwest enters only a selected set of markets. The statistics are consistent with Southwest's actual entry reducing the incumbent's price and its market share significantly, suggesting that an incumbent would be willing to make investments that reduce its current profits if doing so could deter or delay entry.

The summary statistics also suggest that incumbents lower prices by an average of almost \$90 (15%) when Southwest threatens entry (the comparison is most straightforward for the middle columns where the set of markets is the same). This is the pattern documented by Goolsbee and Syverson (2008) using a regression analysis for a broader sample of markets from 1993 to 2004. We have repeated Goolsbee and Syverson's (2008) regression analysis, which estimates price effects for quarters around when Southwest becomes a potential entrant and an actual entrant, controlling for market-incumbent fixed effects,[15] quarter fixed effects, and time-varying controls, using our dominant incumbent sample (app. C.4).

[15] The name of the dominant carrier can change during the sample because of a merger. For example, the dominant incumbent on the Hartford–Minneapolis route was Northwest at the start of our sample and Delta at the end of our sample. In this analysis and in our analysis in sec. IV, we give the carrier the identity of the owner at the end of the sample. On this basis, there is one incumbent for each of the dominant incumbent markets in our sample.

TABLE 2
SUMMARY STATISTICS: DOMINANT INCUMBENT SAMPLE

	Phase 1: $t < t_0$							
	All Markets		Markets with Phase 1 and Phase 2 Observations		Phase 2: $t_0 \leq t < t_e$		Phase 3: $t \geq t_e$	
Variable	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation	Mean	Standard Deviation
Incumbent pricing:								
Yield (average fare per mile)	.516	.331	.527	.339	.452	.323	.311	.166
Average fare	476.77	135.18	514.55	144.44	426.06	117.68	261.83	60.65
Southwest pricing:								
Yield					.296	.150	.235	.072
Average fare					388.50	120.45	214.37	62.63
Passenger shares:								
Incumbent	.797	.213	.743	.235	.840	.122	.461	.198
Southwest					.018	.032	.479	.217
Incumbent capacity and traffic:								
Capacity (seats performed)	75,760	52,459	72,785	49,012	69,770	47,066	90,877	52,314
Segment passengers (including connecting passengers)	46,072	32,141	44,174	29,814	48,478	31,677	64,385	38,585
Load factor	.612	.104	.618	.106	.710	.121	.705	.081
Proportion of passengers connecting	.837	.114	.847	.109	.830	.115	.774	.107
Southwest capacity and traffic:								
Capacity (seats performed)							80,751	62,207
Segment passengers (including connecting passengers)							52,713	39,195
Load factor							.651	.083
Proportion of passengers connecting							.701	.101
Number of markets	109		65		65		59	

For both average yield (average price divided by route distance) and the log of average price measures, as well as percentiles of the price and yield distributions, we estimate that, on average, dominant incumbents lower prices by 10%–14% when Southwest becomes a potential entrant and by an additional 30%–45% if Southwest actually enters, relative to the incumbent's prices more than eight quarters before the start of phase 2. The phase 2 declines are slightly smaller than those estimated by Goolsbee and Syverson (2008), but the phase 3 declines are larger, consistent with a dominant incumbent's phase 1 prices reflecting significant market power. We also observe two other interesting patterns: first, incumbents start to lower prices two quarters before the start of phase 2. This pattern is consistent with our model once we recognize that Southwest's entry is typically announced several months before it operates flights and that incumbents should want to try to influence Southwest's choice of routes to enter from that date, whereas we have defined the start of phase 2 based on when Southwest begins to operate flights at both end points.[16] Second, we estimate that, on average, incumbent prices fall by more over time during phase 2—that is, when Southwest does not actually enter. Additional investigation reveals that this feature is driven by a subset of the dominant incumbent markets in our data and that both our basic model and especially an extended version of our model are able to explain this feature as well (secs. V, VI; app. F).

Table 2 also reports a number of other statistics for the incumbent and Southwest. Over 80% of the incumbent's passengers on our route segments are making connections during phase 2, suggesting that explanations for marginal-cost opaqueness based on connecting passenger flows are appropriate. We can also see that during phase 2 the incumbent's load factor tends to increase and that Southwest carries only a small share of the passengers on the route through its connecting service (of course, our rules for defining dominant incumbents were designed to make sure that Southwest is not a significant competitor when it is a potential entrant). These facts provide some preliminary evidence against explanations for phase 2 price reductions that are based on the incumbent's marginal costs falling (marginal cost should increase in the load factor) or actual competition from Southwest once it serves the end point airports.

IV. Nonmonotonic Relationship between Incumbent Price Reductions and the Probability of Southwest Entry

In this section, we show that in our data there is a nonmonotonic relationship between the probability that Southwest enters a dominant

[16] For a sample of 24 airports where we could identify the exact dates that Southwest announced its entry and began flights, the average gap was 140 days. It is possible that rival airlines anticipate Southwest's entry some weeks before its entry is announced.

incumbent market and how much the incumbent lowers its price in phase 2. This is consistent with the roughly U-shaped relationship predicted in figure 1*d*. We will argue that limit pricing is the explanation that best describes this relationship and other features of the data. Readers should refer to appendix D and Sweeting, Gedge, and Roberts (2018) for additional discussion and results.

We estimate the relationship between the probability of entry and phase 2 price reductions using a two-stage approach. Our second-stage specification is

$$\begin{gathered}\text{Price Measure}_{j,m,t} = \gamma_{j,m} + \tau_t + \alpha X_{j,m,t} + \ldots \\ \beta_0 \text{SWPE}_{m,t} + \beta_1 \widehat{\rho_m} \times \text{SWPE}_{m,t} + \beta_2 \widehat{\rho_m}^2 \times \text{SWPE}_{m,t} + \epsilon_{j,m,t},\end{gathered} \tag{7}$$

where $\widehat{\rho_m}$ is the predicted probability that Southwest will enter within four quarters. Specification (7) is estimated only using observations on the dominant incumbent's prices during phases 1 and 2 (i.e., before Southwest actually enters), and $\text{SWPE}_{m,t}$ is an indicator for phase 2 observations, X includes dummies for the number of observed direct and connecting competitors on the route and jet fuel prices interacted with route distance, and $\gamma_{j,m}$ and τ_t are market-incumbent and quarter fixed effects, so that the β coefficients measure how the incumbent changes prices when entry is threatened as a function of $\widehat{\rho_m}$. We test for a nonmonotonicity using a quadratic specification because of the small number of observations (in app. D.2.2 we show that a plot of the estimated price declines in each market against the probability of entry also indicates a nonmonotonicity). A pattern where $\widehat{\beta_0} \approx 0$, $\widehat{\beta_1} < 0$, and $\widehat{\beta_2} > 0$ will be consistent with figure 1*d*.

Specification (7) is essentially a cross-market regression of changes in one market outcome (the incumbent's price) on the predicted probability of another market outcome (whether Southwest enters). As we do not have an additional set of similar markets where entry was threatened but limit pricing was not possible that we can use as controls, we face a number of possible endogeneity concerns in interpreting the results as reflecting how the threat of entry causes limit pricing behavior. These concerns shape how we construct our $\widehat{\rho_m}$ and lead us to consider a range of possible alternative explanations for a U-shaped relationship.

The parameter $\widehat{\rho_m}$ is estimated in a first stage using a probit specification. The dependent variable equals one if and only if Southwest enters the market within four quarters of becoming a potential entrant.[17] The

[17] We examine entry within four quarters, and end our analysis 1 year from the end of our data, so that we do not have to deal with the truncation that results from different markets being exposed to the threat of entry for different numbers of periods. Our specification assumes that there is a positive and monotonic relationship between the probability that Southwest will enter within four quarters and the probability that it will enter in later quarters if it has not already done so.

TABLE 3
SECOND-STAGE ESTIMATES OF THE RELATIONSHIP BETWEEN THE PROBABILITY THAT SOUTHWEST ENTERS AND CHANGES IN INCUMBENT PRICES, CAPACITIES, SEGMENT TRAFFIC, AND LOAD FACTORS

Dependent Variable	Log Price (1)	Yield (2)	Log Capacity (3)	Log Passengers (4)	Log Load Factor (5)
$SWPE_{m,t}$	−.043*	−.002	.068	.144***	.076***
	(.023)	(.014)	(.043)	(.044)	(.017)
$\widehat{\rho_m} \cdot SWPE_{m,t}$	−.693***	−.732***	.040	.578	.538***
	(.182)	(.142)	(.362)	(.413)	(.142)
$\widehat{\rho_m}^2 \cdot SWPE_{m,t}$	1.169***	1.046***	−.820	−2.053***	−1.233***
	(.256)	(.219)	(.619)	(.749)	(.236)
Observations	3,884	3,884	3,400	3,400	3,400

NOTE.—Heteroskedasticity-robust Newey-West standard errors allowing for one-period serial correlation and corrected for first-stage approximation error in the entry probabilities are given in parentheses. The number of observations reflect differences in the coverage and reporting in the DB1 and T100 data during our sample period. The predicted probability that Southwest enters within four quarters of becoming a potential entrant is based on estimates reported in app. D.1, and these specifications include market-incumbent and quarter fixed effects and time-varying controls listed in the main text.
* Significant at the 10% level.
*** Significant at the 1% level.

explanatory variables include quarter dummies, measures of market size and concentration, and measures of how the route fits into the networks of the incumbent and Southwest. We make two choices to reduce the possibility that phase 2 price cuts could affect the entry decisions in our first-stage specification. First, the probit is estimated using the full sample excluding our dominant incumbent markets. Second, any variables based on passenger flows, which could be affected by prices, are calculated using phase 1 quarters that are more than 1 year before the start of phase 2.[18] Appendix D.2.3 shows that our second-stage results are robust to reducing the set of explanatory variables even further.

The probit estimates are presented in appendix D.1, and they show that Southwest is more likely to enter shorter and larger markets, routes that include one of its focus airports, and markets that are more concentrated before it enters. When we apply the estimates to the 65 dominant incumbent markets with phase 1 and phase 2 observations, the predicted probabilities of entry within four quarters vary from 2.6×10^{-4} to 0.99, with the 20th, 40th, 60th, and 80th percentiles at 0.02, 0.12, 0.28, and 0.54, respectively.

Columns 1 and 2 of table 3 show the estimated second-stage coefficients for the log(average price) and average yield price measures (for

[18] For 474 of the 1,542 markets in the full sample, we have only fewer than four phase 1 quarters, and in this case we use all of the phase 1 quarters that we do have.

graphical illustration, see fig. D.1; figs. D.1, D.2, E.1, E.2, F.1–F.3 are available online). There is a U-shaped relationship between price changes and the probability of entry. The largest and most significant predicted price declines of just under 15% relative to phase 1 prices happen when the probability of entry is in the region of 0.3 or 0.4. In both cases, price declines for very high or low entry probabilities are predicted to be small and/or statistically insignificant.

This pattern is consistent with the prediction of our limit pricing model when we exogenously varied the probability of entry by changing market size, but there are several possible alternative explanations for why we observe this pattern in the data. Here we briefly summarize the arguments against these alternatives that are discussed in detail in appendix D.2.3.

Several explanations would involve the incumbent's prices falling in phase 2 because its marginal costs are falling. One story would be that airport improvements (e.g., capacity increases) lower the incumbent's marginal costs and lead Southwest to consider entering the airport. If this is particularly pronounced for intermediate probability of entry markets, then this could generate a U-shaped pattern. We address this possibility by showing that the estimated nonmonotonicity is robust to including airport × phase 2 fixed effects, so that identification comes from variation in entry probabilities across routes within airports. We also find no evidence of a nonmonotonicity at the end of phase 1, which we might expect if airport developments cause incumbents to lower prices and Southwest to consider entering an airport. Alternative stories would involve the incumbent's marginal costs falling because it responds to the threat of entry by increasing its capacity, possibly to try to deter entry (e.g., Dixit 1980), or because it loses customers, lowering its load factor, once consumers can fly Southwest to other destinations.[19] Columns 3–5 of table 3 address these questions using our specification (7) and the natural logs of the incumbent's capacity, the total number of passengers on its flights, and its average load factor as dependent variables. The estimated coefficients (and the plots available in fig. D.1) indicate that traffic and load factors increase in the intermediate probability of entry markets, while capacity does not change significantly. These results are not consistent with the incumbent's marginal costs falling. In appendix D.2.3, we also present results suggesting that competition from the connecting service that Southwest can provide in phase 2 does not explain the results.

A final alternative explanation is that incumbents lower prices to build up the loyalty of their customers, possibly by encouraging them

[19] The model presented in sec. II did not include capacity investment, and variation in a carrier's optimal capacity investment policy with market size when facing the possibility of new entry as market size varies, even without any deterrence incentives, could affect pricing. This is one reason why we discuss a model where capacity investment is an integral part of the model in sec. VI.

to accumulate miles in frequent-flyer programs (FFPs).[20] Appendix D.3 discusses evidence that suggests that loyalty building is unlikely to be the primary reason why prices fall. We observe significant nonmonotonic price declines across the price distribution, not just for more expensive seats that will tend to be bought by business travelers who are most likely to be members of FFPs, and we are also not able to find any evidence that price reductions increase an incumbent's future demand as a loyalty story would suggest. It also seems unlikely that across-the-board reductions in ticket prices would be more effective at building loyalty or FFP participation than targeted rewards, such as double- or triple-miles promotions, which we cannot observe in the data.

V. Calibration

In this section, we calibrate a version of the model from section II where we allow for a more flexible model of mean entry costs to capture how entry probabilities vary across markets and over time. We choose the demand, marginal cost, and entry cost parameters using no information on how incumbent prices change during phase 2. We show that the calibrated model predicts a pattern of price declines that matches the nonmonotonic pattern of price reductions in the data quite accurately. We use the calibrated model to quantify the welfare effects of limit pricing and of subsidies that would encourage Southwest to enter.

A. Parameter Estimation

1. Overview

Our dominant incumbent sample contains heterogeneous markets with different demands and costs that vary over time and where many factors affect how likely Southwest is to enter. It is computationally infeasible to structurally estimate a version of the model that captures all of this heterogeneity. We therefore choose to use a single set of demand and marginal cost parameters, where dynamics enter only through marginal costs, and we create a transformed market size variable that allows us to capture cross-market variation in entry probabilities in a single dimension. In this subsection, we describe how we choose the demand and marginal cost parameters, transform market size, and match empirical entry hazards to estimate the distribution of entry costs.

[20] This type of strategy could be rationalized by either entry-deterrence or entry-accommodation incentives (loyalty could soften postentry competition or increase the incumbent's demand), although the observed nonmonotonicity is consistent only with a deterrence explanation, as accommodation would suggest that we should see the largest strategic investments in markets where entry is most likely.

2. Demand Estimation

We model passenger demand using a one-level nested logit structure, where the incumbent and Southwest (once it enters) are in one nest and choosing not to travel or flying another carrier form the outside good. The indirect utility function is

$$\begin{aligned} u_{i,j,m,t} &= \mu_j + \tau_1 T_t + \tau_{2-4} Q_t + \gamma X_{j,m,t} - \alpha p_{j,m,t} + \xi_{j,m,t} + \zeta^{FLY}_{i,m,t} + (1-\lambda)\varepsilon_{i,j,m,t} \\ &\equiv \theta_{j,m,t} - \alpha p_{j,m,t} + \xi_{j,m,t} + \zeta^{FLY}_{i,m,t} + (1-\lambda)\varepsilon_{i,j,m,t}, \end{aligned} \tag{8}$$

where we allow mean utility to depend on the number of other carriers that carry any passengers direct (the interpretation is that these carriers affect the value of the outside good); a linear time trend; quarter-of-year dummies; route distance and distance squared; dummies for routes involving a hub, a tourist destination, or an end point in a metropolitan statistical area with multiple major airports; and dummies for Southwest and the major incumbent carriers. We estimate demand using the standard estimating equation for a nested logit model using aggregate data (Berry 1994). Our observations are phase 1 observations for the dominant incumbent and (where available) phase 3 observations for the incumbent and Southwest from the 109 dominant incumbent markets. Table 4 reports the estimates for the price and nesting parameters using ordinary least squares and our preferred two-stage least squares (2SLS) specification, where we instrument for a carrier's price and a carrier's share of its nest using fuel prices interacted with route distance, as well as—for Southwest—a measure of the incumbent carrier's presence (measured by the proportion of traffic served) at the end point airports and whether an end point is a hub for the incumbent and—for the incumbent—an

TABLE 4
Nested Logit Demand: Price and Nesting Parameters

	OLS	2SLS
Fare ($, hundreds; $\hat{\alpha}$)	−.317***	−.446***
	(.011)	(.034)
Inside share ($\hat{\lambda}$)	.748***	.793***
	(.033)	(.072)
Observations	6,037	6,037
R^2	.301	

Note.—Specification also includes a linear time trend, quarter-of-year dummies, dummies for Southwest and the major incumbent carriers, market characteristics (distance, distance^2, indicators for whether the route includes a carrier's hub or a leisure destination or is in a city with another major airport), and dummies for the number of competitors offering direct service. The instruments used for 2SLS are described in the main text. Robust standard errors are given in parentheses. OLS = ordinary least squares.

*** Significant at the 1% level.

indicator for whether Southwest has entered and Southwest's presence at the end points. The 2SLS parameters imply that the incumbent and Southwest are quite close substitutes, and the average phase 3 own-price elasticity for an incumbent is −2.92.

3. Marginal Cost Estimation

We use the demand estimates and the first-order conditions associated with static, complete-information profit maximization for quarters in phases 1 and 3, under the assumption that limit pricing takes place only in phase 2, to infer the carriers' marginal costs in each quarter. The average implied marginal cost for the incumbent is $258. On average, Southwest's implied marginal costs are 31% (or 5.4 cents per mile) lower than the incumbent's during phase 3, which is consistent with differences between the average operating cost per available and per equivalent seat mile for legacy carriers and Southwest reported by the MIT Airline Data project based on data from the Department of Transportation's Form 41 (available at http://web.mit.edu/airlinedata/www/default.html). We estimate an AR(1) process using the implied marginal costs per mile:

$$mc_{j,t} = \rho^{AR} mc_{j,t-1} + X_{j,t}\gamma + \mu_t + \mu_j + \varepsilon_{j,t}, \tag{9}$$

where μ_t and μ_j are quarter and carrier dummies. The controls in X include interactions between the one-quarter-lagged jet fuel price and distance, market size, average end point populations, and a dummy for whether an end point airport is slot controlled. Table 5 shows the estimates of p^{AR} from four specifications. In the 2SLS specifications, we instrument for the lagged marginal cost using three previous lags, as we

TABLE 5
MARGINAL COST EVOLUTION: ESTIMATES OF SERIAL CORRELATION

	OLS All Carriers (1)	2SLS All Carriers (2)	2SLS Southwest (3)	2SLS Incumbents (4)
$\widehat{\text{MC per mile}}_{j,m,t-1}$	.916***	.974***	.978***	.962***
	(.037)	(.013)	(.039)	(.012)
Observations	5,658	4,710	1,492	3,218
R^2	.834			

NOTE.—The dependent variable is $\widehat{\text{MC per mile}}_{j,m,t}$, carrier j's computed marginal cost (MC) per mile in market m in quarter t. The specification also includes market characteristics (market size, average population, distance, and a dummy for whether one of the airports is slot constrained), quarter dummies, carrier dummies, and the lagged price of jet fuel interacted with route distance. In columns 2–4, we use the third through fifth lags of marginal cost per mile to instrument for lagged marginal costs. Robust standard errors, corrected for the uncertainty in the demand estimates, are given in parentheses. OLS = ordinary least squares.

*** Significant at the 1% level.

recognize that our estimates of a carrier's marginal cost in any quarter are functions of noisy estimates of average prices and market share.

4. Choosing the Demand and Marginal Cost Parameters for the Entry Cost Calibration

As explained above, we use a single set of "representative market" demand and marginal cost parameters when performing the calibration.[21] We assume a nested logit model of demand and use the estimated price and nesting coefficients of -0.45 and 0.8, respectively. The value of carrier quality for the incumbent, θ_I, is 0.75, and Southwest's is 0.66.[22] These qualities are treated as fixed over time, although this assumption could be relaxed at the cost of a much greater computational burden.

We assume that Southwest's marginal costs are fixed and equal to \$168. The incumbent's marginal costs are allowed to vary within a range of $\underline{c_I} =$ \$238 and $\overline{c_I} =$ \$278 around the mean of \$258. Based on the estimated AR(1) parameter, we assume that

$$c_{I,t} = 0.97 \cdot c_{I,t-1} + (1 - 0.97) \cdot \frac{\underline{c_I} + \overline{c_I}}{2} + \varepsilon_{I,t}, \tag{10}$$

where $\varepsilon_{I,t} \sim TRN(0, \sigma_c^2, \underline{c_I} - c_{I,t-1}, \overline{c_I} - c_{I,t-1})$ and the untruncated standard deviation, σ_c, is \$36. This standard deviation allows us to match the interquartile range of the estimated innovations in marginal costs in column 2 of table 5 based on a representative market distance of 1,200 miles. We acknowledge that there is some arbitrariness in our choices, as we do not know what portion of the marginal cost innovations is unobserved by the potential entrant. However, we are assuming that the range of marginal costs is similar to the standard deviation of marginal cost innovations, implying that knowledge of the incumbent's current marginal cost should not be especially informative about whether its marginal cost in future periods will be high or low. Therefore, one would expect our assumptions to generate only mild incentives for the incumbent to engage in limit pricing.[23]

[21] This is done partly to reduce the computational burden, but it is also done to avoid double counting how factors such as route distance affect how attractive a market is for Southwest to enter. As we describe below, we will create a rescaled market size variable that accounts for how distance and other variables affect entry probabilities, and this adjustment should capture factors that influence the probability of entry through demand or marginal costs.

[22] During phase 3, the average difference between the estimated $\theta_{j,m,t}$'s of Southwest and the incumbent is -0.088, which is consistent with Southwest having a lower phase 3 price but a similar market share (table 2).

[23] We also note that we did not impose that marginal costs can only lie on an interval when we estimated the AR(1) process. It would be hard to impose the truncation when dealing with markets of different lengths when we are allowing observable time-varying covariates, such as fuel prices, to affect the mean level of marginal costs in different ways in different markets.

5. Predicted Entry Probabilities and the Rescaling of Market Size

We now describe how we rescale market size to capture how many observable factors affect the probability that Southwest will enter and how we choose empirical entry hazards that will be matched when we estimate the distribution of entry costs. We estimate a Weibull hazard model for Southwest's entry once it becomes a potential entrant using the full sample of data. The covariates include market size in the quarter that Southwest becomes a potential entrant, the explanatory variables included in the probit model in section IV, and a dummy for the market being in the dominant incumbent sample.[24] The Weibull structure allows us to capture the fact that the probability that Southwest enters in quarter t conditional on not entering previously tends to fall over time.

We use the estimated parameters on the market-level variables in the baseline hazard function to rescale the market size variable so that the hazards based on the rescaled variable alone are identical to those predicted by the estimated multivariate hazard model. The effect of this rescaling is illustrated in table 6 for three markets that have Omaha as an end point. While Las Vegas–Omaha has a small market size, the probability of entry is relatively high because Las Vegas is a leisure destination and a Southwest focus city. This leads to its rescaled market size being larger than those for the other markets in the table. The table also shows that the implied hazard entry probabilities (i.e., the probability that Southwest will enter in a quarter conditional on not having entered in earlier quarters) decline over time, as well as being heterogeneous across markets. We use a more flexible model of mean entry costs than we assumed in section II to fit this pattern.

6. Entry Cost Parameters

We assume that Southwest's entry costs in period t, where t measures the number of quarters since Southwest became a potential entrant, are normally distributed, $N(\mu_{m,t}, \sigma_\kappa^2)$. We use a single parameter for the standard deviation because this is an important parameter that directly affects shading through its effect on $g(\kappa)$ (see eq. [4]). We allow a flexible model of the log of $\mu_{m,t}$ to fit the heterogeneity in the data. Specifically, it can

[24] We include the dominant incumbent markets in the sample with a dummy explanatory variable so that we exactly match the average probability of entry for these markets. The time until Southwest enters is measured by the number of quarters since Southwest became a potential entrant plus 0.25, where the addition is required so that we can include those markets that Southwest entered in the same quarter that it entered the end point airports. As mentioned below, we will not try to match predicted probabilities for the first quarter, where the chosen addition has a disproportionately large effect on the predicted hazard.

TABLE 6
Weibull Hazard Model: Predicted Hazard Rates and Rescaled Market Size for Three Markets

Route	Original Market Size	$\widehat{h_{m,2}}$	$\widehat{h_{m,10}}$	Rescaled Market Size
Las Vegas–Omaha	19,820	.208	.098	46,462
Omaha–St. Louis	36,568	.092	.042	37,402
Minneapolis–Omaha	38,763	.037	.017	27,948

Note.—The table shows, for three example markets, the original market size (constructed as described in app. C.2); estimated probabilities of entry after two and 10 quarters ("hazard rates"), conditional on not having entered in an earlier period; and our rescaled market size that captures all of the observed variables entering the linear index of the hazard model. The hazard entry probabilities are calculated by finding the survival probability, $S_{m,t}$, for each quarter and then calculating entry probability as $(S_{m,t-1} - S_{m,t})/S_{m,t-1}$.

vary with the log of rescaled market size, and it can increase by a factor of $(1 + \gamma_{m,1})t^{\gamma_{m,2}}$ each quarter, where $\gamma_{m,1}$ is constrained to be positive. We interpret the variation with market size as reflecting the fact that our estimated entry cost should include the discounted value of future fixed costs, including the costs associated with capacity, that Southwest commits to when it enters. It is plausible that capacity costs will be larger in markets that are larger or where Southwest expects to have a larger market share. We assume that the increase in entry costs stops after 30 quarters, at which point the carriers play the limiting infinite-horizon version of our model.[25] Both the incumbent and Southwest anticipate this increase, which provides Southwest with a strong incentive to enter early even when the increases in entry costs are small. We allow the logs of $\gamma_{m,1}$ and $\gamma_{m,2}$ to vary with a quadratic in rescaled market size.[26] The discount factor is 0.98, so that time periods can be interpreted as quarters.

We estimate the entry cost parameters by minimizing the sum of squared differences between the entry probabilities predicted by the model to the predictions from the estimated Weibull model for $t = 2, \ldots, 20$, for every fifth dominant incumbent market, when we order markets by rescaled market size, so that we use 21 markets in total.[27] A nested fixed point approach is feasible because we can solve for equilibrium entry strategies

[25] Our estimates imply that mean entry costs rise very little after 15 quarters, and our results are almost identical if we allow mean entry costs to increase for 50 quarters rather than 30 quarters (see app. B; fig. E.2).

[26] We arrived at these specifications by initially calibrating entry cost distributions for five groups of markets split by rescaled market size with no cross-market heterogeneity in the parameters within each group. Our chosen specifications allow us to match how the estimated parameters varied across the five groups almost perfectly.

[27] The empirical hazard for the first quarter is sensitive to the ad hoc addition to the timing of entry described in n. 24, so we do not try to match it. We have also estimated the model using an objective function that is based on proportional (not absolute) differences between the implied and empirical entry probabilities. This produces very similar qualitative results but larger welfare effects because the implied probability of entry rises in the smallest markets, which generates greater shading.

using a complete-information formulation of the model, so that there is no need to estimate equilibrium limit pricing strategies at each iteration.

Table 7 shows the estimated entry cost parameters. Figure 2 shows that we are able to match the predicted probabilities quite closely,[28] and figure E.1 shows how the implied entry cost parameters vary across markets. Mean initial entry costs vary almost linearly with rescaled market size in our data. For the median market, the mean initial entry cost ($\mu_{m,1}$) is $44.2 million. An increase in rescaled market size of 1,000 people increases mean initial entry costs by around $1.25 million or just over $90 per Southwest passenger per quarter given Southwest's average postentry market share. This compares with average variable Southwest profits per passenger of around $110. If we assume that all of the variation in mean entry costs with market size reflects future fixed costs associated with capacity, we would infer that the remaining true sunk entry cost would be close to $1.4 million, which seems plausible.[29] The standard deviation of entry costs is close to $204,000, which does not seem unreasonable for the types of routes in our sample. Figure E.2 shows the implied path of the mean entry cost (including discounted fixed costs) and the probability of entry for the median market. The small increase in mean entry costs (less than 1% over 6 years) is sufficient to explain the large fall in entry probabilities. We can interpret this increase as reflecting the expiry of financial incentives, such as reduced landing fees and subsidized marketing, that are often available for the first few years after a carrier enters an airport, or a more behavioral explanation involving Southwest's managers being more attentive to possible profitable route additions when they initially enter an airport.

B. *Predicted Limit Pricing and Its Relationship with the Probability of Entry*

Given the calibrated parameters, we solve for equilibrium limit pricing strategies for each market for each quarter after entry starts to be threatened (for the computational details, see app. B). Figure 3*A* shows the relationship between the model-implied probability that Southwest enters in the first four quarters that it is a potential entrant and the expected change in the incumbent's price, relative to the static monopoly price,

[28] The figure is drawn for the 21 markets used in estimation. We have also examined the fit for the 65 markets that identified the nonmonotonic relationship in sec. IV. For the two largest markets, our estimated model implies that entry probabilities are much lower than our hazard model predicts for periods after $t = 10$. However, this difference has almost no effect on our welfare calculations, as the parameters imply that entry within 1 year is almost certain.

[29] This calculation is done assuming that the relationship all the way down to a rescaled market size of zero is linear, which would not be consistent with the assumed functional form, even though the relationship is almost perfectly linear in the data (fig. E.1).

TABLE 7
CALIBRATION OF ENTRY COSTS: PARAMETER ESTIMATES

	Constant	$\text{Log}\left(\frac{\text{Rescaled Market Size}}{100{,}000}\right)$	$\frac{\text{Rescaled Market Size}}{100{,}000}$	$\left(\frac{\text{Rescaled Market Size}}{100{,}000}\right)^2$
$\text{Log}\left(\frac{\text{Mean Entry Costs}}{10 \text{ million}}\right)$	2.524	.968		
	(.016)	(.017)		
$\text{Log}\left(\frac{\text{Standard Deviation of Entry Costs}}{1 \text{ million}}\right)$	−1.588			
	(.511)			
$\text{Log}(\gamma_1)$	−6.790		9.050	−12.819
	(1.745)		(7.174)	(6.135)
γ_2	−1.940		−4.343	10.636
	(1.368)		(4.688)	(4.014)

NOTE.—Parameters minimize the sum of squared residuals comparing predicted hazard probabilities of entry with ones estimated from a Weibull hazard model based on 21 dominant carrier markets. The rescaling of market size is described in the main text. Standard errors in parentheses reflect uncertainty only from the calibration stage of estimation, not from estimation of the Weibull hazard model, the carrier demand, or marginal cost models or from the rescaling of market size.

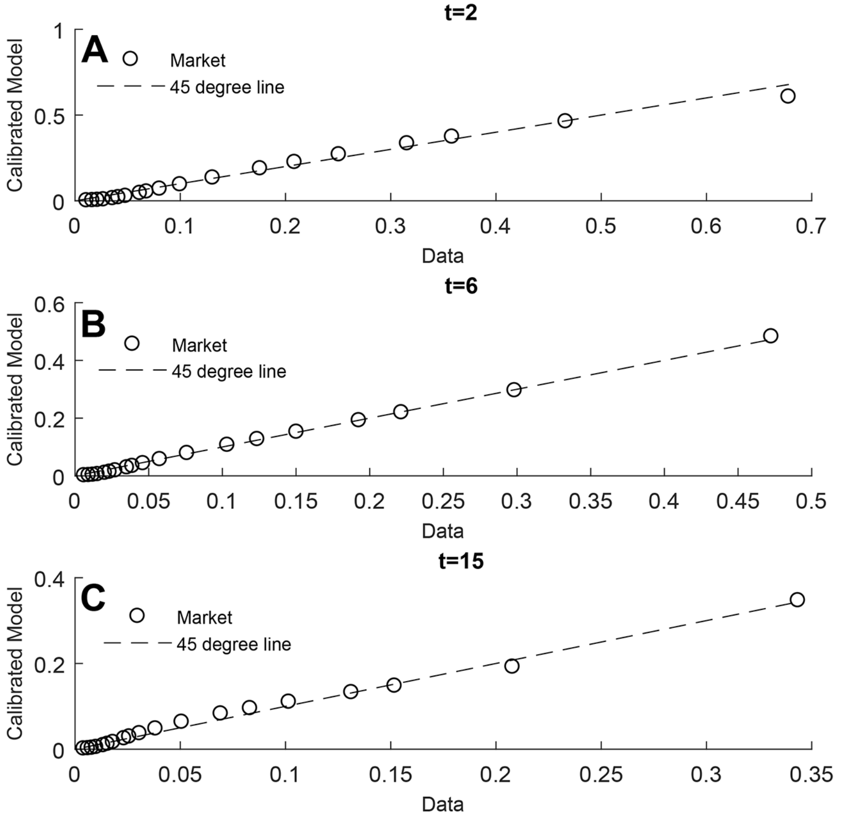

FIG. 2.—Match of empirical entry probabilities (conditional on entry having not already occurred) and the probabilities predicted by the calibrated model for the 21 markets used in the calibration.

during these quarters if entry does not occur. Each circle represents a dominant incumbent market. Figure 3*B* shows the estimated change in log(average price) based on the coefficients in table 3.

The obvious similarities are that both figures show a clear nonmonotonic relationship between price changes and the probability of entry. The largest price decline predicted by the model (17%) is within the confidence intervals of the largest decline in price (15%) estimated from the data, with both occurring for intermediate probabilities of four-quarter entry (0.55 and 0.31). The main difference is that the estimated curve predicts price increases for high probabilities, a feature that our model can never generate (a firm never has a reason to charge more than the static monopoly price). The problem here is with the extrapolation implied by the quadratic: we observe only a few markets with very high entry probabilities where we can identify price effects, and in these markets

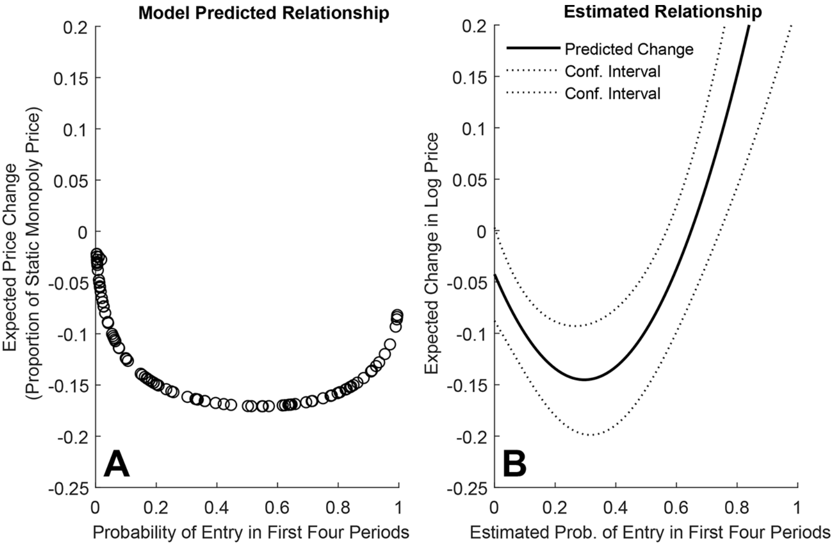

FIG. 3.—Predicted and estimated relationships between price changes and the probability of entry.

there is no evidence of large price increases (see app. D.2.2). Overall, we interpret the comparison as providing solid evidence that our limit pricing model provides a plausible explanation for why dominant incumbents lower prices when Southwest threatens entry.

C. *Welfare Effects of Potential Competition under Asymmetric and Complete Information*

We use the model to perform two types of calculation. The first calculation estimates the welfare effects of limit pricing in our dominant incumbent markets by comparing outcomes under asymmetric information and under complete information about the incumbent's marginal costs. The results are shown in table 8 for three example markets and when we add all of the dominant incumbent markets together. Consumer surplus and incumbent profits are computed using our "true" market size measure, which is consistent with viewing the additional factors that enter rescaled market size as being ones that affect Southwest's entry costs. We assume that Southwest arrives as a potential entrant once the incumbent has chosen its static monopoly price in the first period and can choose to enter immediately, so that limit pricing begins in the second period if entry does not occur.

In the Hartford–Minneapolis market, Southwest is unlikely to enter, and our model predicts that the threat of possible entry will reduce the

TABLE 8

Welfare Effects of Limit Pricing and Counterfactual Fixed Cost Subsidies

	Market			
	Hartford–Minneapolis	Manchester, New Hampshire–Philadelphia	Las Vegas–San Jose	All Dominant Incumbent Markets
Market rank (by rescaled market size, out of 109 markets)	20	65	105	
Actual market size	33,828	45,481	136,861	Total: 5.7 million
Model predictions:				
Second quarter:				
Probability of entry (if no entry in first quarter)	.002	.095	.606	Mean: .151
Shading ($, %; relative to static monopoly price)	20.07, 3.8	86.49, 16.6	57.04, 10.9	Mean: 59.83, 11.4
Twentieth quarter:				
Probability of entry (if no entry previously)	.002	.046	.266	Mean: .050
Shading ($, %; relative to static monopoly price)	16.87, 3.2	69.23, 13.3	117.06, 22.4	Mean: 52.44, 10.1
Probability of entry within four quarters	.010	.339	.973	Mean: .355
Welfare effects of limit pricing (relative to complete information):				
PDV of reduced prices ($, millions)	4.32	6.20	.76	Total: 538.74
PDV of change in consumer surplus ($, millions)	4.38	7.07	.84	Total: 592.27
PDV of change in incumbent profits ($, millions)	−.18	−1.35	−.13	Total: −86.18
Impact of a $1,000 per quarter subsidy:				
Probability of entry within four quarters	.018	.372	.974	Mean: .374
Second-period shading ($, %)	27.40, 5.3	89.62, 16.3	60.98, 10.9	Mean: 54.50, 10.5
PDV of the cost to government ($, millions)	.007	.039	.048	Total: 3.397
Changes under complete information:				
PDV of change in consumer surplus ($, millions)	7.136	4.127	.078	Total: 577.74
PDV of change in incumbent profits ($, millions)	−3.880	−2.239	−.042	Total: −314.15
Changes under asymmetric information:				
PDV of consumer surplus gain ($, millions)	8.553	3.264	.059	Total: 553.91
PDV of change in incumbent profits ($, millions)	−4.038	−2.083	−.039	Total: −312.14

Note.—PDV = present discounted value.

incumbent's price by around \$20 (or 3.8%). However, using a quarterly discount factor of 0.98, this percentage reduction implies a present value of savings for consumers who would have traveled with monopoly pricing of \$4.32 million (in 2009 dollars) while the incumbent remains a monopolist. As entry decisions would be the same under complete information, this number also measures the savings that consumers make in a model of asymmetric information. The increase in consumer surplus is slightly larger, as lower fares cause some additional consumers to travel. As we are considering small reductions away from the profit-maximizing price, the reduction in the incumbent's profits is much smaller than the gain in consumer surplus.

Our model predicts much greater price shading when entry is threatened in the larger Manchester–Philadelphia market, but because limit pricing ends when entry happens, the present discounted value of consumer benefits from limit pricing increases by only 50% compared with Hartford–Minneapolis. For the largest markets, such as Las Vegas–San Jose, Southwest will likely enter before limit pricing can occur, so that the welfare effects of asymmetric information are limited. However, because most of our dominant incumbent markets are quite small, the present discounted value of limit pricing for consumers aggregated across the 109 markets in our sample is over \$590 million, a substantial effect.

D. *Welfare Effects of Entry Subsidies*

The second calculation uses our model to investigate the welfare effects of small subsidies to Southwest when it serves a route. Many airports or local governments provide financial incentives for carriers to add routes, with Ryerson (2016) estimating that 26 US airports spent \$171.5 million on "Airline Service Incentive Programs" between 2012 and 2015. For example, Columbus offers marketing subsidies of up to \$100,000 and 1 year with no landing fees in a widely praised program designed to encourage entry on a targeted set of routes (Port Columbus International Airport 2010; Kinney 2017). These incentives are usually granted only to the first carrier serving a route, but our results will show that programs that encourage at least the possibility of additional entry could be valuable. We consider a subsidy that would pay Southwest \$1,000 every quarter once it enters (implying a maximum present value of \$50,000).

The lower section of table 8 shows the effects of the subsidy on the probability of entry, the amount of shading, consumer surplus, and the profits of the incumbent. We compare the effects of the subsidy program under complete information, where the effects come only from raising the probability of actual entry by the incumbent, and under asymmetric information. Whether the increase in consumer surplus is greater under complete or asymmetric information depends on two effects. First, as consumer surplus prior to actual entry is higher under asymmetric information, the value of increasing the probability of entry will tend to be greater under complete information, especially when there is more shading. Second, the subsidy can change the amount of shading that occurs.

In the Hartford–Minneapolis market, the increased probability of entry causes shading to increase (e.g., from an average of \$20 to \$27 in the first period that the incumbent can engage in limit pricing), and because the probability of entry is still low, the increase in consumer surplus is greater under asymmetric information. The welfare changes are also large: under asymmetric information, the present value of consumer surplus increases by \$8.5 million and the value of incumbent profits falls by \$4.0 million. The expected cost to the government is around \$7,000. To illustrate how the level of subsidy affects the size of the increase in consumer surplus, figure 4 shows how the probability of entry, shading, and the gain in consumer surplus change when we increase per-quarter subsidies from \$0 to \$100,000 per quarter. At the upper end of this range, it is almost certain that entry will happen quickly, and an increase in the subsidy will

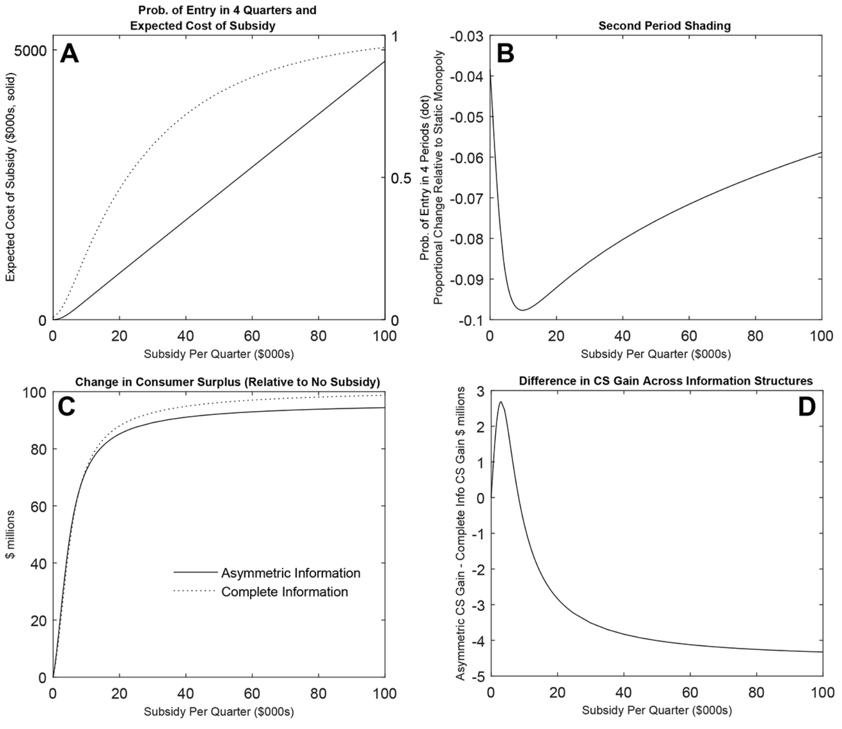

FIG. 4.—Predicted effect of fixed-cost subsidies for Southwest on entry, incumbent shading, and consumer surplus in the Hartford–Minneapolis market. CS = consumer surplus.

reduce any shading that does occur, so the welfare benefits of subsidies will be greater under complete information. At low entry probabilities, a small subsidy increases shading and subsidies raise consumer surplus more under asymmetric information.

For intermediate-size markets, such as Manchester–Philadelphia, the subsidy continues to have large and positive welfare effects, although the gains are larger under complete information. In contrast, in the largest markets, entry is almost certain without the subsidy, and the subsidy is effectively just a transfer to Southwest, with any increases in consumer surplus having a similar scale to the cost of the subsidy.

Our results are consistent with the idea that subsidy programs should be targeted at markets that are truly marginal rather than ones where entry is very likely. However, our results also suggest that, especially in the presence of asymmetric information, there may be significant benefits to offering subsidies in markets where entry is quite unlikely, because even if entry does not occur, the market power of the incumbent can be constrained if small probabilities of entry are raised even slightly.

VI. Extensions

As emphasized in section II, we focus on our basic model largely for reasons of tractability. There are two types of criticism that can be leveled at the simplicity of the model. The first criticism is that it cannot explain some features of the incumbent's phase 2 pricing, notably the fact that, on average, incumbents seem to cut prices by more over time when Southwest does not enter. While this can happen in some markets in the model that we calibrate (e.g., as shown in table 8, we predict that average shading would increase from 10.9% to 22.4% of the static monopoly price from the second to the twentieth period if entry does not occur in the Las Vegas–San Jose market where Southwest's entry probability is high), it does not happen on average. In appendix F, we show that the finding of additional price cuts in the data is driven by a subset of our markets and that one way we can explain increasing price cuts is by extending our model to allow for the possibility that the incumbent is also learning about the probability that Southwest will enter (e.g., because it is uninformed about the mean of Southwest's entry cost distribution). The introduction of two-way learning is an interesting extension to the literature in its own right.

The second criticism is that the model misses some key features of the airline industry. In particular, it is not clear what makes the incumbent's marginal cost opaque, and the exogeneity of the marginal cost innovations is inconsistent with the fact that marginal costs will depend on carriers' capacity investments, even if we do not observe large capacity changes in the data when entry is threatened. In appendix F, we address this criticism by building a model where marginal costs depend on endogenous capacities and the amount of demand that a carrier has from passengers who want to travel the route segment as part of a longer itinerary. As previously noted, Edlin and Farrell (2004) and Elzinga and Mills (2005), in the context of alleged predation, argue that it is difficult to assess a carrier's marginal costs when its flights are used to serve many connecting passengers. We have seen that connecting passengers fill the majority of seats on the dominant incumbent routes in our sample. Our extended model also allows the amount of connecting traffic available to Southwest to be correlated with the incumbent's demand, which provides the incumbent with an additional entry-deterring motivation to signal that connecting demand is low. We show that this extended model continues to generate large price declines when entry is threatened and that these declines vary nonmonotonically with the probability of entry. We also find that even though a carrier could choose to invest in greater (observed) capacity to try to deter entry in our model, predicted changes in capacity tend to be very small across the range of entry probabilities, and this is also consistent with our empirical results (table 3; fig. D.1).

VII. Conclusion

We have presented theoretical and empirical frameworks for analyzing a classic form of strategic behavior—entry deterrence by setting a low price—in a dynamic setting. Our model assumes that an incumbent has an unobserved state variable that is serially correlated but not perfectly persistent over time. We show that under a standard refinement, our model has a unique MPBE in which the incumbent's pricing policy perfectly reveals its true type in each period. Our characterization of the equilibrium makes it straightforward to compute equilibrium pricing strategies, and we predict that an incumbent could keep prices low for a sustained period of time before entry occurs. The resulting tractability is striking given the perception in the applied literature that dynamic games with persistent asymmetric information are too intractable to be used in empirical work. We exploit this tractability to investigate whether a limit pricing model can explain why incumbent carriers lower prices significantly when routes are threatened with entry by Southwest. This is a natural setting to study, given that it provides the largest documented effect of potential competition on prices.

We show how the introduction of dynamics can lead to larger price reductions than in the canonical two-period model (Milgrom and Roberts 1982), especially in markets where the probability of entry is not too high. In the application, this feature can explain why incumbent carriers keep prices low when Southwest remains a potential (but not an actual) entrant for quite long periods of time, and our model can also explain why incumbents cut prices even before Southwest has actually started operating at the end point airports. We provide new reduced-form evidence that a limit pricing explanation can explain why prices fall, by showing that there is a nonmonotonic relationship between price changes and the probability of entry and by providing evidence against explanations involving alternative entry-deterring strategies, such as capacity investment. We show that when we calibrate our model, without using any information on price changes when entry is threatened, it predicts a pattern of price changes across markets that is qualitatively and quantitatively similar to the pattern in the data. The welfare effects of limit pricing are estimated to be substantial (increasing the present value of consumer surplus by over $590 million) even though we have focused on a sample of only 109 routes, most of which are fairly small. We illustrate how limit pricing may affect the value of a government subsidy program that encourages a carrier to consider entering as a second nonstop carrier. We have also shown that we can extend our model in several directions that preserve the prediction of significant and nonmonotonic price reductions and can also allow us to explain additional features of the data.

As noted in section II, our model does have some limitations, and it generates results that some readers may find unintuitive. For example, the incumbent may be willing to cut prices quite dramatically even when the equilibrium probability of entry is small (e.g., 0.03 or 0.04), and the potential entrant should already have a quite precise prior about the profitability of entry before it sees the incumbent's signal. But as we show, our results reflect the fact that in a dynamic model it can be very valuable to deter entry when future entry probabilities are low, because deterrence can lead to many future periods of monopoly, as well as because the standard feature of signaling models that the precision of the receiver's prior does not affect equilibrium strategies when there is full separation. Indeed, we see a contribution of our paper as showing that signaling may provide a more powerful explanation for real-world phenomena than has been recognized in the empirical literature.

While we have explored one type of asymmetric information model and one application, we believe that there are many areas in which to explore how asymmetric information may impact firm behavior. For example, it is often claimed that predatory pricing is motivated by incumbents wanting to signal information on their costs or their intentions to both the current competitor and potential future competitors, and it would be interesting to compare how well this type of signaling story compares quantitatively against noninformational models of predation where the dominant incumbent makes observable investments (e.g., in capacity [Snider 2009; Williams 2012] or learning by doing [Besanko, Doraszelski, and Kryukov 2014]) that commit it to lower future costs. Sweeting, Tao, and Yao (2019) show that when oligopolists are uncertain about each other's marginal costs or alternatively how much weight each firm puts on profits and revenues when setting prices, equilibrium prices can be much higher than static models would predict, and static models may underpredict how much mergers will raise prices. Closer to our current application, we would also like to explore whether there are assumptions under which a model with several incumbents has a tractable equilibrium with significant limit pricing behavior. This would allow us to expand our analysis in this paper to a broader set of industries and markets.

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