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ABSTRACT

The one-shot nature of most theoretical models of strategic investment, especially those based on asymmetric information, limits our ability to test whether they can fit the data. We develop a dynamic version of the classic Milgrom and Roberts (1982) model of limit pricing, where a monopolist incumbent has incentives to repeatedly signal information about its costs to a potential entrant by setting prices below monopoly levels. The model has a unique Markov Perfect Bayesian Equilibrium under a standard form of refinement, and equilibrium strategies can be computed easily, making it well suited for empirical work. We provide reduced-form evidence that our model can explain why incumbent airlines cut prices when Southwest becomes a potential entrant into airport-pair route markets, and we also calibrate our model to show that it can generate the large price declines that are observed in the data.

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1 Introduction

Since at least the work of Kaldor (1935) and Bain (1949), economists have been aware that incumbent firms may have incentives to take actions that deter entry by rivals. While models of entry deterrence form much of the core of theoretical Industrial Organization (e.g., chapters 8 and 9 of Tirole (1994)), and surveys support the claim that managers often make investments for strategic reasons (Smiley (1988)), empirical evidence that any particular model explains real-world data is limited. One reason why is that it is unclear what the stylized two-period models that form the backbone of the theoretical literature predict should happen when incumbents and potential entrants interact repeatedly. This is especially true of the many theoretical models that rely on asymmetric information.

To see why, consider, like we will, the classic two-period Milgrom and Roberts (1982) (MR) model of limit pricing.[1] In their model, an incumbent faces a potential entrant who is not informed about some aspect of the market, such as the incumbent's marginal cost. In equilibrium, the incumbent may deter entry by choosing a price that is low enough to credibly signal that the potential entrant's post-entry profits will not cover its entry costs. However, once the model is extended so that an incumbent can set prices in multiple periods and the potential entrant has multiple opportunities to enter it is unclear *a priori* whether the model can give a unique prediction about how the incumbent should price (for example, does it need to set low prices in every period or only in a set of initial periods?). It is therefore also unclear whether the model could ever be claimed to explain how an actual incumbent sets prices when it is threatened by entry. Indeed, the common perception in the applied literature is that dynamic games with persistent asymmetric information are too intractable to work with, at least using standard equilibrium concepts (Doraszelski and Pakes (2007), Fershtman and Pakes (2012)).

We analyze a natural dynamic extension of the MR model where the incumbent's marginal cost is serially correlated but not perfectly persistent over time. We show that Markov Perfect Bayesian Equilibrium strategies and beliefs on the equilibrium path are unique under an application of the D1 refinement when a set of simple conditions on the primitives of the model

[1] The idea that incumbents might set low prices to deter entry is much older (Kaldor (1935), Clark (1940) and Bain (1949)), but it was often rationalized by arbitrarily assuming that potential entrants would perceive incumbents as committed to pre-entry prices (Gaskins (1971), Kamien and Schwartz (1971), Baron (1973) and, for a critique, Friedman (1979)). MR addressed this issue with a model where the incumbent can use a low price to signal information to an uninformed potential entrant. Matthews and Mirman (1983) and Harrington (1986) provide early developments of the MR framework.

are satisfied, and that strategies can be easily computed. The equilibrium strategies involve the incumbent engaging in limit pricing to perfectly reveal its current marginal cost in every period, so that our model predicts that the incumbent will keep prices low until entry actually occurs (at which point we assume, like MR, that the game changes to be one of complete information).

Having developed the model, we explore whether it provides a potential explanation for the phenomenon that incumbent airlines cut their prices significantly when Southwest, the most successful U.S. low-cost carrier, becomes a potential entrant on an airport-pair route market but does not yet serve the route.[2] As documented by Morrison (2001) and Goolsbee and Syverson (2008) (GS) these price cuts can be large, as much as 20% of previous prices, and have substantial welfare effects. For example, Morrison estimates that Southwest's presence as a potential competitor reduced consumers' annual spending on airfares by $3.3 billion in 1998.

We provide two types of empirical evidence. First, we present new reduced-form evidence that favors a limit pricing explanation. To do so, we focus on a set of markets with a single dominant incumbent, to match the assumptions of our theoretical model, and where the incumbents' marginal costs are likely to be opaque.[3,4] Following the strategy of Ellison and Ellison (2011) (EE), we examine how the size of the incumbents' price cuts varies with the probability of entry by Southwest, which is estimated based on exogenous market characteristics such as market size.[5] We find that the price declines tend to be much larger in markets with intermediate probabilities of entry, rather than on routes where entry is either very likely or very unlikely. This is exactly what we would expect to see if the price cuts are aimed at trying to deter entry, rather than, for example, being part of an entry accommodation strategy which would lead to the size of the price reductions increasing monotonically with the probability of entry. In contrast, we show that some other strategies, such as increased code-sharing (Goetz and Shapiro (2012)), do appear to be motivated by a desire to accommodate entry. We also provide evidence against

[2]Southwest will be defined as a potential entrant when it serves both endpoint airports.

[3]The routes in our sample typically involve the dominant incumbent's hub and most of the traffic on the incumbent's flights are connecting to or from other destinations. As we discuss in Section 3.1, the resulting network effects will tend to make it hard for outsiders to judge the incumbent's marginal cost.

[4]In contrast, Morrison (2001) and GS consider a wide range of markets with heterogeneous market structures where the incentives for strategic investment are also likely to vary significantly. It is intuitive that incentives to invest in strategic entry deterrence should be weaker when there are several incumbents because of the incentive to free ride (e.g., Waldman (1983), McLean and Riordan (1989)) although there are models where oligopolists can engage in significant deterring behavior in equilibrium (e.g., Gilbert and Vives (1986), Waldman (1987), Kirman and Masson (1986)).

[5]EE's empirical application is to branded pharmaceuticals that face patent expiry. Dafny (2005) provides another application of the same approach to hospital procedure markets.

other explanations for why prices fall, including entry-deterring investments in capacity that might lower incumbents' marginal costs.

Second, we exploit our model's tractability by calibrating it using demand and marginal cost parameters that we estimate using data from our sample markets. We show that our simple model is able to generate the size of the price declines that are observed for markets with intermediate probabilities of Southwest entry. We also use our calibrated model to provide insights into which parameters lead to more aggressive limit pricing in equilibrium and to compare welfare under limit pricing to welfare when the incumbent's marginal costs are observed or the incumbent cannot use prices to signal.

Our work is related to several literatures beyond those dealing directly with models of limit pricing and the effect of Southwest on its competitors' prices. One example is the broader theoretical literature on signaling games. We make extensive use of results from Mailath (1987), Mailath and von Thadden (2013) and Ramey (1996), which characterize equilibria and refinements in models where there is only one opportunity to signal, in proving our theoretical results. In particular, we apply their results recursively in our dynamic, finite-horizon game, showing that a set of simple conditions on static payoffs and quantities are sufficient to generate a unique and fully separating equilibrium outcome in every period. Roddie (2012a) and Roddie (2012b) consider a dynamic quantity-setting game between duopolists where one of the firm's marginal costs is private information. This model has a similar structure to ours, and, like us, Roddie also claims that there can be a unique fully separating Markov Perfect Bayesian equilibrium under a recursive application of the D1 refinement, which in his case involves the informed firm behaving like a Stackelberg leader. We differ from Roddie, however, in that we use a slightly different set of high-level theoretical conditions, and, more importantly, we show how our high-level conditions will be satisfied throughout the game under a set of relatively weak restrictions on the static monopoly and duopoly payoffs and quantity outcomes. Kaya (2009) and, in a limit pricing context, Toxvaerd (2013) consider repeated signaling models where the sender's type is fixed over time, which can lead to signaling only at the beginning of the game in equilibrium. In contrast, we allow the incumbent's type to evolve over time, according to a Markov process, which leads to repeated signaling in equilibrium.[6]

[6] A model where the incumbent's type is fixed would have difficulty in explaining two aspects of our empirical application. First, incumbents not only cut prices when Southwest first appears as a potential entrant, they also keep prices low even if Southwest does not initially enter. Second, and more fundamentally, if the incumbent's

A second connected literature is the broader empirical literature on strategic investment. Most of this literature has adopted a qualitative approach, providing evidence by comparing the investment decisions of different types of firms (e.g., Lieberman (1987)) or showing correlations between incumbent investments and subsequent entry decisions (e.g., Chevalier (1995)), without identifying the precise mechanism involved.[7] The EE approach that we apply in Section 4 is also qualitative, but, by applying the idea to different types of investment, we provide evidence that a limit pricing story appears to provide the best explanation of the data. Recently Snider (2009), Williams (2012), both in the context of alleged predation by airlines, and Chicu (2012) have estimated structural Ericson and Pakes (1995)-style dynamic oligopoly models with complete information (up to i.i.d. payoff shocks) where incumbents can deter entry or induce exit by investing in capacity. These models often have multiple Markov Perfect Equilibria. We differ from these papers in considering a dynamic model with asymmetric information and deriving conditions under which the Markov Perfect Bayesian equilibrium that we look at is unique under refinement. We also approach our empirical exercise in Section 5 by calibrating our model rather than imposing it on the data, with the main goal of showing that our model can generate the magnitude of price declines that we observe.[8] We also provide evidence against the hypothesis that capacity investment is used to deter entry in our setting.

A final related literature is concerned with modeling dynamic games in applied Industrial Organization. Almost all of the existing literature follows Ericson and Pakes (1995) in assuming that firms either observe all payoff-relevant variables or observe them up to some payoff shocks that are i.i.d. over time. Given these assumptions, there is no scope for firms to signal information about the future profitability of entry or any need for potential entrants to form beliefs about their opponents' types, ruling out by assumption many of the types of strategic investment behavior proposed in the theoretical literature. In a recent paper, Fershtman and Pakes (2012) (FP) provide a general framework for modeling a dynamic game with persistent

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.

[7]Salvo (2010) argues that Brazilian cement producers set prices at a level that prevents imports from being profitable. However, Salvo's setting differs from standard models of strategic investment where a potential entrant has to pay a sunk cost to enter the market.

[8]We hope to develop and implement a direct estimation approach in future work, but to do so would likely require developing a more complicated version of the model to allow, for example, time-varying carrier quality and entry or exit by other firms. We would still require some element of calibration to pick bounds for the supports of marginal cost that can affect the results. In the current paper we prefer to stay close to the relatively simple theoretical model developed in Section 2, which is a natural dynamic extension of MR.

incomplete information. As they argue, solving these models can be computationally challenging not least because of the need to store the potentially complicated beliefs that players may have about other players' types. They suggest circumventing this computational problem using an alternative solution concept, Experience Based Equilibrium (EBE). In an EBE, players only have beliefs about expected payoffs from their own actions rather than their rivals' types; these expectations are based only on some limited observed history; and, optimality is only required in an endogenously-determined recurrent class of states. These assumptions simplify computation and storage, but they may tend to increase the number of equilibria, and, if there are multiple EBEs, there is no clear way either to enumerate them or to select a particular prediction. Our approach is quite different. We consider a specific model of a dynamic game with asymmetric information where, under some additional conditions, we are able to characterize a PBE that has a very tractable form which allows us to avoid the computational problems that FP identify.[9] While our approach lacks the generality of the approach proposed by FP, it has two advantages for our goal of studying dynamic limit pricing in an empirical setting. First, we can use existing concepts to show that our equilibrium is unique under refinement, so that it is clear what our model predicts.[10] Second, because beliefs are explicitly modeled it is natural to talk about signaling, and there is a clear link between our model and the two-period MR model of limit pricing.

The rest of the paper is organized as follows. Section 2 lays out our model of dynamic limit pricing and characterizes the equilibrium. Section 3 describes our data. It also discusses in some detail why we view our model as being potentially applicable to understanding how incumbents respond to the threat of entry in our sample of markets. Section 4 provides the reduced-form (GS and EE-style) evidence in support of our limit pricing model and Section 5 describes our calibration of the model. Section 6 concludes. Appendix A contains all of our theoretical proofs with additional appendices detailing aspects of our empirical work.

[9] These are not the only differences. FP consider a model with finite state and action spaces. This may also limit a player's ability to signal its type, by requiring at least some pooling when there are more types than possible actions. In contrast, we consider a game where the signaling firm chooses a continuous action (price).

[10] Of course, refinements impose additional assumptions, here on the inferences that a potential entrant would make if it observed an off-the-equilibrium-path action, that a critic might view as unreasonable.

2 Model

In this section we develop our theoretical model of a dynamic entry deterrence game with serially correlated asymmetric information. We describe the Markov Perfect Bayesian Equilibrium (MPBE) of the model where incumbents perfectly reveal their type each period and explain the conditions under which this equilibrium both exists and is unique when the D1 refinement is applied recursively. Proofs are in Appendix A. Finally, we explain how equilibrium strategies can be computed using a recursive algorithm.

We present the model in an abstract way to be clear about what features of our results are general, rather than dependent on specific parametric choices that we will make to calibrate our model using airline data. In the next section we explain why we believe that our model may be useful for understanding how incumbents behave in at least some airline markets.

2.1 Model Specification

There is a finite sequence of discrete time periods, $t = 1, ..., T$, two long-lived firms and a common discount factor of $0 < \beta < 1$. We assume finite T so that we can apply backwards induction to prove certain properties of the model, but, when illustrating strategies in our calibration exercise below, we will assume that T is large and focus on the strategies that will be (almost) stationary in the early part of the game.[11]

At the start of the game, firm I is an incumbent, who is assumed to remain in the market forever, and firm E is a long-lived potential entrant. It is assumed that E will remain as a potential entrant until it enters, and that, once it enters, it will also remain in the market forever. The marginal costs of the firms, $c_{E,t}$ and $c_{I,t}$ lie on compact intervals $C_E := [\underline{c_E}, \overline{c_E}]$ and $C_I := [\underline{c_I}, \overline{c_I}]$ and evolve, independently, according to Markov processes $\psi_I : c_{I,t-1} \to c_{I,t}$ and $\psi_E : c_{E,t-1} \to c_{E,t}$, with full support (i.e., costs can evolve to any point on the support in the next period). We denote the conditional probability density functions (pdfs) by $\psi_I(c_{I,t}|c_{I,t-1})$ and $\psi_E(c_{E,t}|c_{E,t-1})$. We make the following assumptions.

Assumption 1 ***Marginal Cost Transitions***

[11] We could follow Toxvaerd (2008) who takes the $T \to \infty$ limit of finite horizon games, for which properties can be shown using backwards induction, to prove the properties of equilibria in a game with an infinite horizon.

1. *$\psi_I(c_{I,t}|c_{I,t-1})$ and $\psi_E(c_{E,t}|c_{E,t-1})$ are continuous and differentiable (with appropriate one-sided derivatives at the boundaries).*

2. *$\psi_I(c_{I,t}|c_{I,t-1})$ and $\psi_E(c_{E,t}|c_{E,t-1})$ are strictly increasing i.e., a higher cost in one period implies that higher costs in the following period are more likely. Specifically, we will require that for all $c_{j,t-1}$ there is some x' such that $\frac{\partial\psi_j(c_{j,t}|c_{j,t-1})}{\partial c_{j,t-1}}|_{c_{j,t}=x'} = 0$ and $\frac{\partial\psi_j(c_{j,t}|c_{j,t-1})}{\partial c_{j,t-1}} < 0$ for all $c_{j,t} < x'$ and $\frac{\partial\psi_j(c_{j,t}|c_{j,t-1})}{\partial c_{j,t-1}} > 0$ for all $c_{j,t} > x'$. Obviously it will also be the case that $\int_{\underline{c_j}}^{\overline{c_j}} \frac{\partial\psi_j(c_{j,t}|c_{j,t-1})}{\partial c_{j,t-1}} dc_{j,t} = 0$.*

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

Assumption 2 ***Entry Cost Distribution***

1. *$\overline{\kappa}$ 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.*

2. *$G(\cdot)$ is continuous and differentiable and the density $g(\kappa) > 0$ for all $\kappa \in [0, \overline{\kappa}]$.*

Demand is assumed to be common knowledge and fixed, although it would be straightforward to extend the model to allow for time-varying demand as long as it is observed by both firms. Similarly one can allow for an observed common element of marginal costs (e.g., fuel prices) that changes over time, with the Markov processes described above only affecting the idiosyncratic component of costs.

2.1.1 Pre-Entry Game

Before E has entered, so that I is a monopolist, E does not observe $c_{I,t}$. E does observe the whole history of the game to that point. The timing of the game in each of these periods is as follows:

1. I and E observe $c_{E,t}$ (the entrant's marginal cost).

2. E observes κ_t (I does not).

3. I sets a price $p_{I,t}$, and receives 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

$$p_I^{\text{static monopoly}}(c_I) \equiv \text{argmax}_{p_I} q^M(p_I)(p_I - c_I) \tag{2}$$

The incumbent can choose a price from the compact interval $[\underline{p}, \overline{p}]$ where $\overline{p}$ must be greater than $p_I^{\text{static monopoly}}(\overline{c_I})$, the static monopoly price that an incumbent with cost $\overline{c_I}$ would choose. All of our theoretical results would hold when the monopolist sets a quantity, but we choose not to present our model in this way because it is more natural to assume price-setting when talking about limit pricing. The choice of strategic variable in the duopoly game that follows entry may matter, as will be explained below.

4. E observes $p_{I,t}$.

5. E decides whether to enter (paying κ_t if it does so). If it enters, it is active at the start of the following period.

6. Marginal costs of both firms evolve independently according to ψ_I and ψ_E.

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. *$\pi_I^M(p_I, c_I)$ is continuous and differentiable in both arguments, has a unique optimum in price and for any $p_I \in [\underline{p}, \overline{p}]$ where $\frac{\partial^2 \pi_I^M(p_I, c_I)}{\partial p_I^2} > 0$ $\exists k > 0$ such that $\left|\frac{\partial \pi_I^M(p_I, c_I)}{\partial p_I}\right| > k$ for all c_I.* These assumptions are consistent, for example, with strict quasi-concavity of the profit function.

3. *$\overline{p} \geq p_I^{\text{static monopoly}}(\overline{c_I})$ 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.*[12]

[12] For some parameters, although not those in our calibration, this could require $\underline{p} < 0$. The purpose of this

2.1.2 Post-Entry Game

We assume that once E enters both marginal costs, which continue to evolve as before, are observed before choices are made each period, so there is no scope for further signaling, and that both firms receive static equilibrium per-period profits, $\pi_I^D(c_{I,t}, c_{E,t})$ and $\pi_E^D(c_{E,t}, c_{I,t})$, where the different functions allow for fixed quality differences between the firms. The firms' equilibrium outputs are $q_I^D(c_{I,t}, c_{E,t})$ and $q_E^D(c_{E,t}, c_{I,t})$. The choice variables of the firms in the static duopoly game are $a_{I,t}$ and $a_{E,t}$ (which could be prices or quantities).

Assumption 4 ***Duopoly Payoffs and Output***

1. $\pi_I^D(c_I, c_E), \pi_E^D(c_E, c_I) \geq 0$ *for all* (c_I, c_E). This assumption also rationalizes why neither firm exits.

2. $\pi_I^D(c_I, c_E)$ *and* $\pi_E^D(c_E, c_I)$ *are continuous and differentiable in both arguments. For both firms, duopoly profits are strictly monotonically increasing in their rival's marginal cost and strictly monotonically decreasing in their own marginal cost.*

3. $\pi_I^D(c_I, c_E) < \pi_I^M(p_I^{\text{static monopoly}}(c_I), c_I)$ *for all* (c_I, c_E).

4. $q_I^D(c_I, c_E) - q^M(p_I^{\text{static monopoly}}(c_I)) - \frac{\partial \pi_I^D(c_I, c_E)}{\partial a_E} \frac{\partial a_E}{\partial c_I} < 0$ *for all* (c_I, c_E).

The fourth assumption here is the key condition that we use to show that a single crossing property will hold in our model in every period because it determines that a decrease in marginal cost is more advantageous to a monopolist than a duopolist.[13] The sign of the last term will depend on whether the duopolists compete in strategic complements (prices) or substitutes (quantities), with the condition being easier to satisfy when they compete in prices as an increase in the incumbent's marginal cost will lead to the entrant setting a higher price, which is good for the incumbent.[14] While it is perhaps natural to assume that the post-entry game involves simultaneous price or quantity choices, this does not need to be the case as long as

restriction is to ensure that the action space is large enough to allow all types to separate.

[13]Note that because demand is decreasing in price, if this condition holds when a monopolist incumbent sets the monopoly price then it will also hold if it sets a lower limit price, a fact that is used in the proof.

[14]In his presentation of the two-period MR model, Tirole (1994) suggests a condition that a static monopolist produces more than a duopolist with the same marginal cost is reasonable. However, it 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.

payoffs and outputs satisfy the conditions in Assumption 4. For example, one might assume that the incumbent maintains some advantage and acts as a Stackelberg leader.[15]

2.1.3 Comparison with Milgrom and Roberts (1982)

MR provide the classic two-period model of limit pricing in which one firm (our I) is a monopolist in the first period, and a second firm (E) can observe its price or output before deciding whether to enter in the second period. In the model on which they focus, the marginal costs of both firms are private information in the first period while E's entry cost is commonly known. The marginal costs of both firms, which in their case do not vary over time, are publicly revealed if E enters, so that, with entry, second period competition is static Cournot or Bertrand. I can attempt to deter entry by using its first-period quantity/price choice to signal its marginal cost to E.

Our cost assumptions differ in two respects. First, in our model the incumbent's marginal costs can evolve over time, specifically in a positively serially correlated way. We need correlation, which takes an extreme form in the MR model, in order for the monopolist to have a state variable that will affect an entrant's profit from entering to signal. On the other hand, we need the incumbent's marginal cost to be able to change from period-to-period in order to generate an incentive for the incumbent to engage in limit pricing in every period before entry occurs. As a comparison, Kaya (2009) and Toxvaerd (2013) consider dynamic models in which the informed party's type is fixed over time, where the natural equilibrium to consider involves it signaling only in initial periods after which point the receiver is convinced of the informed party's type.

Second, we assume that the entrant's marginal costs, which we allow to be serially correlated, are observed, but that its entry costs, which are i.i.d. draws, are not. As a result, in our model, as in MR, only one player (E) is learning and E's entry is probabilistic from the perspective of I.[16] On the other hand, in a model where E has any unobserved but serially correlated state variable, I would want to draw inferences about that variable from E's entry decision, leading to a quite different kind of model to the one considered by MR. Modeling entry costs as unobserved

[15] Moving further away from the simple structure of the MR model, there is also scope to relax the assumption that there is complete and symmetric information post-entry, by following Roddie (2012a) who considers a duopoly game where firms choose quantities simultaneously but the costs of one of the firms is unknown. In this case, our characterization of behavior in the pre-entry game would still hold if the payoff and output conditions in Assumption 4 hold during all periods of the continuation game that follows entry.

[16] We could also assume that κ_t is only revealed after $p_{I,t}$ has been chosen, but that at that point it is observed by both firms.

and i.i.d. while E's marginal costs are observed and possibly serially correlated is also attractive for two additional reasons: first, in the entry games literature it is quite standard to treat entry cost draws as being private information and independent; and, second, it seems natural to allow for serial correlation in the entrant's marginal costs given our assumptions on I's marginal costs and our estimation results in Section 5. We will also argue below that Southwest's business model, which involves a simpler network structure than legacy carriers, adds some plausibility to the idea that Southwest's marginal costs might be more transparent than those of legacy carriers.[17]

2.2 Equilibrium

Unique Nash equilibrium behavior post-entry, when the two firms play a complete information duopoly game, is assumed.[18] We are therefore interested in characterizing play before E enters. Our basic equilibrium concept is MPBE (Roddie (2012a), Toxvaerd (2008)). The definition of a MPBE requires, for each period:

- a time-specific pricing strategy for I, as a function of both firms' marginal costs $\varsigma_{I,t} : (c_{I,t}, c_{E,t}) \to p_{I,t}$;
- a time-specific entry rule for E, $\sigma_{E,t}$, as a function of its beliefs about I's marginal cost, its own marginal costs 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.

In an equilibrium, for all possible $c_{E,t}$ and $c_{I,t}$, E's entry rule should be optimal given its beliefs, its beliefs should be consistent with I's strategy on the equilibrium path and the evolution of marginal costs, and I's pricing rule must be optimal given what E will infer from I's price and how E will react based on these inferences.

[17] Note that if we instead assumed that entry costs are serially correlated and observed and the entrant's marginal cost is unobserved but i.i.d. (so there would still be one-way learning) then we would have to change the model in some way so that E's expected future profits would depend on its private information, as this is necessary for its entry decision to be probabilistic from the perspective of the incumbent. For example, we might assume that the potential entrant decides to enter once it knows its marginal cost for the next period, or that it is actually able to compete in some part of the current period.

[18] Existence and uniqueness of the post-entry equilibrium will depend on the particular form of demand assumed, and will hold for the common demand specifications (e.g., linear, logit, nested logit) with single product firms and linear marginal costs.

Fully Separating Riley Equilibrium (FSRE). We will consider an equilibrium where I's price perfectly reveals its current marginal cost, i.e., there is full separation, and where signaling is achieved at minimum cost to I subject to the incentive compatibility constraints being satisfied (i.e. the 'Riley equilibrium' (Riley (1979)).

The following theorem contains our main theoretical results.

Theorem 1 *Consider the following strategies and beliefs:*

In the last period, $t = T$, a monopolist incumbent will set the static monopoly price, and the potential entrant will not enter whatever price the incumbent sets.

In all periods $t < T$:

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

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

where $\mathbb{E}_t(V_{t+1}^E|\widehat{c}_{I,t}, c_{E,t})$ 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 $\mathbb{E}_t(\phi_{t+1}^E|\widehat{c}_{I,t}, c_{E,t})$ is its expected value of being a duopolist in period $t+1$ (which assumes it has entered prior to $t+1$).[19] *The threshold $\kappa_t^*(\widehat{c}_{I,t}, c_{E,t})$ is strictly decreasing in $c_{E,t}$ and strictly increasing in $\widehat{c}_{I,t}$;*

(ii) I's pricing strategy, $\varsigma_{I,t} : (c_{I,t}, c_{E,t}) \to p_{I,t}^*$, will, for a given value of $c_{E,t}$, be the solution to a differential equation

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

and an upper boundary condition $p_{I,t}^*(\overline{c_I}, c_{E,t}) = p^{\text{static monopoly}}(\overline{c_I})$. $\mathbb{E}_t[V_{t+1}^I|c_{I,t}, c_{E,t}]$ 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 $t+1$. $\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}, c_{E,t}]$ is its expected value of being a duopolist in period $t+1$;

[19] We define values at the beginning of each stage. See the discussion in Appendix A for more details.

(iii) E's beliefs on the equilibrium path: observing a price $p_{I,t}$, E believes that I's marginal cost is $\varsigma_{I,t}^{-1}(p_{I,t}, c_{E,t})$.

This equilibrium exists, and the above form the unique MPBE strategies and equilibrium-path beliefs consistent with a recursive application of the D1 refinement. For completeness we assume that if E observes a price which is not in the range of $\varsigma_{I,t}(c_{I,t}, c_{E,t})$ then it believes that the incumbent has marginal cost $\overline{c_I}$.

Proof. See Appendix A. ■

Our proof applies results from the theoretical literature on one-shot signaling models recursively. The first result that we use is from Mailath and von Thadden (2013).[20] They provide conditions on signaling payoffs[21] that imply that there will be only one separating equilibrium, where the strategy of the party that is signaling is determined by a differential equation and a boundary condition. The key conditions are type monotonicity (a given price reduction always implies a greater loss in current payoffs for an incumbent with a higher marginal cost), belief monotonicity (the incumbent always benefits when the entrant believes that he has lower $c_{I,t}$, which reflects the monotonicity of the entrant's entry rule) and a single crossing condition (a lower cost incumbent is always willing to cut the current price slightly more in order to differentiate itself from higher cost incumbents). Our contribution is to show that our assumptions on the primitives of the model (or more precisely, static monopoly and duopoly quantities and payoffs) are *sufficient* for I's signaling payoff function to satisfy these conditions in every period by applying backwards induction.[22] Our conditions are not necessary, only sufficient, so that our equilibrium may exist more generally.

Mailath and von Thadden's results do not rule out the possible existence of pooling equilibria. To do so we recursively apply the D1 refinement (Cho and Sobel (1990), Ramey (1996)), which is a restriction on the possible inferences that E could make when observing off-the-equilibrium-path actions. Specifically, in a one-shot signaling game, D1 restricts how off-the-equilibrium-path

[20] Mailath and von Thadden (2013) provides a generalization of Mailath (1987), expanding the set of models to which the results apply.

[21] The signaling payoff function can be written as $\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})$ where $\widehat{c}_{I,t}$ is E's point belief about the incumbent's marginal cost when taking its period t entry decision. An alternative way of writing the payoff function that is used when ruling out pooling equilibria is $\Pi^{I,t}(c_{I,t}, \kappa', p_{I,t}, c_{E,t})$ where κ' is the threshold used by the potential entrant.

[22] This also involves showing that E's strategy in every period will be a threshold rule.

signals are interpreted by requiring 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. Theorem 3 of Ramey (1996) shows that as long as a pool does not involve the incumbent choosing (in our setting) the lowest possible price, pooling equilibria can be eliminated when the signaling payoff function satisfies a single crossing condition.

Applying D1 in a setting with repeated signaling is potentially complicated by the possibility that an off-the-equilibrium-path signal in one period could change how the receiver interprets signals in future periods. Here we follow Roddie (2012a) in applying a recursive version of D1, where we work backwards through the game, applying the refinement in each period, where, even if an out-of-equilibrium action is observed, the players believe that they would use refined equilibrium strategies in subsequent periods.

2.3 Solving the Model

Given a specific parameterization of the model (e.g., the form of demand and the supports and transition processes for marginal costs), it is straightforward to compute pricing strategies and entry probabilities. The solution algorithm is as follows.

Step 1. Specify a grid for c_I and c_E.[23]

Step 2. For each of the grid-points, calculate each firm's single-period profits in the specified full information duopoly game that follows entry.

Step 3. Consider period T. Calculate the incumbent's static monopoly profits for each discretized value of c_I (in this period it does not face the threat of entry and so it prices as a static monopolist). The incumbent's static monopoly and duopoly profits define V_T^I and ϕ_T^I for each value on the grid. For the potential entrant $V_T^E = 0$ and ϕ_T^E is the static duopoly profit.

Step 4. Consider period $T-1$. (a) For a given value of $c_{E,T-1}$, use the assumed form of the transition processes for marginal costs to calculate the value of $\mathbb{E}_{T-1}[\phi_T^E | c_{I,T-1}, c_{E,T-1}]$ for each value of $c_{I,T-1}$. As $\mathbb{E}_{T-1}[V_T^E | c_{I,T-1}, c_{E,T-1}] = 0$ and $\kappa^*_{T-1}(c_{I,T-1}, c_{E,T-1}) = \beta \mathbb{E}_{T-1}[\phi_T^E | c_{I,T-1}, c_{E,T-1}]$, we compute $g(\kappa^*_{T-1})$ and $\frac{\partial \kappa^*_{T-1}(c_{I,T-1}, c_{E,T-1})}{\partial c_{I,T-1}}$ for each of these values. (b) Next, we solve for the pricing strategy of the incumbent as a function of its marginal cost, by solving the differential

[23] In Section 5 we use an evenly-spaced grid with 100 points for each cost variable, and the results are essentially identical using 50 or 200 points.

equation starting from the boundary solution that the firm with the highest marginal cost sets the static monopoly price

$$\frac{\partial p^*_{I,T-1}}{\partial c_{I,T-1}} = \frac{\beta g(\kappa^*_{T-1}) \frac{\partial \kappa^*_{T-1}(c_{I,T-1}, c_{E,T-1})}{\partial c_{I,t}} \{\mathbb{E}_{T-1}[V^I_T | c_{I,T-1}, c_{E,T-1}] - \mathbb{E}_{T-1}[\phi^I_T | c_{I,T-1}, c_{E,T-1}]\}}{q^M(p_{I,T-1}) + \frac{\partial q^M(p_{I,T-1})}{\partial p_{I,T-1}}(p_{I,T-1} - c_{I,T-1})} \tag{5}$$

This is done using `ode113` in MATLAB. Given known demand, the denominator can be computed exactly for any value of $c_{I,T-1}$ considered by the differential equation solver. We store this result, and then repeat for all other values of $c_{E,T-1}$. (c) Given the entry and pricing strategies we can calculate $V^i_{T-1}(c_{I,T-1}, c_{E,T-1})$ and $\phi^i_{T-1}(c_{I,T-1}, c_{E,T-1})$ for both firms (i.e., the values of each firm as a monopolist/potential entrant/duopolist) as appropriate given the cost state.

Step 5. Consider period $T-2$. Here we proceed using the same steps as in Step 4, except that $\kappa^*_{T-2}(c_{I,T-2}, c_{E,T-2}) = \beta\{\mathbb{E}_{T-2}[\phi^E_{T-1} | c_{I,T-2}, c_{E,T-2}] - \mathbb{E}_{T-2}[V^E_{T-1} | c_{I,T-2}, c_{E,T-2}]\}$.

Step 6. Repeat Step 5 for all previous periods.

3 Can Our Limit Pricing Model Explain How Incumbent Carriers Respond to the Threat of Entry by Southwest?

We now turn to the question of whether our dynamic limit pricing model can explain why incumbent carriers cut prices substantially when Southwest becomes a potential entrant on an airline route. We present two types of evidence. First, in Section 4, we present reduced-form evidence that indicates, for a set of routes that match the assumptions of our model, that incumbents lower prices in order to try to deter entry, while providing evidence against alternative explanations. Second, in Section 5, we perform a calibration that shows that our model can generate price cuts of the magnitude observed in the data when we use demand and marginal cost parameters that are estimated using data from our sample markets. In this section we introduce our data and explain, in some detail, why we believe that our model may plausibly describe behavior in a subset of airline markets.

3.1 Relevance of Our Model to Entry By Southwest

Competition in airline markets, which we define as the routes between pairs of airports[24], is heterogeneous with routes between small cities often having no non-stop service, while large markets may have several carriers competing non-stop. Previous analysis of the effects of potential competition from Southwest (e.g., in GS) has used data from this wide range of markets. However, we will test our model, which assumes an incumbent monopolist, by focusing on a subset of markets with one dominant incumbent when Southwest becomes a potential entrant (defined as Southwest serving both of the endpoint airports but not the route itself) and we will focus on the pricing and other possibly strategic choices of this carrier.

Our model assumes that, prior to entry, the incumbent's marginal cost is private information, while the potential entrant's marginal cost is public information but its entry costs are unobserved.[25] While it would complicate solving our model by adding additional state variables, we could allow for additional factors, such as fuel costs or changes in the economy or airport capacity, that affect marginal costs or demand and are observed by both firms, so what is really critical is that there is an idiosyncratic portion of the incumbent's marginal cost of serving a route that is private information and serially correlated.

Why is it reasonable to believe that some part of the incumbent's marginal cost is not observed by other carriers? The key is the nature of economic costs on the routes in our dominant incumbent sample. 90% of these routes involve a dominant legacy carrier, such as Delta, US Airways or Continental, flying a route from one of its hubs to a non-hub airport. Its effective marginal opportunity cost of selling a seat to someone who only wants to travel between these airports will depend on the probability that this displaces a sale to someone else who wants to travel the route as a segment that is part of a longer journey; the profitability of customers making these onward connections; how operating planes on the route fits into the carrier's overall network configuration; and, the possible profits that the carrier could make if the capacity (planes or gates) were to be switched to other routes. As has been well documented in cases of alleged predation

[24] We follow GS in defining markets as airport-pairs. An alternative approach would be to use city-pairs, but using city-pairs would leave us with a very small sample of markets with a dominant incumbent carrier where Southwest becomes a potential entrant during our sample. Morrison (2001) estimates that Southwest has substantially smaller effects on fares when it only serves nearby airports as either an actual or a potential competitor.

[25] In our conclusion we will discuss why we believe it makes sense to focus on a model where it is the incumbent's marginal costs that are not observed rather than some feature of demand.

by legacy airlines (Edlin and Farrell (2004), Elzinga and Mills (2005)), these network-related opportunity costs make it very difficult to determine a carrier's marginal cost on routes involving hubs even ex-post and with access to the carrier's accounting data. Therefore, the incumbent's current marginal cost should certainly be somewhat opaque to carriers, like Southwest, that are making contemporaneous decisions about whether to enter.[26] The network component of costs is also likely to be time-varying but highly persistent as the carrier's network and the alternative options that passengers have for making connections evolve slowly. In contrast, Southwest's marginal costs, which we assume are observed, are likely to be relatively transparent because it operates a simpler point-to-point network using a fleet composed entirely of Boeing 737s.

In our view, the two informational assumptions that are actually harder to justify are that Southwest's current entry costs are unobserved to the incumbent and that the incumbent's marginal costs are observed once the potential entrant enters. The first assumption is designed to capture the idea that, even if an incumbent knows factors that affect the attractiveness of entry, it is likely difficult for it to determine exactly when Southwest will enter routes that appear likely to be marginal in terms of Southwest's profitability. In the context of our model one could interpret this type of uncertainty as uncertainty about Southwest's entry cost. As noted in footnote 15, the second assumption is made so that our model is as similar as possible to MR and for convenience, in the sense that assuming complete information post-entry simplifies the assumptions required to characterize the equilibrium in the pre-entry game. At a general level, it also seems plausible that entrants into a market should have a clearer view of their rivals' marginal costs than potential entrants.[27]

While we can defend our cost assumptions, there are clearly important features of the industry that our model abstracts away from. For example, a carrier's marginal costs on different routes are likely to be correlated so that a potential entrant should try to make inferences about costs on a particular route from pricing on other routes as well. Our model is a model of a single market

[26] One might object that other carriers can use publicly available data to understand these network flows. However, the Department of Transportation only releases these data with a lag of at least three months, and our theoretical results hold even if we assume that the incumbent's current marginal cost is revealed to the entrant after it has made its entry decision.

[27] Dixit and Chintagunta (2007) estimate a model of route exit for discount airlines, excluding Southwest, where they allow for discount airlines to learn about market conditions once they enter. While this implies that entrants do not have complete information, they find that entrants learn very quickly (within one year), and, consistent with our model, they also find that these conditions significantly affect the willingness of discount carriers to compete. They exclude Southwest from their analysis on the basis that it very rarely exits markets that it enters.

and we cannot capture cross-route effects. On a particular route a carrier also sets many prices (first or business class and economy tickets, and tickets with and without restrictions that may be available on different dates before departure). Our model ignores this feature, assuming that the incumbent sets a single price. However, we will provide evidence that, on at least the routes that fit the assumptions of our model, incumbent carriers cut prices across the entire distribution of fares, which, at least intuitively, seems consistent with the idea of a carrier trying to signal that its marginal cost of filling a seat is low. This fact will also provide some evidence against alternative explanations for why incumbents cut prices when Southwest becomes a potential entrant.

Another feature of our markets that differs from our model is that there are potential entrants other than Southwest. While focusing only on the threat of entry by Southwest is a simplification, it makes some sense given that Southwest's rapid growth during our data and the very large effect that it has on prices once it enters (Morrison (2001) and our results below) should make incumbents particularly keen to deter Southwest's entry if possible.[28] Of course, one might also be concerned that Southwest's entry decisions would not be sufficiently sensitive to what it believes about the incumbent's marginal cost to generate significant limit pricing. Note, however, that in our empirical examination we will focus on entry decisions at the route (airport-pair) level, treating airport entry as exogenous, and we will identify price changes from routes that Southwest does not initially enter.[29] Therefore while Southwest almost always enters routes to its focus airports, such as Chicago Midway and Las Vegas, as soon as it enters an airport and there is probably very little that an incumbent could do to prevent this entry, we will be focused on other routes. We are assuming, however, that there is some subset of routes which, during our data, really are marginal for Southwest to enter so that its decisions could

[28] Wu (2012) compares the effects that potential entry by Southwest and JetBlue have on incumbent prices. He finds that JetBlue has a substantially smaller effect. However, recent work by bin Salam and McMullen (2013), who focus on how Southwest sets prices on routes where legacy carriers merge, and Wittman and Swelbar (2013), who look at both the level of Southwest's own prices and the prices that legacy carriers set as a function of Southwest's presence at an airport, suggests that the extent to which the presence of Southwest tends to lower airfares has diminished since 2008. Our sample ends in 2010.

[29] Our regressions will include market (i.e., airport-pair) fixed effects. The key issue for identifying the effect of an entry threat is whether the timing of Southwest's entry decisions into airports is correlated with declines in incumbent marginal costs in future periods. While one might be able to develop stories where this type of correlation would exist (e.g., improvements in airport infrastructure that reduce incumbent marginal costs and could also encourage Southwest to enter), our evidence in favor of our limit pricing model will primarily be based on a comparison *between* routes based on how likely Southwest is to enter them, where the entry probability will be determined by exogenous characteristics such as market size.

be influenced by its beliefs about how competitive the incumbent would be if it entered. Our empirical results will be consistent with this assumption: incumbents in markets where the probability of entry, estimated based on exogenous route characteristics, is either very high or very low will not tend to lower prices significantly when Southwest becomes a potential entrant whereas on those routes where entry probabilities are intermediate, which it is natural to view as marginal routes, incumbents cut prices significantly.[30] The assumption that airline entry decisions (not necessarily by Southwest) are sensitive to incumbent costs is also supported by Zou (2013) who shows that route-level entry decisions are significantly affected by accounting disclosures on how an incumbent's fuel hedging strategy will affect its future operating costs, and that entry decisions become more sensitive to this information when more complete disclosure is required.

3.2 Data

Most of our data is drawn from the U.S. Department of Transportation's Origin-Destination Survey of Airline Passenger Traffic (Databank 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. Our data covers the period from Q1 1993-Q4 2010 (72 quarters).[31]

Following GS, we define a market to be a non-directional airport-pair with quarters as periods. We only consider 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 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 non-stop passengers on the route in DB1, and we

[30] The fact that, at least since the mid-1990s, Southwest's entry is not completely determined by exogenous market characteristics is supported by existing research. For example, Boguslaski, Ito, and Lee (2004) show that the ability of a simple probit (based on exogenous market characteristics) to predict Southwest's entry decisions declined significantly in the 1990s (explaining only 41% of entry decisions from 1995-2000 compared with almost 60% for the 1990-2000 decade as whole).

[31] There are some changes in reporting requirements and practices over time. For example, prior to 1998 operating and ticketing carriers are not distinguished in DB1, making it impossible to analyze code-sharing. Prior to 2002 regional affiliates, such as Air Wisconsin operating as United Express, were not required to report T100 data, which introduces some limitations when we look at measures of capacity based on T100 such as the number of available seats that a carrier has on a route.

consider it to be a potential entrant once it serves at least one route out of each of the endpoint airports.

Based on our potential entrant definition there are 1,872 markets where Southwest becomes a potential entrant after the first quarter of our data and before Q4 2009, a cutoff that we use so we can see whether Southwest enters the market in the following year, an observed outcome that we will use to estimate which market characteristics make entry more likely. Southwest enters 339 of these markets during the period of our data. We will call these 1,872 markets our "full sample". Most of our analysis will focus on the subset of these markets where there is one carrier that is a *dominant incumbent* before Southwest enters. As we want to identify only carriers that are really committed to a market rather than just serving it briefly, we use the following rules to identify a dominant carrier:

1. to be considered active in a quarter it must carry at least 150 DB1 non-stop passengers;
2. once it becomes active in a market the carrier must be active in at least 70% of quarters before Southwest enters, and in 80% of those quarters it must account for 80% of direct traffic on the market and at least 50% of total traffic.[32]

We identify 106 markets with a dominant incumbent before Southwest enters, but in some of these markets Southwest enters at the same time as it becomes a potential entrant (i.e., the market is one of the first ones that Southwest enters when it begins serving one of the endpoint airports) and in a few of them the dominant incumbent becomes active only after Southwest is a potential entrant on the route. In 65 markets we observe quarters where the incumbent carrier is dominant both before Southwest becomes a potential entrant and after it is a potential entrant but before it actually entered. It is data from these routes that will identify the effects of the potential entry threat on the price set by a dominant incumbent, although we include the remaining 41 routes in our regressions as they help to pin down the coefficients on the time effects and other controls included in the specification.[33] The 106 and 65 markets are listed in

[32]To apply this definition we have to deal with carrier mergers (for example, Northwest was the dominant carrier on the Minneapolis-Oklahoma City route before it merged with Delta in 2008, after which Delta is the dominant carrier). When we define fixed effects we treat the dominant carrier before and after a merger as the same carrier even if the name of the carrier changed.

[33]For example, Southwest began service out of Philadelphia (PHL) in Q3 2004. It already operated at both Chicago Midway (MDW) and Columbus, OH (CMH), and so, under our definitions, it became a potential entrant into both the PHL-MDW (where the dominant incumbent was ATA) and PHL-CMH (where the dominant incumbent was US Airways) markets in Q3 2004. However, it immediately began service on the PHL-MDW route, but did not enter the PHL-CMH market until Q4 2006.

Table 1: Comparison of the Full and Dominant Incumbent Samples

	Full Sample		Dominant Incumbent Samples			
	Mean	Std. Dev	Mean	Std. Dev	Mean	Std. Dev
Mean endpoint pop. (m.)	2.373	1.974	2.850	1.894	3.155	2.081
Round-trip distance (miles)	2,548.48	1,327.04	1,251.44	749.58	1,315.10	803.07
Constructed market size	27,837	44,541	62,751	66,633	47,975	61,397
Origin or destination is a:						
primary airport	0.161	0.368	0.330	0.473	0.277	0.451
secondary airport	0.301	0.459	0.321	0.469	0.354	0.482
big city	0.587	0.492	0.858	0.350	0.877	0.331
leisure destination	0.093	0.291	0.113	0.318	0.108	0.312
slot controlled airport	0.033	0.179	0.057	0.230	0.092	0.292
Number of markets	1,872		106		65	

Appendix B.

Table 1 provides some statistics for the full sample, and the sub-samples of 106 and 65 markets. Relative to the full sample, the dominant incumbent markets tend to be shorter with larger endpoint cities measured either by average population or by one of the cities being a city that Gerardi and Shapiro (2009) identify as a "big city". All of the markets in our dominant firm sample are shorter than routes that Southwest flies non-stop (these include long, cross-country routes such as Las Vegas-Providence), so, by this metric, it is plausible that Southwest could enter any of our routes.[34,35] As only the largest cities have multiple major airports, the dominant incumbent markets are also more likely to involve an airport identified as a primary or secondary airport. On the other hand, the standard deviations show that both sets of markets are quite heterogeneous with respect to these market characteristics.

Table 1 also reports a constructed estimate of market size, which we will use when estimating demand in Section 5 and as an additional variable for predicting the probability that Southwest enters a market. As explained in Appendix C, this variable is constructed by estimating a gener-

[34]The longest route in the dominant firm sample is Las Vegas-Pittsburgh, which is one of the markets that Southwest enters immediately. Even though some longer routes are flown by only one carrier, they fail to meet our definition of dominance because many people will fly these routes via connecting service on other carriers.

[35]Gerardi and Shapiro (2009) define the largest 30 MSAs as being big cities, although they exclude some MSAs, such as Orlando, on the basis that are primarily vacation destinations. We also follow them in defining "leisure" destinations, which include cities such as New Orleans and Charleston, SC, as well as Las Vegas and several cities in Florida. We define slot controlled airports as JFK, LaGuardia and Newark in the New York area, Washington National and Chicago O'Hare, although O'Hare is no longer slot controlled. We identify metropolitan areas with more than one major airport using http://en.wikipedia.org/wiki/List_of_cities_with_more_than_one_airport, and identify the primary airport in a city as the one with the most passenger traffic in 2012.

alized gravity equation using the Poisson Pseudo-Maximum Likelihood approach recommended by Silva and Tenreyro (2006), which allows us to capture the fact that the amount of travel on a route varies systematically with distance and the popularity of the particular airports.

Table 2 reports, for the dominant incumbent markets, summary statistics for variables that vary over time, such as average prices (in Q4 2009 dollars), yield (average fare divided by route distance, a widely used metric for comparing fares across routes of different lengths) and market shares. Quarters are aggregated into three groups, which we will refer to frequently below: "Phase 1" - before Southwest is a potential entrant; "Phase 2" - when Southwest is a potential entrant but has not yet entered the route; and, "Phase 3" - after Southwest enters (if it enters during the sample). Entered markets will obviously be a selected set of markets which explains why the dominant carrier's average capacity and passenger numbers for the Phase 3 markets are higher than for the other groups. The summary statistics are, however, consistent with Southwest's actual entry into a market reducing prices dramatically, so that an incumbent should be willing to make investments to deter entry if it is likely that they would be effective, and with incumbents responding to the threat of entry by lowering prices, suggesting that limit pricing may be one of these investments.[36]

The summary statistics also provide some evidence against an alternative story for why prices fall in Phase 2. Recall that in Phase 2, Southwest serves both endpoint airports so that passengers may be able to travel the route by connecting on Southwest[37], in which case one might argue that Southwest should be viewed as a competitor with an inferior product rather than just a potential entrant. This could provide an alternative explanation for why prices fall. However, from the table we see that Southwest's average market share in Phase 2 is less than 1.5%, compared with the dominant carrier's share of over 80%, while its average fare is quite high compared to the fares that Southwest charges when it enters the market. Therefore, the degree of direct competitive pressure that Southwest exerts on the incumbent's pricing in Phase 2 should be small. In Section 4 we will provide additional evidence against this "actual competition" explanation for why prices fall when entry is threatened.

[36]Yields and average fares do not vary in the same proportion across the phases, consistent with the fact that the set of markets that Southwest enters are not random with respect to the length of the route. For this reason we will look at both price metrics in the results below.

[37]Southwest does not always allow customers to buy tickets between any pair of airports that it serves, reflecting the fact that, compared to the legacy carriers, its business model is more focused on point-to-point travel. However, we do not have data on which routes it will sell tickets that involve connections.

Table 2: Summary Statistics: Dominant Incumbent Sample

	Phase 1: $t < t_0$		Phase 2: $t_0 \leq t < t_e$		Phase 3: $t \geq t_e$	
Variable	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Incumbent Pricing						
Yield (average fare / distance)	0.544	0.384	0.394	0.280	0.285	0.126
Average fare	511.92	162.89	447.65	120.33	259.88	73.25
Southwest Pricing						
Yield (average fare / distance)		-	0.274	0.095	0.231	0.066
Average fare		-	375.49	76.19	222.41	67.78
Passenger Shares						
Incumbent	0.740	0.264	0.831	0.147	0.517	0.228
Southwest		-	0.014	0.033	0.434	0.232
Incumbent Capacity and Traffic (T100)						
Capacity (seats performed)	76,239	53,217	75,820	44,637	114,312	62,041
Segment Passengers (incl. connecting passengers)	49,092	34,165	56,695	35,701	82,277	45,060
Number of markets	106		65		54	

The last lines of the table show the amount of capacity (seats) and the total number of passengers that the dominant incumbent carries on its planes that fly the route non-stop (both numbers come from T100). Reflecting the fact that almost all of the routes in our sample involve the dominant carrier's hub, on average 85% of these passengers are making connections to or from other routes.[38] As network effects are the key reason why the dominant incumbent's marginal cost is likely to be opaque, this high percentage of connecting passengers makes it more plausible that we might observe MR-style limit pricing on the routes in our sample.

4 Evidence of Limit Pricing in the Dominant Incumbent Sample

In this section we present reduced-form evidence that our model may be useful for understanding why incumbents cut prices when Southwest becomes a potential entrant on an airline route. In doing so, we extend the analysis in GS by testing alternative explanations for why prices fall in more detail by using the ideas in EE and focusing on dominant incumbent markets that fit the market structure assumed by most models of strategic investment, including ours.

4.1 The Effect of Threatened Entry in Dominant Incumbent Markets

We begin our analysis by confirming that dominant incumbents do cut prices significantly when Southwest becomes a potential entrant on a route by serving both endpoint airports but not yet serving the route (Phase 2). To do so we follow GS, who use markets with any number of incumbents, by utilizing the following regression specification:

$$\text{Price Measure}_{j,m,t} = \gamma_{j,m} + \tau_t + \alpha X_{j,m,t} + ...$$
$$\sum_{\tau=-8}^{8+} \beta_\tau SWPE_{m,t_0+\tau} + \sum_{\tau=0}^{3+} \beta_\tau SWE_{m,t_e+\tau} + \varepsilon_{j,m,t} \tag{6}$$

where $\gamma_{j,m}$ are market-carrier fixed effects and τ_t are quarter fixed effects. Carriers other than the dominant carrier are not included in our version of the regression. X includes the number

[38] To be clear, when we measure prices we use passengers who are only traveling between the endpoints, not those making connections to or from other destinations.

of other carriers serving the market (separate counts for direct and connecting service) as well as interactions between the jet fuel price[39] and route distance. t_0 is the quarter in which Southwest becomes a potential entrant, so $SWPE_{m,t_0+\tau}$ is an indicator for Southwest being a potential entrant, but not an actual entrant, into market m at quarter $t_0 + \tau$. If Southwest enters it does so at t_e, and $SWE_{m,t_e+\tau}$ is an indicator for Southwest actually serving the market in quarter $t_e + \tau$. We use observations for up to three years (12 quarters) before Southwest becomes a potential entrant, and the β coefficients measure price changes relative to those quarters that are more than eight quarters before Southwest becomes a potential entrant or, if Southwest becomes a potential entrant within the first eight quarters that the dominant carrier is observed in the data, the first quarter that it is observed. We estimate separate coefficients for the quarters immediately around the entry events, but aggregate those quarters further away from the event where we have fewer observations. In our analysis markets are weighted equally, but the results are similar if observations are weighted by the average number of passengers carried on the route.

Table 3 presents two sets of coefficient estimates, using the log of the average price and the yield as alternative price measures. Average prices fall by 10-14% when Southwest becomes a potential entrant and, consistent with our model where the incumbent continues to signal even if the potential entrant does not initially enter the route, they do not subsequently increase. In fact, the price declines actually tend to become slightly larger over time in Phase 2, which can happen in our model as those incumbents who experience the most favorable changes in marginal cost will also be the most likely to deter entry. The average yield in Phase 1 is 0.544, so the yield coefficients imply similar proportional changes. If Southwest enters, average prices decline by an *additional* 30-45%, giving a decline of 45-60% relative to prices at the start of Phase 1. While our Phase 2 price declines are slightly smaller than those identified by GS, our Phase 3 declines are significantly larger, presumably reflecting the fact that dominant incumbents have more market power prior to Southwest's entry than the average incumbent in GS's sample.

One feature of the results, also found in GS, is that prices start declining two quarters before Southwest becomes a potential entrant. In some settings, one would be concerned that observing a price decline prior to the treatment (here, the entry threat) becoming effective would suggest that it is not the treatment that causes prices to decline but rather some other factor that also causes Southwest to enter the endpoint airports. However, in our setting this pattern reflects

[39]Specifically, U.S. Gulf Coast Kerosene-Type Jet Fuel Spot Price FOB (in $/gallon).

Table 3: Incumbent Pricing In Response to Southwest's Actual and Potential Entry

	Phase 1		*Phase 2*		*Phase 3*	
Fare						
	$t_0 - 8$	-0.047	t_0	-0.105^{***}	t_e	-0.416^{***}
		(0.029)		(0.031)		(0.066)
	$t_0 - 7$	-0.022	$t_0 + 1$	-0.115^{***}	$t_e + 1$	-0.514^{***}
		(0.0307)		(0.034)		(0.069)
	$t_0 - 6$	-0.040	$t_0 + 2$	-0.131^{***}	$t_e + 2$	-0.539^{***}
		(0.034)		(0.032)		(0.077)
	$t_0 - 5$	-0.041	$t_0 + 3$	-0.131^{***}	$t_e + 3$	-0.602^{***}
		(0.034)		(0.032)		(0.080)
	$t_0 - 4$	-0.015	$t_0 + 4$	-0.135^{***}	$t_e + 4$	-0.608^{***}
		(0.033)		(0.034)		(0.082)
	$t_0 - 3$	-0.009	$t_0 + 5$	-0.137^{***}	$t_e + 5$	-0.577^{***}
		(0.029)		(0.038)		(0.084)
	$t_0 - 2$	-0.0761^{**}	$t_0 + 6\text{-}12$	-0.206^{***}	$t_e + 6\text{-}12$	-0.589^{***}
		(0.029)		(0.047)		(0.081)
	$t_0 - 1$	-0.0874^{***}	$t_0 + 13+$	-0.309^{***}	$t_e + 13+$	-0.589^{***}
		(0.029)		(0.051)		(0.086)
Yield						
	$t_0 - 8$	-0.027	t_0	-0.060^{***}	t_e	-0.234^{***}
		(0.014)		(0.019)		(0.051)
	$t_0 - 7$	-0.005	$t_0 + 1$	-0.051^{**}	$t_e + 1$	-0.273^{***}
		(0.017)		(0.021)		(0.052)
	$t_0 - 6$	-0.011	$t_0 + 2$	-0.063^{***}	$t_e + 2$	-0.286^{***}
		(0.018)		(0.019)		(0.056)
	$t_0 - 5$	-0.008	$t_0 + 3$	-0.062^{***}	$t_e + 3$	-0.308^{***}
		(0.018)		(0.019)		(0.057)
	$t_0 - 4$	-0.009	$t_0 + 4$	-0.066^{***}	$t_e + 4$	-0.315^{***}
		(0.018)		(0.019)		(0.059)
	$t_0 - 3$	-0.008	$t_0 + 5$	-0.066^{***}	$t_e + 5$	-0.313^{***}
		(0.017)		(0.022)		(0.060)
	$t_0 - 2$	-0.042^{**}	$t_0 + 6\text{-}12$	-0.115^{***}	$t_e + 6\text{-}12$	-0.332^{***}
		(0.018)		(0.027)		(0.059)
	$t_0 - 1$	-0.047^{**}	$t_0 + 13+$	-0.185^{***}	$t_e + 13+$	-0.361^{***}
		(0.018)		(0.034)		(0.067)

Notes: Estimates of specification (6) with the dependent variable as either the log of the mean passenger-weighted fare on the dominant incumbent ("Fare") or this fare divided by the non-stop route distance ("Yield"). Specifications include market-carrier fixed effects, quarter fixed effects and controls for the number of other competitors on the route (separately for direct or connecting), fuel prices and fuel prices×route distance. Standard errors clustered by route-carrier are in parentheses. ***, ** and * denote significance at the 1, 5 and 10% levels respectively. Number of observations is 3,904 and the adjusted R^2s are 0.81 ("Fare") and 0.86 ("Yield"). Phases are defined in the text.

the fact that Southwest announces that it will begin service from an airport some months in advance, and that incumbent carriers start changing some prices as soon as this announcement occurs. This is, of course, consistent with our model's explanation for why prices decline because once Southwest announces it will serve an airport it will also be deciding which routes to enter in its first several quarters of service, so incumbents that want to deter entry will have incentives to start signaling as soon as the airport-entry announcement occurs, especially on routes that may be of marginal attractiveness to Southwest.[40]

On airline routes, few passengers pay the average fare (Borenstein and Rose (1995) and Gerardi and Shapiro (2009)). In Appendix D we report estimates of specification (6) where we use different percentiles of the fare or yield distribution as the dependent variable. The results reveal that when Southwest threatens entry, prices decline significantly across the fare distribution. As well as illustrating the very robust nature of the GS effect in our dominant incumbent sample, the patterns are also useful in providing evidence against two non-deterrence explanations for why prices decline.

One of these explanations, already mentioned, is that Southwest may provide actual competition, through connecting service, in Phase 2. In this case, we might expect that the competition would increase primarily for price-elastic customers (who would be willing to substitute to connecting service) who would typically purchase cheaper (advance) tickets, so that the price declines should be concentrated at the low end of the fare distribution.[41] Instead, the declines are significant across the distribution and are actually slightly greater for the median and 75th percentiles. On the other hand, a theory that has often been mentioned to us is that carriers may cut prices as part of an entry accommodation, not a deterrence, strategy, where they try to build up the loyalty, or program status, of frequent-flyers to soften competition once Southwest enters. This could explain why incumbents cut high-priced tickets, which are most likely to be bought by frequent business travelers, but it is not clear why they would necessarily cut the prices of low-priced tickets that are typically sold at different times (relative to departure) and are targeted at infrequent, leisure travelers. In contrast, declines across the fare distribution are consistent with a model where the incumbent is signaling the marginal opportunity cost of selling a seat

[40] On the other hand, if prices fall in Phase 2 because of actual competition from connecting service on Southwest there is no reason why they should be falling before these connections are actually available.

[41] Borenstein and Rose (1995) argue that actual competition tends to increase within-carrier fare dispersion in the airline industry for this reason.

to someone who only wants to fly the segment, as this should affect pricing whatever type of consumer the ticket is sold to. We now turn to the EE approach which allows us to distinguish between accommodation and deterrence strategies in a more systematic fashion.

4.2 Testing Alternative Explanations for Why Prices Fall When Entry is Threatened

In the context of a fairly general model of strategic investment by an incumbent monopolist, EE argue that, when deterrence incentives are present, they can generate a non-monotonic relationship between the level of investment and the probability of entry. In our setting, their logic would apply in the following way. When Southwest becomes a potential entrant, an incumbent will not choose to cut prices (very much) in markets where entry is very unattractive to Southwest, because it is likely only to be sacrificing monopoly profits. In markets where entry is very attractive, the monopolist will also not want to cut prices because it is unlikely that entry can be deterred and it will only be sacrificing the profits that it can make before entry happens. On the other hand, in markets that are marginal for entry, it is possible that entry will be prevented (or delayed) if the incumbent signals that its marginal costs are low enough. EE show how this insight can be developed into a two-stage empirical strategy for identifying strategic investment in settings where observable and exogenous variables, such as market size, change the attractiveness of entry.[42] In the first stage, a simple model of the entry probability is estimated to construct a single index of the attractiveness of the market to the potential entrant and then, in the second stage, the monotonicity of the relationship between this index and the incumbent's (possibly strategic) investment is examined.

For our first stage, we estimate a probit model of Southwest's entry using the full sample of 1,872 markets where an observation is a route and the dependent variable is equal to one if Southwest entered within four quarters of becoming a potential entrant.[43] The explanatory

[42] GS compare incumbent pricing behavior in the quarters immediately prior to Southwest becoming a potential entrant on routes where Southwest had already announced it would enter and routes where it had not. They observe larger declines in prices on routes where entry had not been pre-announced, but, in their sample, the differences are generally not statistically significant. However, the direction of their results is consistent with our findings as we see no significant price declines in markets where entry is very likely.

[43] It would be inappropriate to use a dummy for Southwest ever entering because, in our relatively long sample, different markets are exposed to the possibility of entry for different periods of time. Using a four quarter rule also means that we minimize the truncation problem associated with the end of the sample while still having a significant number of observations.

variables include several measures (and their squares) of market size, including measures of endpoint population and our gravity model-based market size measure; route distance; measures of carrier presence at the endpoint airports; and, an indicator for whether one of the airports is slot constrained. Further details of the variables included and the estimated coefficients are given in Appendix E. Consistent with previous research, e.g. Boguslaski, Ito, and Lee (2004), we are able to explain a reasonable degree of variation (pseudo-R^2 0.37) in Southwest's entry decisions in the full sample, with Southwest more likely to enter shorter routes between bigger cities, especially when it already serves a significant number of routes out of the endpoints. For the subset of 65 markets the predicted within-four-quarter entry probabilities vary from 0.01 to 0.9, with the 20th, 40th and 60th and 80th percentiles at 0.02, 0.085, 0.204 and 0.512.

In the second stage, we only use Phase 1 and 2 observations from the dominant incumbent sample, and we test how the size of the Phase 2 price decline varies with the entry probability using the following market-carrier fixed effects specification:

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

where $\widehat{\rho_m}$ is the predicted probability of entry (within one year) for market m, j is the dominant carrier, $\gamma_{j,m}$ and τ_t are market-carrier and quarter fixed effects, and $X_{j,m,t}$ includes the same controls that were used in the GS specification. $SWPE_{m,t}$ is an indicator for a market-quarter in which Southwest is a potential entrant (i.e., a Phase 2 observation). Standard errors are adjusted to allow for uncertainty in the first-stage estimate $\widehat{\rho_m}$, as well as heteroskedasticity and first-order serial correlation in the residuals.[44] If the incumbent is using a limit pricing strategy then we would expect $\widehat{\beta_0} \approx 0$, $\widehat{\beta_1} < 0$ and $\widehat{\beta_2} > 0$. On the other hand, an entry accommodation explanation for falling prices would predict that $\widehat{\beta_0} \approx 0$ and a combination of $\widehat{\beta_1}$ and $\widehat{\beta_2}$ such that prices are expected to fall more in markets where entry is more likely.

Figure 1 shows the estimated quadratic relationship between the price change in Phase 2 and the entry probability using the log of the average fare (left panel) and average yield (right panel)

[44] To do this, we specify the derivatives of the first-stage log-likelihood as an additional set of moment conditions and use the methodology outlined by Ho (2006). Regressions using the estimated second-stage residuals indicate that only first-order serial correlation is significant, and allowing for additional periods of serial correlation does not change the standard errors significantly.

price measures. The coefficients for yield are reported in column (1) of Table 4. Consistent with a deterrence explanation, but not an accommodation explanation, the results indicate that, on average, the price declines are largest and statistically significant for intermediate probabilities of Southwest entry, but are smaller, and not necessarily significantly different from zero, for markets where entry probabilities are either high or very low. In the regression both the linear and the quadratic terms are statistically significant at the 1% level (this is also true in the log(average price) regression). The coefficients remain statistically significant in column (2) where we control for the convenience of using connecting service on Southwest, to guard against the possibility that prices on some routes fall in Phase 2 because connecting service on Southwest provides an attractive alternative to the dominant carrier for some proportion of consumers. We do so by including three additional dummies interacted with $SWPE_{m,t}$ that divide the markets into three groups based on the convenience of a Southwest connection.[45] Further evidence against the actual competition explanation is provided by the fact that the coefficients on the new variables indicate that incumbent prices tend to fall most on the routes where connections on Southwest are least convenient.

Figure 2 plots the estimated change in yield for each of the dominant incumbent markets separately against the estimated entry probability (the figure using log of the average fare looks very similar). These market-specific effects are estimated by replacing the three $SWPE_{m,t}$ terms in specification (7) with $SWPE_{m,t}\times$market dummy interactions, with the plotted points being the point estimates of the coefficients on these interactions. While the effects for individual markets are heterogeneous, which is consistent with a limit pricing model where incumbents have different levels of marginal cost and may perceive different degrees of entry threat that are not measured perfectly by the $\widehat{\rho}$s, it is clear that prices do not tend to decrease in markets with high or very low entry probabilities, while many of the markets in between experience quite large Phase 2 price declines.

Of course, while this pattern is consistent with prices falling as part of an entry deterrence strategy, it does not necessarily imply that dominant incumbents use limit pricing strategies of the type that arise in our model, where prices are lowered in order to signal information to an uninformed potential entrant. One alternative explanation would be that Southwest observes

[45] For each market, we calculate the total distance that would be involved in traveling via the most convenient of Southwest's focus airports (Baltimore, Chicago Midway, Phoenix and Las Vegas) and divide that by the non-stop round-trip distance. We divide the markets into three equally-sized groups based on this convenience measure.

Table 4: EE Reduced-Form Analysis: Second Stage

	(1)	(2)	(3)	(4)	(5)	(6)
			Log	Log	Log Load	Prop.
Dependent Variable	Yield	Yield	Capacity	Passengers	Factor	Code-share
$SWPE_{m,t}$	0.0139	-0.064	0.079	0.139**	0.0599***	0.0030
	(0.0147)	(0.059)	(0.052)	(0.053)	(0.0169)	(0.0026)
$\widehat{\rho_m} * SWPE_{m,t}$	-0.721***	-0.555**	-0.2436	0.451	0.695***	-0.023
	(0.136)	(0.273)	(0.402)	(0.423)	(0.177)	(0.030)
$\widehat{\rho_m}^2 * SWPE_{m,t}$	0.921***	0.722**	0.2045	-1.009	-1.214***	0.123**
	(0.194)	(0.315)	(0.515)	(0.581)	(0.3118)	(0.049)
Observations	3,622	3,622	3,100	3,100	3,100	2,243

Notes: Heteroskedasticity robust Newey-West standard errors allowing for one period serial correlation and corrected for first-stage approximation error in the entry probabilities in parentheses. Column (2) includes controls for the convenience of connecting on Southwest. ***, ** and * denote significance at the 1, 5 and 10% levels respectively.

Figure 1: Predicted incumbent price and yield changes in Phase 2 as a function of Southwest's predicted probability of entry.

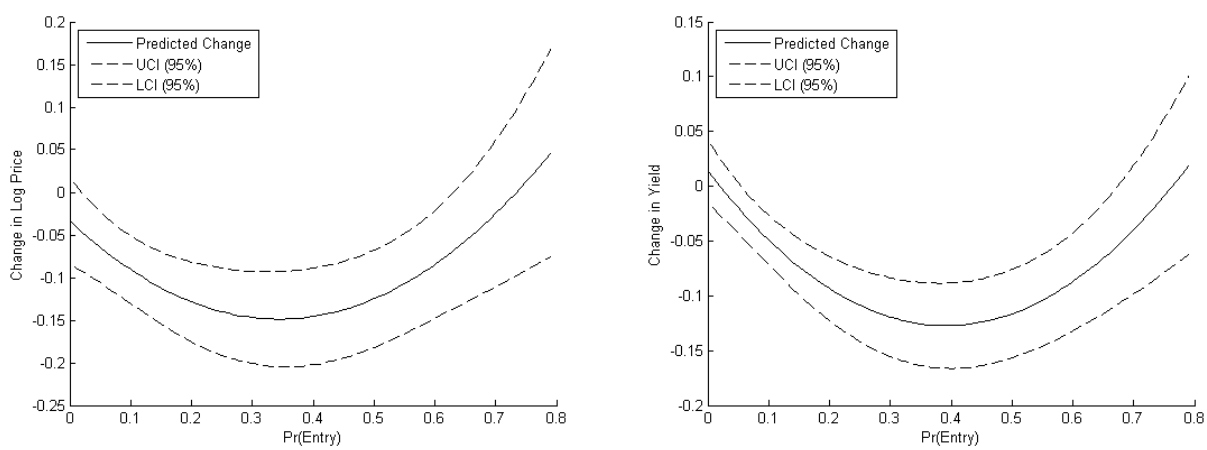
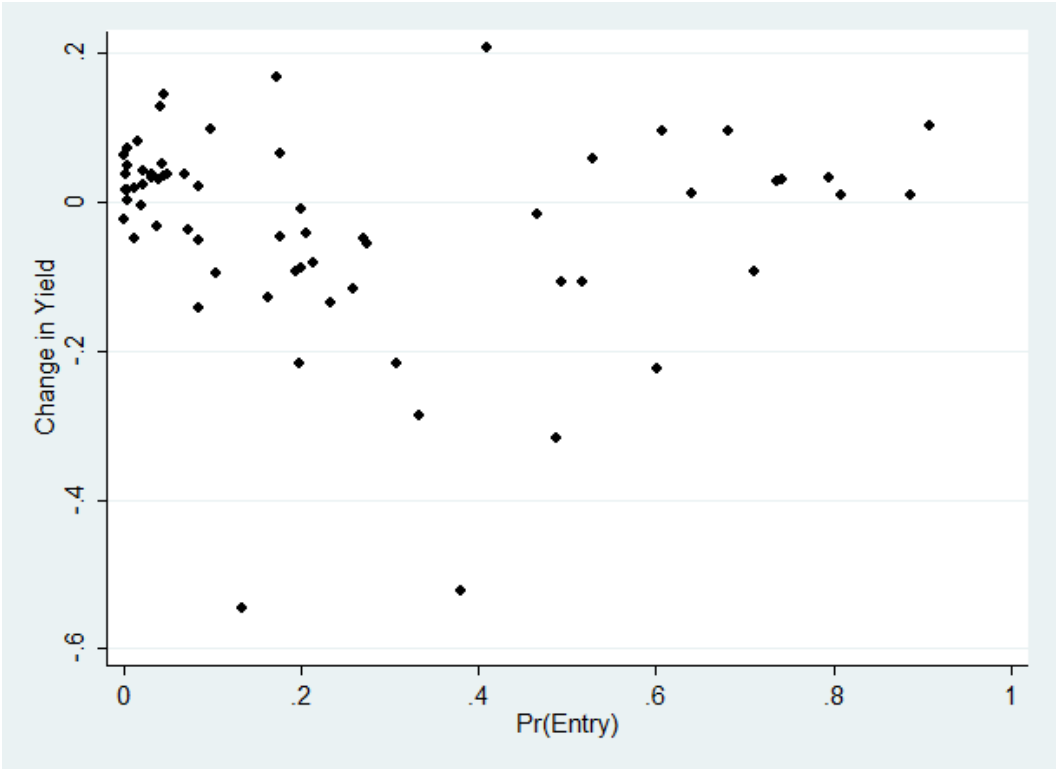


Figure 2: Market-by-market predicted yield declines in Phase 2 as a function of Southwest's predicted probability of entry.



the incumbent's marginal cost, but that in markets that are marginal for Southwest to enter, incumbents invest in capacity to lower their marginal cost of selling additional seats, in order to deter entry, which will also reduce their optimal monopoly prices. In their recent models of predation in the airline industry, both Snider (2009) and Williams (2012) advance models where incumbent legacy carriers invest in capacity for exactly this reason in order to induce low-cost competitors to exit.[46]

To investigate this alternative model of deterrence we use the log of the incumbent's capacity on the route (T100 seats performed) as the dependent variable in specification (7). If the capacity-driven cost reduction story were correct then we would expect to observe increasing capacity on routes with intermediate probabilities of entry. Instead, as seen in Table 4, column (3) and Figure 3 (top-left panel) capacity does not tend to change significantly when Southwest becomes a potential entrant in any type of market, irrespective of the entry probability.[47]

[46] They argue that capacity adjustment costs imply some commitment to low future prices when a carrier invests in capacity.

[47] The number of observations is lower in these regressions because of incomplete coverage of flights scheduled by regional affiliates prior to 2002 in T100, so that we observe no capacity for some market-quarter observations. The estimates are very similar using scheduled seats rather than performed seats.

An alternative explanation for the price results would be that the incumbent's marginal cost falls in some markets when Southwest becomes a potential entrant because, even if its capacity does not change, the number of passengers who want to fly on that segment as part of a longer itinerary may fall.[48] While it is not clear why this would particularly affect markets with intermediate probabilities of entry, we can also test this story directly by using both the log of the number of passengers flying on the dominant incumbent on the route segment and the log of the dominant incumbent's load factor (segment passengers divided by seat capacity) as alternative dependent variables. The results are in columns (4) and (5) of Table 4 and the top-right and bottom-left panels of Figure 3, and we observe that, in fact, when Southwest becomes a potential entrant, the dominant carrier tends to carry more passengers and have higher load factors in markets with intermediate probabilities of entry, suggesting that, if anything, its marginal cost should be increasing rather than decreasing. This provides further evidence in favor of a limit pricing explanation for why prices fall.

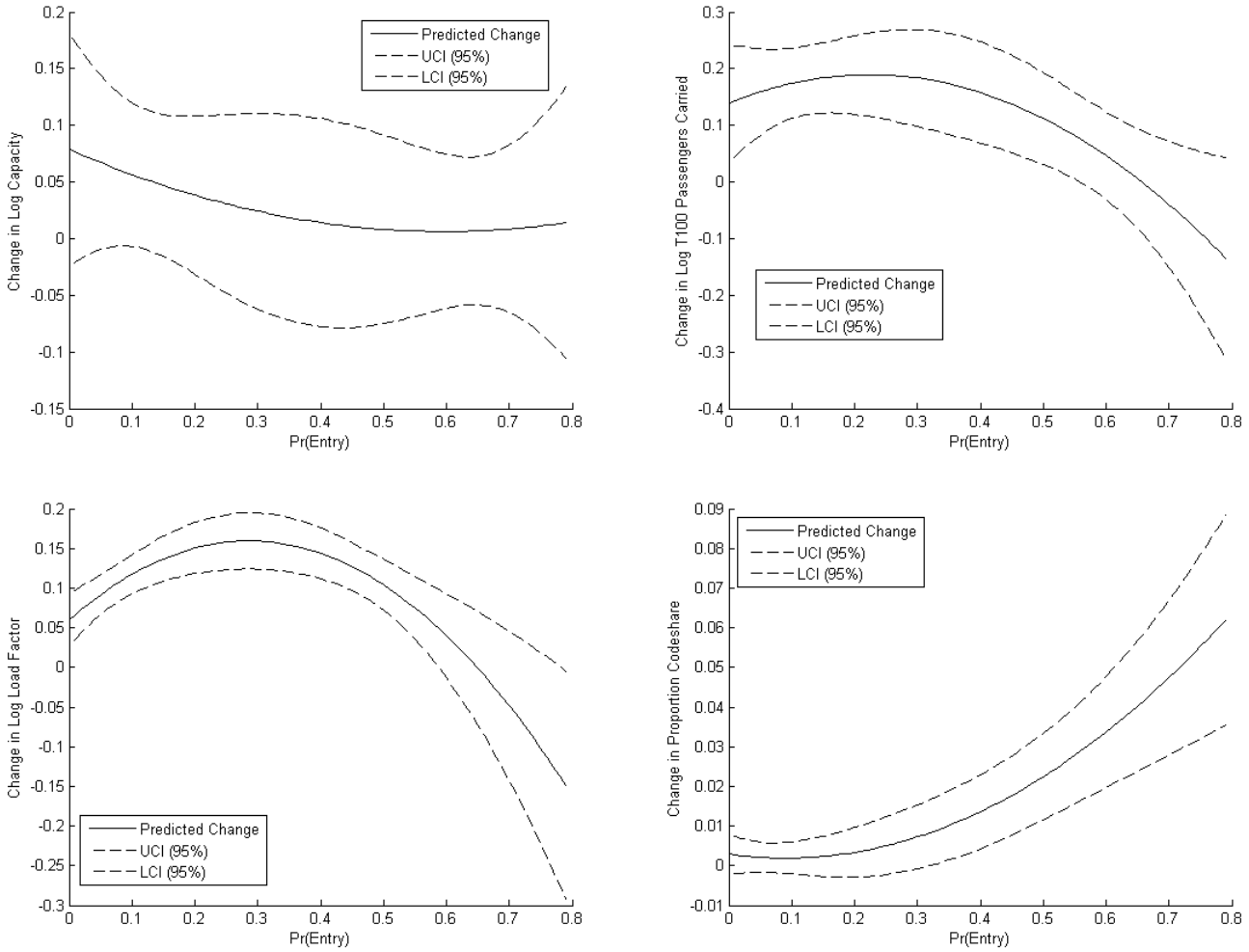
Obviously, carriers might use strategies in addition to limit pricing to try to deter entry. For example, Goetz and Shapiro (2012) find that when Southwest becomes a potential entrant, incumbents also tend to increase code-sharing with other carriers, although it is unclear whether this is for the purposes of deterrence or accommodation.[49] To investigate how code-sharing is used strategically, we use the proportion of the dominant incumbent's passengers on a route that were ticketed by a different carrier as the dependent variable in specification (7).[50] We are necessarily restricted to using quarters after 1998 when operating and ticketing carriers are distinguished in DB1. The results in column (6) of Table 4 and the bottom-right panel of Figure 3 indicate that, when Southwest becomes a potential entrant, dominant carriers increase code-sharing on routes where Southwest's entry is most likely. This suggests that code-sharing, unlike lower prices, is used primarily as a strategy for accommodating Southwest's entry.

[48] For example, when Southwest enters an airport it will typically offer direct flights to Las Vegas. This may reduce the demand for seats on flights between the airport and the hub airports of legacy carriers from consumers who want to go to Las Vegas.

[49] A code-sharing arrangement allows specific non-operating (marketing) carriers to sell tickets on a flight operated by another carrier. For example, Continental and Northwest, and United and US Airways engaged in fairly extensive code-sharing in periods of our data.

[50] Results are similar if we instead use a dummy for any of the dominant incumbent's passengers being ticketed by another carrier which is the variable used by Goetz and Shapiro (2012). On average, 15% of routes satisfy this definition of being code-shared in Phase 1 and 35% in Phase 2, illustrating that the pattern noted by Goetz and Shapiro (2012) in a broader sample of markets is also found in our dominant incumbent sample.

Figure 3: Predicted incumbent responses in Phase 2 as a function of Southwest's predicted probability of entry. The responses shown are the log of capacity (seats performed) (top-left panel), the log of segment passengers (includes passengers connecting onto other routes) (top-right), the log of the load factor, (bottom-left panel), and proportion of passengers carried that have a different ticketing carrier (code-shared) (bottom-right panel).



5 Calibration

While the reduced-form evidence is consistent with dominant incumbents using limit pricing to try to deter entry, this raises the question of whether our simple model can generate the large price declines that are observed in the data. We address this question by calibrating our model, which we then use to illustrate the welfare effects of limit pricing. The model is calibrated using a mixture of estimated parameters (e.g., price sensitivity of demand, process describing the evolution of marginal cost) and parameters that are chosen (e.g., bounds on marginal costs and the distribution of entry costs) to satisfy the assumptions of our model and match the pricing patterns observed in the data. We parameterize the model from Section 2 in the following way:

- demand has a one-level nested logit structure where the nests are 'fly' and 'not fly'. The nesting and price sensitivity parameters, and the difference between incumbent and entrant qualities are estimated from the data. When solving the model we hold the product qualities of the incumbent and entrant fixed over time;
- the marginal costs of both firms evolve according to independent AR(1) processes, that we estimate, with truncated normal innovations. We set the mean difference in incumbent and potential entrant marginal costs to be consistent with our data;
- a truncated normal entry cost distribution for the potential entrant, where we choose the parameters; and,
- firms are assumed to choose prices simultaneously as differentiated Bertrand duopolists once entry occurs.

5.1 Parameters

5.1.1 Demand

We estimate demand using the dominant incumbent sample for Phases 1 and 3 (i.e., before Southwest becomes a potential entrant, and after Southwest enters, if it enters), so that we do not use observations where we believe that limit pricing may be taking place.[51] Markets are

[51] We also restrict ourselves to Phase 1 observations where the dominant incumbent has at least 50 direct DB1 passengers and Phase 3 observations where the formerly dominant incumbent and Southwest have 50 DB1 passengers, although these restrictions have little impact on our sample or our estimates of demand.

non-directional, and we use our gravity model-based definition of market size, with carriers other than the dominant incumbent and Southwest included in the outside good.[52] We do, however, control for the number of other carriers flying any passengers non-stop in our specification of utility.

Viewing each carrier in the market as offering a single product, we assume the standard nested logit indirect utility specification with a single level of nesting (e.g., Berry (1994)):

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

where μ_j is a carrier j effect, T_t is a time trend, and Q_t are quarter-of-year dummies. $p_{j,m,t}$ is the passenger-weighted average round-trip fare for carrier j on market m in quarter t and $\xi_{j,m,t}$ is an unobserved (to the econometrician) quality characteristic. $X_{j,m,t}$ includes an indicator for whether the market is a hub for carrier j, a set of market characteristics (distance, distance^2, and indicators for whether one of the route's endpoint cities has another major airport or is a leisure destination) and a set of dummies for the number of other firms serving the market non-stop.

We estimate the model using the standard estimating equation for a nested logit model with aggregate data (Berry (1994)):

$$\log\left(\frac{s_{j,m,t}}{s_{0,m,t}}\right) = \mu_j + \tau_1 T_t + \tau_{2-4} Q_t + \gamma X_{j,m,t} - \alpha p_{j,m,t} + \lambda \log(\overline{s}_{j,m,t|FLY}) + \xi_{j,m,t} \tag{9}$$

where $\overline{s}_{j,m,t|FLY}$ is carrier j's share of passengers flying the route on the incumbent or Southwest and $s_{j,m,t}$ is firm j's market share.

Appendix Table F presents OLS and 2SLS estimates of the demand model, where we instrument for $p_{j,m,t}$ and $\overline{s}_{j,m,t|FLY}$ using the one-period lagged price of jet fuel, the interaction of the lagged jet fuel price and non-stop route distance, each carrier's average presence at the endpoint airports in that quarter[53], and, for the incumbent, whether Southwest has entered the market and, for Southwest, whether the route involves a hub for the incumbent. Controlling for endogeneity increases the estimated price elasticity of demand (the average is -2.4 in column (2))

[52] We use non-directional markets because entry decisions are non-directional and in our model we are assuming that incumbents set one price for each market.

[53] A carrier's presence at an airport is defined as being equal to its share of originating traffic (calculated using DB1) at the airport.

and, consistent with previous research, consumers are estimated to prefer traveling on a carrier with a hub at one of the endpoints. Based on the 2SLS results, we calibrate the model using $\widehat{\alpha} = -0.408$ and $\widehat{\lambda} = 0.762$, and assume a market size of 58,777, which is the mean size (during Phase 2) of the 65 markets for which we have Phase 2 observations. In the calibration we also set θ_j equal to 0.33 and 0.30 for the incumbent and potential entrant respectively and fix the $\xi_{j,t}$s to be equal to zero so that, ignoring price, carrier quality does not vary over time. The choice of θ for the incumbent matches the average value implied by the estimates for incumbent carriers in Phase 3, while the value for the potential entrant allows us to match the average difference in incumbent and Southwest qualities in Phase 3 estimated using a route-quarter fixed effects regression (not reported).

5.1.2 Marginal Costs

We specify that the marginal costs of the firm j exist on a support $[\underline{c_j}, \overline{c_j}]$ and evolve according to an AR(1) process: $mc_{j,t} = \rho^{AR} mc_{j,t-1} + (1-\rho^{AR})\frac{\underline{c_j}+\overline{c_j}}{2} + \varepsilon_{j,t}$. The $\varepsilon_{j,t}$ innovation is drawn from a normal distribution that is truncated so that marginal costs remain on their support and the untruncated distribution has mean zero and standard deviation σ_ε. This process implies that in the long-run each carrier's expected marginal cost is equal to the mid-point of its support.

To estimate the ρ^{AR} and the average difference in marginal costs, we use the 2SLS demand estimates and back out the marginal cost for each carrier-route-quarter observation assuming that pricing in Phases 1 and 3 is characterized by the standard static monopoly/Bertrand Nash first-order conditions (recall that Phase 2 observations, where the incumbent may be limit pricing, are not used for estimation). To make comparisons across routes, we transform these marginal costs to \$s-per-mile of the non-stop route. The median and mean marginal costs calculated in this way are \$0.13/mile and \$0.16/mile, comparable to the average \$0.134 of total operating expenses per available seat mile that carriers reported on the Department of Transportation's Form 41 in 2010. A route-quarter fixed effects regression using observations from Phase 3 (not reported) indicates that Southwest has an average marginal cost advantage of \$0.055 per mile (significant at the 1% level).

In our calibration we will consider a market with a round-trip distance of 1,200 miles, close to the median for the dominant incumbent markets in our data (examples from our data that are close to this length include Los Angeles-Salt Lake City and Minneapolis-Tulsa), implying

an average marginal cost advantage for Southwest of close to \$70. We choose supports of $[\underline{c_I}, \overline{c_I}] = [\$160, \$280]$ and $[\underline{c_E}, \overline{c_E}] = [\$90, \$210]$. The width of these supports is chosen so that our assumption that $q_I^D(c_{I,t}, c_{E,t}) - q^M(p_I^{\text{static monopoly}}(c_{I,t})) - \frac{\partial \pi_I^D(c_{I,t}, c_{E,t})}{\partial a_{E,t}} \frac{\partial a_{E,t}}{\partial c_{I,t}} < 0$ holds for all possible costs.

We estimate ρ^{AR} by regressing per-mile marginal costs on its one-period lagged value, controlling for observed route characteristics (such as distance, market size and the presence of slot constraints at either endpoint), carrier dummies, a full set of quarter dummies and, as a measure of a component of costs that is presumably observed by carriers, the one-quarter lagged jet fuel price interacted with route distance. Column (1) of Table F.2 shows the estimates when we pool observations for all carriers. As the implied marginal costs are likely to be measured with error (partly because market shares and average prices are based on the limited sample of passengers included in the DB1 data), in column (2) we instrument for the lagged marginal cost with the third through fifth lags of marginal cost. The estimated persistence of marginal costs increases significantly. In the third and fourth columns, we provide 2SLS estimates for the incumbent carriers and Southwest separately. In both cases $\widehat{\rho^{AR}} \approx 0.97$ and we use this value in the calibration. We set σ_ε, the standard deviation of innovations to marginal cost for our representative 1,200 mile route, equal to \$36.[54]

5.1.3 Entry Costs

In our baseline specification we assume that E's entry costs are drawn from a truncated normal (support of $[\$0, \$100 \text{ million}]$) where the untruncated distribution has a mean of \$55.4 million and a standard deviation of \$2 million. The mean and standard deviation parameters were selected, based on a coarse grid search, so that the average degree to which the incumbent shades prices below the static monopoly price when strategies are approximately stationary at the start of the game is similar to the size of the price cuts observed in markets with intermediate probabilities of entry when Southwest becomes a potential entrant. Of course, this raises the question of whether entry costs of this size are reasonable. As our model does not explicitly include fixed costs and we are assuming that once E has entered it will stay in the market forever, the entry cost should be interpreted as including the discounted value of all of the future fixed costs

[54] The distribution of estimated innovations has fatter tails than a normal. Our choice of standard deviation allows us to match the interquartile range of cost innovations based on the IV estimates in column (2) of Table F.2.

that Southwest will incur in operating the route, which might include, for example, the fixed component of the costs associated with leasing additional gates and the opportunity costs of using them on the route in question rather than on other profitable routes. The attractiveness of entry will be determined, of course, by the level of the entry cost relative to the discounted value of variable profits that the entrant can expect to make if it enters. Given our demand and cost parameters, the average steady-state variable profit of Southwest as a duopolist is \$1.5 million per quarter, which translates to a present discounted value of \$74.8 million. Our specification therefore assumes that entry and fixed costs combined account for roughly 75% of discounted variable profits, which does not seem unreasonable *a priori*.

5.2 Equilibrium Strategies

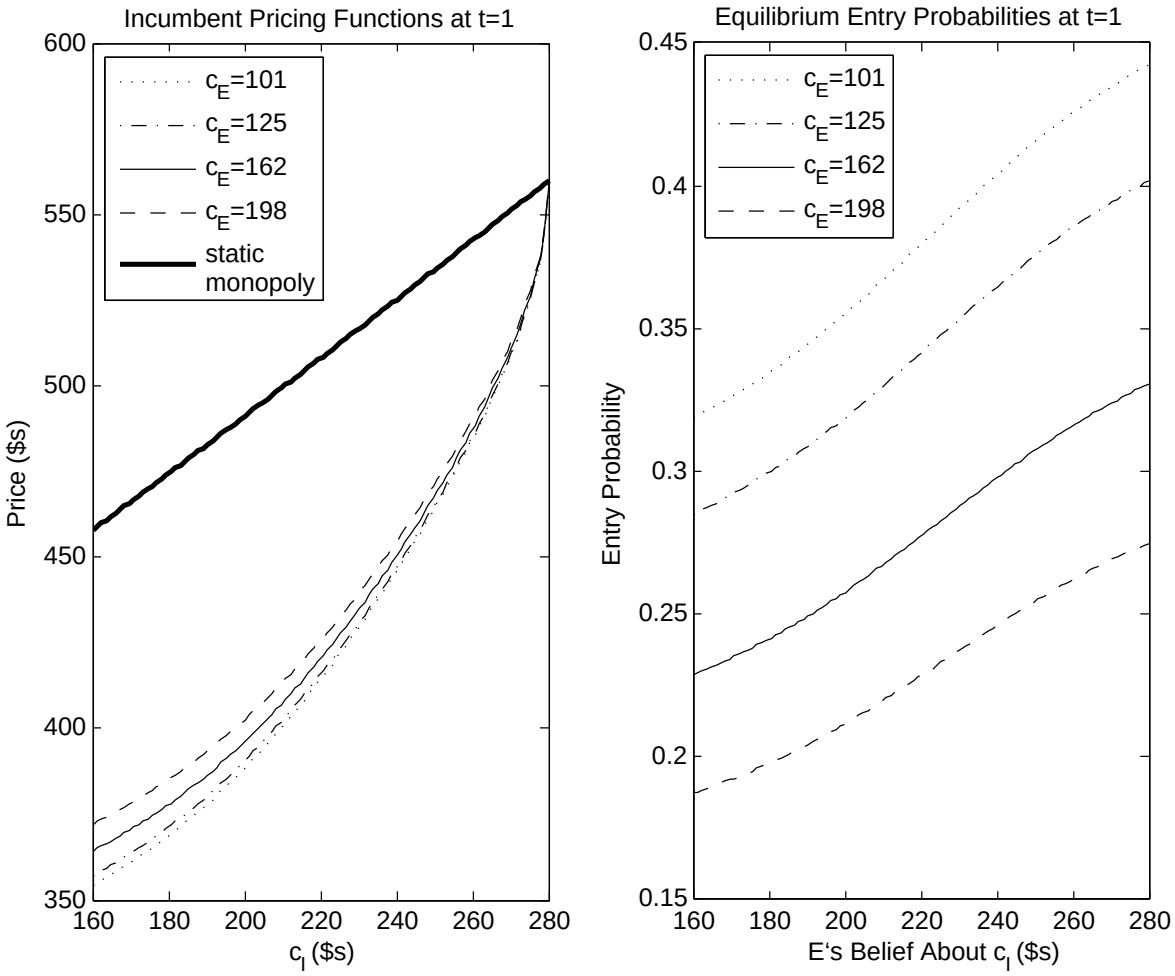
Given these parameters we solve the model, using the method described in Section 2.3, assuming that $T = 200$. For this T, entry probabilities and pricing strategies are stationary (to four decimal places) at the start of the game. Figure 4 shows the incumbent's pricing functions at $t = 1$ for several values of c_E together with Southwest's entry probabilities as a function of its beliefs about the incumbent's marginal costs, which are correct in equilibrium.

In equilibrium, there is substantial shading below the monopoly price for all $c_I < \overline{c_I}$. Using the probability weights implied by the steady state distribution of marginal costs for each firm, the average shading below the monopoly price is \$80.54 or 16.1% of the monopoly price, illustrating that our model can match the average size of the price reductions observed when Southwest becomes a potential entrant in markets with intermediate probabilities of entry.[55] Shading is substantial in this example because E's entry decision is relatively sensitive to its beliefs about the incumbent's marginal cost, and, consistent with the insights in EE, the average level of the entry probability is neither very high nor very low. Based on solving many games with different parameters, the degree of shading increases when there is greater serial correlation in the incumbent's marginal cost or the variance of the entry cost distribution falls.[56] Greater serial

[55] While our focus is on what happens when strategies are stationary, it is worth noting that, as t increases, the average degree of shading changes in a non-monotonic way. For our parameters, the degree of shading is effectively constant until $t \approx 104$, at which point it increases rapidly, reaching a maximum of 43.5% at $t = 136$ before decreasing rapidly and becoming very close to zero by $t = 150$, by which point the level of entry costs means that entry is effectively blockaded. The incentives to try to deter entry immediately before this point are therefore very strong, because if deterrence is successful a long period of monopoly profit will be enjoyed, resulting in the high degree of shading.

[56] For example, if $\rho^{AR} = 0.99$ and the standard deviation of marginal cost innovations and entry costs are \$5

Figure 4: Incumbent's Pricing Strategies and Potential Entrant's Entry Probabilities at $t = 1$ for Different Values of c_E.



correlation leads to more shading in equilibrium for two reasons. First, from the perspective of the entrant, the incumbent's marginal cost becomes a better predictor of the entrant's profits if it enters, so the entry decision becomes more sensitive to its beliefs. Second, from the perspective of a low-cost incumbent, it also implies that if entry is deterred in the current period it is also likely to be deterred, in equilibrium, in subsequent periods. Both of these effects increase the incumbent's incentive to invest in entry deterrence by reducing the current price. A lower variance of the entry cost distribution makes the entry decision more sensitive to beliefs about the incumbent, which also increases the incumbent's incentive to limit price. On the other hand, if we either increase or decrease market size substantially then, because the average attractiveness of entry changes in the same direction, and away from the intermediate values that maximize

and \$1.5 million respectively, the average degree of shading at the beginning of the game is 29%.

deterrence incentives, the degree of shading falls.[57]

5.3 Welfare Calculations

We can also use our model to quantify the welfare effects of limit pricing. As in the two-period MR model with a fully separating equilibrium, limit pricing is unambiguously welfare increasing (as long as limit prices are above marginal costs) in our model relative to a model where the potential entrant can observe the incumbent's marginal cost (full information), as entry decisions are the same on the equilibrium path but prices are lower before entry occurs because of limit pricing. For our baseline parameters, the gains in welfare that occur before entry occurs are quite large in percentage terms. Based on the steady-state distribution of marginal costs for this single representative market, the 16.1% shading increases expected consumer surplus by \$843,000 per quarter (26.5% of the full information consumer surplus), while reducing the incumbent's profits by \$154,000 (6.4%).

Of course, welfare would be increased if there were more entry (specifically expected per period total welfare is \$8.03 million, \$4.87 million and \$5.56 million under duopoly, full information monopoly and limit pricing monopoly respectively), and there may be too little entry in our model as entrants fail to capture all of the surplus that they create. While entry is the same in both the limit pricing and full information models, it would be different if there were incomplete information and pricing were too opaque to allow for meaningful signaling. For example, a potential entrant might only be able to observe list prices, while transaction prices, which may involve substantial discounts, would be more indicative of the incumbent's marginal costs. In this case, E would have to take an entry decision based only on its own costs (uninformed entry), and depending on the shape of the E's value functions with respect to its beliefs in the limit pricing model, this could result in more entry. The question is whether this effect could be large enough to increase total welfare.

Given the baseline parameters, the limit pricing equilibrium yields substantially higher welfare than uninformed entry (as well as full information). The reason is that uninformed entry only

[57] When we move to a market size of 10,000 people (between the 5th and 10th percentiles of observed market sizes), the equilibrium entry probabilities are always tiny (less than 1e-10) and the incumbent's strategy involves essentially no shading. On the other hand, when we move to a market size of 200,000 (between the 90th and 95th percentiles), the equilibrium entry probabilities at the start of the game are greater than 0.86, and the average degree of shading is less than 4% of the monopoly price.

raises the probability of entry by 1% (from 0.298 to 0.301 given the steady-state distribution of costs), and while this tends to increase welfare relative to full information, the effect is not large enough to overcome the loss of consumer surplus associated with monopoly pricing before entry occurs.[58] In addition, compared with limit pricing, entry is less likely to occur when the incumbent is inefficient, which is when entry would be particularly valuable. As an illustration, across the first two periods of the game expected consumer surplus is \$5.65 million, \$5.66 million and \$7.08 million with full information, uninformed entry (with its slightly greater competition in the second period) and limit pricing respectively. Of course, while these numbers illustrate that limit pricing can involve substantial gains in welfare relative to two benchmark alternatives, they take no account of the possible costs or benefits involved with the creation of the monopoly position in the first place.

6 Conclusion

We have developed theoretical and empirical frameworks for analyzing a classic form of strategic behavior, entry deterrence by setting a low price, in a dynamic setting. Under some weak conditions on the primitives and a standard refinement, our model has a unique Markov Perfect Bayesian Equilibrium in which the incumbent's pricing policy reveals its marginal cost each period. This characterization of the equilibrium makes it straightforward to compute equilibrium pricing strategies. The resulting tractability stands in contrast to the widely-held belief in the applied literature that dynamic games with persistent asymmetric information are too intractable to be used in empirical work, at least when using standard equilibrium concepts. While our model is a special case in many respects, and uniqueness of a dynamic MPBE is certainly not general, it is the natural extension of one of the most widely-cited two-period models in the theoretical literature (Milgrom and Roberts (1982)).

We exploit tractability to study whether our model of dynamic limit pricing can explain why incumbent carriers cut prices when Southwest becomes a potential entrant on a particular airline route. Here we provide new evidence, both in the reduced-form and by calibrating our

[58] When the expected value of being a duopolist in the next period, $\mathbb{E}_t[\phi^E_{t+1}|c_{I,t}, c_{E,t}]$, is graphed against $\widehat{c}_{I,t}$, the relationship is close to linear. If the nesting parameter in demand were closer to one, then there are values of $c_{E,t}$ where the relationship is more clearly convex, which can induce a greater difference in expected entry under limit pricing/full information and uninformed entry.

model, that limit pricing can explain both the qualitative pattern and the quantitative size of the observed price cuts.

One question that we have often been asked is whether we are necessarily attached to the idea that, when an incumbent sets a low price, it is indicating that its marginal costs are low rather than demand is low, which could also make entry unattractive. The answer is that while it may be possible to create a model where this form of equilibrium behavior arises, in which case it would be difficult to distinguish from our model without exogenous variation in the predictability of demand, it is not straightforward to come up with a specification where it would be the case that incumbents would want to lower prices when faced by an entry threat and the sufficient conditions for the uniqueness of a fully separating equilibrium hold.

To see why, consider some specific examples. Suppose that demand has a simple logit specification, marginal costs are known and constant (both with respect to output and across time) but that the current market size parameter is only observed by the incumbent and is serially correlated over time. In this case, the optimal monopoly price will not depend on market size, but it will be cheaper for an incumbent to cut price when the market size is small. However, the single crossing property required in our proofs of existence and uniqueness may not hold because the expected future benefit of keeping the potential entrant out of the market will tend to increase with the size of the market. In contrast, in our model when an incumbent has a lower marginal cost it is both more valuable for the incumbent to preserve monopoly and cheaper for the incumbent to lower its price. The same kind of problem can arise under an alternative specification where it is the price sensitivity of demand that is not observed by the potential entrant: it will be cheaper to cut price below the monopoly level when demand is more price sensitive, but it may be more valuable to preserve monopoly when demand is less price sensitive. Finally, suppose that what the potential entrant does not know is how attractive consumers find the legacy incumbent carrier (both in absolute terms and relative to how they perceive the potential entrant). In this model, even if it is the case that Southwest's profits from entering decline in the attractiveness of the incumbent and it is more valuable for the incumbent to preserve monopoly when the incumbent is more attractive to consumers, a separating equilibrium would tend to involve a more attractive incumbent *increasing* prices above the full information monopoly level. Therefore while this variant of the model might have a fully separating equilibrium, it could not explain why incumbent airlines cut prices when they face the threat of entry by Southwest. For

these reasons, we believe that our focus on a model where the incumbent's marginal costs are not observed is appropriate.

This discussion does, however, indicate that there is much open ground for exploring, both theoretically and empirically, how different types of asymmetric information can lead to different types of dynamic behavior, and we believe that our approach could be applied to at least some of these alternative models. To examine a wider array of industries and markets, it would also be necessary to extend our model to cases where there are several incumbents, and identify conditions under which these types of models also give clear predictions that can be tested empirically.

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A Proof of Theorem 1

In this Appendix, we prove that the strategies described in Theorem 1 form a fully separating Markov Perfect Bayesian Equilibrium that is unique under a recursive application of the D1 Refinement. The proof uses induction and makes extensive use of theoretical results for one-shot signaling games from Mailath and von Thadden (2013) and Ramey (1996).

A.1 Notation and the Definition of Values

At many points in the proof we will make use of notation indicating expectations of a firm's value in a future period, e.g., $\mathbb{E}_t[V^E_{t+1}|\widehat{c}_{I,t}, c_{E,t}]$. We will use several conventions.

1. $\phi^E_t(c_{E,t}, c_{I,t})$ denotes E's expected present discounted future value when it is a duopolist at the beginning of period t, and its marginal cost is $c_{E,t}$ and I's marginal cost is $c_{I,t}$. Under our assumption that duopolists use unique static Nash equilibrium strategies in a complete information game, $\phi^E_t(c_{E,t}, c_{I,t})$ is uniquely defined.

2. $\phi^I_t(c_{I,t}, c_{E,t})$ denotes I's expected present discounted future value when it is a duopolist at the beginning of period t, and its marginal cost is $c_{I,t}$ and E's marginal cost is $c_{E,t}$. Under our assumption that duopolists use unique static Nash equilibrium strategies in a complete information game, $\phi^E_t(c_{I,t}, c_{E,t})$ is uniquely defined.

3. $V^I_t(c_{I,t}, c_{E,t})$ denotes I's expected present discounted future value when it is an incumbent monopolist at the beginning of period t, and its marginal cost is $c_{I,t}$ and the E's marginal cost, which I knows, is $c_{E,t}$. κ_t is not known when the value is defined (so the value is the expectation over the different possible values of κ_t). This value will be dependent on the pricing strategy that I will use in period t, E's period t entry strategy and both firms strategies in future periods.

4. $V^E_t(c_{E,t}, c_{I,t})$ denotes E's expected present discounted future value when it is a potential entrant at the beginning of period t, its marginal cost is $c_{E,t}$ and I's marginal cost is $c_{I,t}$. Of course, E does not know $c_{I,t}$ at the moment when this value is being defined (i.e., prior to I choosing a price) but defining values in this way is convenient both because it defines the value of both firms at the same moment each period (the beginning) and it economizes

on the amount of notation. κ_t is not known when the value is defined (so the value is the expectation over the different possible values of κ_t).

When we write ϕ_t^E, ϕ_t^I, V_t^E or V_t^I to economize on notation, their dependence on $c_{E,t}$ and $c_{I,t}$ should be understood. For example, $\mathbb{E}_t[V_{t+1}^E|\widehat{c}_{I,t}, c_{E,t}]$ is the expected value of E as a potential entrant at the start of period $t+1$ given the period t value of $c_{E,t}$ and a belief that $c_{I,t}$ is exactly $\widehat{c}_{I,t}$. As in this example, when E has point beliefs we will denote the believed value as $\widehat{c}_{I,t}$. If E does not have a point belief, we will denote their density as $q(\widetilde{c_{I,t}})$ and assume that only values on the interval $[\underline{c_I}, \overline{c_I}]$ can have positive density.

A.2 Useful Lemmas

We will make frequent use of several results:

Lemma 1 *Suppose that $f(x,y)$ is a strictly positive function, $g(x|w)$ is a strictly positive conditional pdf on $x, w \in [\underline{x}, \overline{x}]$ and $h(y)$ is a strictly positive pdf on $y \in [\underline{y}, \overline{y}]$.*[59] *Further suppose that (i) for a given value of w $\exists x' \in (\underline{x}, \overline{x})$ such that $\frac{\partial g(x'|w)}{\partial w} = 0$, $\frac{\partial g(x|w)}{\partial w} < 0$ $\forall x < x'$ and $\frac{\partial g(x|w)}{\partial w} > 0$ for $\forall x > x'$ and (ii) $k \equiv \int_{\underline{y}}^{\overline{y}} \int_{\underline{x}}^{\overline{x}} f(x,y) \frac{\partial g(x|w)}{\partial w} h(y) dx dy$. If $\forall x, y$ $\frac{\partial f(x,y)}{\partial x} > 0$ then $k > 0$. On the other hand, if $\forall x, y$ $\frac{\partial f(x,y)}{\partial x} < 0$ then $k < 0$.*

Proof.

$$
\begin{aligned}
k &\equiv \int_{\underline{y}}^{\overline{y}} \int_{\underline{x}}^{\overline{x}} f(x,y) \frac{\partial g(x|w)}{\partial w} h(y) dx dy \\
&= \int_{\underline{y}}^{\overline{y}} \int_{\underline{x}}^{x'} f(x,y) \frac{\partial g(x|w)}{\partial w} h(y) dx dy + \int_{\underline{y}}^{\overline{y}} \int_{x'}^{\overline{x}} f(x,y) \frac{\partial g(x|w)}{\partial w} h(y) dx dy \\
&> \int_{\underline{y}}^{\overline{y}} f(x',y) \left\{ \int_{\underline{x}}^{x'} \frac{\partial g(x|w)}{\partial w} dx + \int_{x'}^{\overline{x}} \frac{\partial g(x|w)}{\partial w} dx \right\} h(y) dy = 0 \text{ if } \frac{\partial f(x,y)}{\partial x} > 0 \\
\text{or} &< \int_{\underline{y}}^{\overline{y}} f(x',y) \left\{ \int_{\underline{x}}^{x'} \frac{\partial g(x|w)}{\partial w} dx + \int_{x'}^{\overline{x}} \frac{\partial g(x|w)}{\partial w} dx \right\} h(y) dy = 0 \text{ if } \frac{\partial f(x,y)}{\partial x} < 0
\end{aligned}
$$

■

There are several useful corollaries of Lemma 1.

Corollary 1 *Suppose that $\phi^E_{t+1}(c_{E,t+1}, c_{I,t+1}) > V^E_{t+1}(c_{E,t+1}, c_{I,t+1})$, $\frac{\partial \{\phi^E_{t+1}(c_{E,t+1}, c_{I,t+1}) - V^E_{t+1}(c_{E,t+1}, c_{I,t+1})\}}{\partial c_{I,t+1}} > 0$ for all $(c_{E,t+1}, c_{I,t+1})$ and $\frac{\partial \psi_I(c_{I,t+1}|\widehat{c}_{I,t})}{\partial \widehat{c}_{I,t}}$ satisfies Assumption 1, then*

$$
\frac{\partial \mathbb{E}_t[\phi^E_{t+1}|\widehat{c}_{I,t}, c_{E,t}]}{\partial \widehat{c}_{I,t}} - \frac{\partial \mathbb{E}_t[V^E_{t+1}|\widehat{c}_{I,t}, c_{E,t}]}{\partial \widehat{c}_{I,t}} = \int_{\underline{c_I}}^{\overline{c_I}} \int_{\underline{c_E}}^{\overline{c_E}} \left[\phi^E_{t+1}(c_{E,t+1}, c_{I,t+1}) - V^E_{t+1}(c_{E,t+1}, c_{I,t+1})\right] \frac{\partial \psi_I(c_{I,t+1}|\widehat{c}_{I,t})}{\partial \widehat{c}_{I,t}} \psi_E(c_{E,t+1}|c_{E,t}) dc_{I,t+1} dc_{E,t+1} > 0.
$$

[59] In particular, we will assume that $\int_{\underline{y}}^{\overline{y}} h(y) dy = 1$ and $\int_{\underline{x}}^{\overline{x}} \frac{\partial g(x|w)}{\partial w} dx = 0$. $h(y)$ could be a conditional or an unconditional pdf.

Corollary 2 *Suppose that* $\phi^E_{t+1}(c_{E,t+1}, c_{I,t+1}) > V^E_{t+1}(c_{E,t+1}, c_{I,t+1})$, $\frac{\partial\{\phi^E_{t+1}(c_{E,t+1},c_{I,t+1})-V^E_{t+1}(c_{E,t+1},c_{I,t+1})\}}{\partial c_{E,t+1}} < 0$ *for all* $(c_{E,t+1}, c_{I,t+1})$ *and* $\frac{\partial\psi_E(c_{E,t+1}|c_{E,t})}{\partial c_{E,t}}$ *satisfies Assumption 1, then*

$$\frac{\partial\mathbb{E}_t[\phi^E_{t+1}|\widehat{c}_{I,t}, c_{E,t}]}{\partial c_{E,t}} - \frac{\partial\mathbb{E}_t[V^E_{t+1}|\widehat{c}_{I,t}, c_{E,t}]}{\partial c_{E,t}} = \int\limits_{\underline{c_I}}^{\overline{c_I}}\int\limits_{\underline{c_E}}^{\overline{c_E}} \left[\phi^E_{t+1}(c_{E,t+1}, c_{I,t+1}) - V^E_{t+1}(c_{E,t+1}, c_{I,t+1})\right] \frac{\partial\psi_E(c_{E,t+1}|c_{E,t})}{\partial c_{E,t}} \psi_I(c_{I,t+1}|c_{I,t}) dc_{I,t+1} dc_{E,t+1} < 0.$$

Corollary 3 *Suppose that* $V^I_{t+1}(c_{I,t+1}, c_{E,t+1}) > \phi^I_{t+1}(c_{I,t+1}, c_{E,t+1})$, $\frac{\partial\{V^I_{t+1}(c_{I,t+1},c_{E,t+1})-\phi^I_{t+1}(c_{I,t+1},c_{E,t+1})\}}{\partial c_{I,t+1}} < 0$ *for all* $(c_{I,t+1}, c_{E,t+1})$ *and* $\frac{\partial\psi_I(c_{I,t+1}|c_{I,t})}{\partial c_{I,t}}$ *satisfies Assumption 1, then*

$$\frac{\partial\mathbb{E}_t[V^I_{t+1}|c_{I,t}, c_{E,t}]}{\partial c_{I,t}} - \frac{\partial\mathbb{E}_t[\phi^E_{t+1}|c_{I,t}, c_{E,t}]}{\partial c_{I,t}} = \int\limits_{\underline{c_I}}^{\overline{c_I}}\int\limits_{\underline{c_E}}^{\overline{c_E}} \left[V^I_{t+1}(c_{I,t+1}, c_{E,t+1}) - \phi^I_{t+1}(c_{I,t+1}, c_{E,t+1})\right] \frac{\partial\psi_I(c_{I,t+1}|c_{I,t})}{\partial c_{I,t}} \psi_E(c_{E,t+1}|c_{E,t}) dc_{I,t+1} dc_{E,t+1} < 0.$$

A further, very straightforward, result that will be referred to frequently is:

Lemma 2 *(a) Suppose that* $\phi^E_{t+1}(c_{E,t+1}, c_{I,t+1}) > V^E_{t+1}(c_{E,t+1}, c_{I,t+1})$ *for all* $(c_{E,t+1}, c_{I,t+1})$ *and* ψ_I *and* ψ_E *satisfy Assumption 1 then*

$$\mathbb{E}_t[\phi^E_{t+1}|q(\widetilde{c_{I,t}}), c_{E,t}] - \mathbb{E}_t[V^E_{t+1}|q(\widetilde{c_{I,t}}), c_{E,t}] =$$
$$\int\limits_{\underline{c_I}}^{\overline{c_I}}\int\limits_{\underline{c_E}}^{\overline{c_E}} \left\{ \begin{array}{c} \left[\phi^E_{t+1}(c_{E,t+1}, c_{I,t+1}) - V^E_{t+1}(c_{I,t+1}, c_{E,t+1})\right] \times \ldots \\ \psi_I(c_{I,t+1}|\widetilde{c_{I,t}})\psi_E(c_{E,t+1}|c_{E,t})q(\widetilde{c_{I,t}}) \end{array} \right\} dc_{E,t+1} dc_{I,t+1} d\widetilde{c_{I,t}} > 0$$

including the case where E has a point belief about I's marginal cost as a special case; and,
(b) Suppose that $V^I_{t+1}(c_{I,t+1}, c_{E,t+1}) > \phi^I_{t+1}(c_{I,t+1}, c_{E,t+1})$ *for all* $(c_{E,t+1}, c_{I,t+1})$ *and* ψ_I *and* ψ_E *satisfy Assumption 1 then*

$$\mathbb{E}_t[V^I_{t+1}|c_{I,t}, c_{E,t}] - \mathbb{E}_t[\phi^I_{t+1}|c_{I,t}, c_{E,t}] =$$
$$\int\limits_{\underline{c_I}}^{\overline{c_I}}\int\limits_{\underline{c_E}}^{\overline{c_E}} \left[V^I_{t+1}(c_{I,t+1}, c_{E,t+1}) - \phi^I_{t+1}(c_{I,t+1}, c_{E,t+1})\right] \psi_I(c_{I,t+1}|c_{I,t})\psi_E(c_{E,t+1}|c_{E,t}) dc_{E,t+1} dc_{I,t+1} > 0.$$

Proof. Follows immediately from the assumptions as $\psi_I(c_{I,t+1}|\widehat{c}_{I,t}) > 0$ for all costs on $\left[\underline{c_I}, \overline{c_I}\right]$ and $\psi_E(c_{E,t+1}|c_{E,t}) > 0$ for all costs on $\left[\underline{c_E}, \overline{c_E}\right]$. ■

A.3 Outline

Our proof uses induction. We first show that if the value functions of both firms satisfy several properties at the start of period $t+1$ then, together with our Assumptions 1-4, it follows that the unique equilibrium strategies in period t satisfying the D1 refinement will be those described in Theorem 1. We then show that this result implies that the value functions at the start of period t will have the same set of properties. Finally, we show that the value functions at the start of the last period satisfy these properties, which is very straightforward.

A.4 Proof for Period t Given Value Function Properties at $t+1$

We will assume that the entrant's value functions as defined at the start of period $t+1$ have the following properties:

E1^{t+1}. $\phi^E_{t+1}(c_{E,t+1}, c_{I,t+1}) > V^E_{t+1}(c_{E,t+1}, c_{I,t+1})$; and

E2^{t+1}. $\phi^E_{t+1}(c_{E,t+1}, c_{I,t+1})$ and $V^E_{t+1}(c_{E,t+1}, c_{I,t+1})$ are uniquely defined functions of c_{It+1} and $c_{E,t+1}$, and do not depend on κ_t or any earlier values of κ;

E3^{t+1}. $\phi^E_{t+1}(c_{E,t+1}, c_{I,t+1})$ and $V^E_{t+1}(c_{E,t+1}, c_{I,t+1})$ are continuous and differentiable in both arguments; and

E4^{t+1}. $\frac{\partial[\phi^E_{t+1}(c_{E,t+1},c_{I,t+1})]}{\partial c_{I,t+1}} > \frac{\partial[V^E_{t+1}(c_{E,t+1},c_{I,t+1})]}{\partial c_{I,t+1}}$ and $\frac{\partial[\phi^E_{t+1}(c_{E,t+1},c_{I,t+1})]}{\partial c_{E,t+1}} < \frac{\partial[V^E_{t+1}(c_{E,t+1},c_{I,t+1})]}{\partial c_{E,t+1}}$

A.4.1 Potential Entrant Strategy in Period t

E will compare its expected continuation value if it enters, $\mathbb{E}_t[\phi^E_{t+1}|\widehat{c}_{I,t}, c_{E,t}]$ if it has a point belief and otherwise $\mathbb{E}_t[\phi^E_{t+1}|q(\widetilde{c_{I,t}}), c_{E,t}]$, less its entry cost, κ_t, with its expected continuation value if it does not enter, $\mathbb{E}_t[V^E_{t+1}|\widehat{c}_{I,t}, c_{E,t}]$ or $\mathbb{E}_t[V^E_{t+1}|q(\widetilde{c_{I,t}}), c_{E,t}]$. By E2^{t+1} these continuation values do not depend on κ_t or earlier entry costs, so that E's optimal entry stategy will be a period-specific threshold rule in its entry cost. Specifically E will enter if and only if

$$\kappa_t < \kappa^*_t(\widehat{c}_{I,t}, c_{E,t}) = \beta\left\{\mathbb{E}_t[\phi^E_{t+1}|\widehat{c}_{I,t}, c_{E,t}] - \mathbb{E}_t[V^E_{t+1}|\widehat{c}_{I,t}, c_{E,t}]\right\}$$

if E has a point belief $\widehat{c}_{I,t}$; and otherwise its entry strategy will be to enter if and only if

$$\kappa_t < \kappa^*_t(q(\widetilde{c_{I,t}}), c_{E,t}) = \beta\left\{\mathbb{E}_t[\phi^E_{t+1}|q(\widetilde{c_{I,t}}), c_{E,t}] - \mathbb{E}_t[V^E_{t+1}|q(\widetilde{c_{I,t}}), c_{E,t}]\right\}$$

To derive the incumbent's strategy we also need to show that the threshold has certain properties. Specifically, we need it to be the case that $\kappa_t^* > \underline{\kappa} = 0$ and $\kappa_t^* < \overline{\kappa}$; and, that if E has a point belief, its threshold κ_t^* is continuous and differentiable and strictly decreasing in $c_{E,t}$ and strictly increasing in $\widehat{c}_{I,t}$. $\kappa_t^* > \underline{\kappa} = 0$ follows from combining E1^{t+1} and Lemma 2 (a). $\kappa_t^*(\widehat{c}_{I,t}, c_{E,t})$ will be continuous and differentiable if $\phi_{t+1}^E(c_{E,t+1}, c_{I,t+1})$ and $V_{t+1}^E(c_{E,t+1}, c_{I,t+1})$ are continuous and differentiable (E3^{t+1}) and ψ_I and ψ_E are continuous and differentiable (Assumption 1). $\kappa_t^*(\widehat{c}_{I,t}, c_{E,t})$ is strictly increasing in $\widehat{c}_{I,t}$ if $\frac{\partial \mathbb{E}_t[\phi_{t+1}^E|\widehat{c}_{I,t}, c_{E,t}]}{\partial \widehat{c}_{I,t}} - \frac{\partial \mathbb{E}_{t-1}[V_{t+1}^E|\widehat{c}_{I,t}, c_{E,t}]}{\partial \widehat{c}_{I,t}} > 0$, which follows from E4^{t+1} and Corollary 1. $\kappa_t^*(\widehat{c}_{I,t}, c_{E,t})$ will be strictly decreasing in $c_{E,t}$ if $\frac{\partial \mathbb{E}_t[\phi_{t+1}^E|\widehat{c_{I,t}}, c_{E,t}]}{\partial c_{E,t}} - \frac{\partial \mathbb{E}_{t-1}[V_{t+1}^E|\widehat{c}_{I,t}, c_{E,t}]}{\partial c_{E,t}} < 0$, which follows from E4^{t+1} and Corollary 2.

A.4.2 Incumbent Strategy in Period t

Existence of a Unique Separating Signaling Strategy To show the existence of a unique separating strategy for the incumbent we will rely on Theorem 1 of Mailath and von Thadden (2013), which is a useful generalization of the results in Mailath (1987). This theorem imposes conditions on the incumbent's 'signaling payoff function' $\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})$ where, in this application, the first argument is the incumbent's marginal cost, the second argument is E's (point) belief about the I's marginal cost, $p_{I,t}$ is the price that I sets and $c_{E,t}$ is E's marginal cost.

Theorem [Based on Mailath and von Thadden (2013)] *If (MT-i)* $\Pi^{I,t}(c_{I,t}, c_{I,t}, p_{I,t}, c_{E,t})$ *has a unique optimum in* $p_{I,t}$*, and for any* $p_{I,t} \in [\underline{p}, \overline{p}]$ *where* $\Pi_{33}^{I,t}(c_{I,t}, c_{I,t}, p_{I,t}, c_{E,t}) > 0$*, there* $\exists k > 0$ *such that* $\left|\Pi_3^{I,t}(c_{I,t}, c_{I,t}, p_{I,t}, c_{E,t})\right| > k$ *for all* $(c_{I,t}, c_{E,t})$*; (MT-ii)* $\Pi_{13}^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t}) \neq 0$ *for all* $(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})$*; (MT-iii)* $\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t}) \neq 0$ *for all* $(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})$*; (MT-iv)* $\frac{\Pi_3^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})}{\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})}$ *is a monotone function of* $c_{I,t}$ *for all* $(\widehat{c}_{I,t}, c_{E,t})$ *and all* $p_{I,t}$ *below the static monopoly price; (MT-v)* $\overline{p} \geq p^{\text{static monopoly}}(\overline{c_I})$ *and* $\Pi^{I,t}(\underline{c_{I,t}}, \underline{c_{I,t}}, \underline{p}, c_{E,t}) < \max_p \Pi^{I,t}(\underline{c_{I,t}}, \overline{c_{I,t}}, p, c_{E,t})$ *for all* $c_{E,t}$*, then, for given* $c_{E,t}$*,* I*'s period* t *unique separating pricing strategy is differentiable on the interior of* $[\underline{c_I}, \overline{c_I}]$ *and satisfies the differential equation*

$$\frac{\partial p_{I,t}^*}{\partial c_{I,t}} = -\frac{\Pi_2^{I,t}}{\Pi_3^{I,t}}$$

with boundary condition that $p_{I,t}^*(\overline{c_I}, c_{E,t}) = p^{\text{static monopoly}}(\overline{c_I})$.

We now show that the conditions (MT-i)-(MT-v) hold assuming that

I1^{t+1}. $V^I_{t+1}(c_{I,t+1}, c_{E,t+1}) > \phi^I_{t+1}(c_{I,t+1}, c_{E,t+1})$;

I2^{t+1}. $V^I_{t+1}(c_{I,t+1}, c_{E,t+1})$ and $\phi^I_{t+1}(c_{I,t+1}, c_{E,t+1})$ are continuous and differentiable; and,

I3^{t+1}. $\frac{\partial V^I_{t+1}(c_{I,t+1}, c_{E,t+1})}{\partial c_{I,t+1}} < \frac{\partial \phi^I_t(c_{I,t+1}, c_{E,t+1})}{\partial c_{I,t+1}}$,

as well as the conditions on E's period t entry threshold that were derived above.

Condition (MT-v) is simply a condition on the support of prices, with the second part requiring that $\underline{p}$ is so low that I would always prefer to set some higher price even if this resulted in E having the worst (i.e., highest) possible beliefs about I's marginal cost whereas setting price $\underline{p}$ would have resulted in E having the best (i.e., lowest) possible beliefs. This is implied by Assumption 3.

The signaling payoff function is defined as

$$\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t}) = q^M(p_{I,t})(p_{I,t} - c_{I,t}) + ... \tag{10}$$
$$\beta((1 - G(\kappa^*_t(\widehat{c}_{I,t}, c_{E,t})))\mathbb{E}_t[V^I_{t+1}|c_{I,t}, c_{E,t}] + G(\kappa^*_t(\widehat{c}_{I,t}, c_{E,t}))\mathbb{E}_t[\phi^I_{t+1}|c_{I,t}, c_{E,t}])$$

where $G(\kappa^*_t(\widehat{c}_{I,t}, c_{E,t}))$ is the probability that E enters given its entry strategy.

Condition (MT-i): $\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})$ only depends on $p_{I,t}$ through the static monopoly profit function $\pi^M_{I,t} = q^M(p_{I,t})(p_{I,t} - c_{I,t})$. The assumptions on the monopoly profit function in Assumption 3 therefore imply that (MT-i) is satisfied.

Condition (MT-ii): Differentiation of $\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})$ gives

$$\Pi^{I,t}_{13}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t}) = -\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}} \tag{11}$$

$\Pi^{I,t}_{13}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t}) \neq 0$ for all $(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})$ because monopoly demand is strictly downward sloping on $[\underline{p}, \overline{p}]$ (Assumption 3).

Condition (MT-iii): Differentiating $\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})$ gives

$$\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t}) = -\beta g(\kappa_t^*(\widehat{c}_{I,t}, c_{E,t}))\frac{\partial \kappa_t^*(\widehat{c_{I,t}}, c_{E,t})}{\partial \widehat{c}_{I,t}} \left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}, c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}, c_{E,t}]\right\} \tag{12}$$

$\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t}) \neq 0$ for all $(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})$ as $g(\kappa_t^*(\widehat{c}_{I,t}, c_{E,t})) > 0$ (which is true given Assumption 2 and the previous result that $\underline{\kappa} < \kappa_t^*(\widehat{c}_{I,t}, c_{E,t}) < \overline{\kappa}$), $\frac{\partial \kappa_t^*(\widehat{c}_{I,t}, c_{E,t})}{\partial \widehat{c}_{I,t}} > 0$ for all $(\widehat{c}_{I,t}, c_{E,t})$ (true given the previous result on the monotonicity of E's entry threshold rule in perceived incumbent marginal cost), and $\mathbb{E}_t[V_{t+1}^I|c_{I,t}, c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}, c_{E,t}] > 0$ (assumption I1^{t+1} and Lemma 2(b)).

Condition (MT-iv): Using equations (11) and (12) we have

$$\frac{\Pi_3^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})}{\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})} = \frac{\left[q^M(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})\right]}{\left(-\beta g(\kappa_t^*(\widehat{c}_{I,t}, c_{E,t}))\frac{\partial \kappa_t^*(\widehat{c}_{I,t}, c_{E,t})}{\partial \widehat{c}_{I,t}} \left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}, c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}, c_{E,t}]\right\}\right)}$$

Differentiation with respect to $c_{I,t}$ gives

$$\frac{\partial \frac{\Pi_3^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})}{\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})}}{\partial c_{I,t}} = \frac{\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}}{\left(\beta g(\kappa_t^*(\widehat{c}_{I,t}, c_{E,t}))\frac{\partial \kappa_t^*(\widehat{c}_{I,t}, c_{E,t})}{\partial \widehat{c}_{I,t}} \left\{\mathbb{E}_t[V_{t+1}^I] - \mathbb{E}_t[\phi_{t+1}^I]\right\}\right)} + \ldots \tag{13}$$

$$\frac{\left[q(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})\right] \frac{\partial \left\{\mathbb{E}_t[V_{t+1}] - \mathbb{E}_t[\phi_{t+1}^I]\right\}}{\partial c_{I,t}} \left(\beta g(\kappa_t^*(\widehat{c}_{I,t}, c_{E,t}))\frac{\partial \kappa_t^*(\widehat{c}_{I,t}, c_{E,t})}{\partial \widehat{c}_{I,t}}\right)}{\left(\beta g(\kappa_t^*(\widehat{c}_{I,t}, c_{E,t}))\frac{\partial \kappa_t^*(\widehat{c_{I,t}}, c_{E,t})}{\partial \widehat{c}_{I,t}} \left\{\mathbb{E}_t[V_{t+1}^I] - \mathbb{E}_t[\phi_{t+1}^I]\right\}\right)^2}$$

where $\mathbb{E}_t[V_{t+1}^I|c_{I,t}, c_{E,t}]$ and $\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}, c_{E,t}]$ have been written as $\mathbb{E}_t[V_{t+1}^I]$ and $\mathbb{E}_t[\phi_{t+1}^I]$ to save space.

Sufficient conditions for $\frac{\partial \frac{\Pi_3^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})}{\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})}}{\partial c_{I,t}}$ to be < 0 (implying $\frac{\Pi_3^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})}{\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}, c_{E,t})}$ is monotonic in $c_{I,t}$) are: $\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}, c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}, c_{E,t}]\right\} > 0$ (follows from assumption I1^{t+1} and Lemma 2(b));

$\frac{\partial \left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}, c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}, c_{E,t}]\right\}}{\partial c_{I,t}} < 0$ (assumption I3^{t+1} and Corollary 3);

$\left[q(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})\right] \geq 0$ for all prices below the monopoly price (implied by strict quasi-concavity of the profit function); $g(\kappa_t^*(\widehat{c}_{I,t}, c_{E,t})) > 0$ (Assumption 2 and the previous result

that $\underline{\kappa} < \kappa_t^*(\widehat{c}_{I,t}, c_{E,t}) < \overline{\kappa}$); $\frac{\partial \kappa_t^*(\widehat{c}_{I,t}, c_{E,t})}{\partial \widehat{c}_{I,t}} > 0$ (proved above); and, $\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}} < 0$ (Assumption 3).

Uniqueness of the Separating Strategy under the D1 Refinement The Mailath and von Thadden theorem allows us to show that there is only one fully separating strategy, but it does not show that there can be no pooling equilibria. To show this, we use the D1 Refinement and Theorem 3 of Ramey (1996).

Theorem [Based on Ramey (1996)] *Take I's signaling payoff $\Pi^{I,t}(c_{I,t}, \kappa_t', p_{I,t}, c_{E,t})$ where κ_t' is E's entry threshold. If Conditions (R-i) $\Pi_2^{I,t}(c_{I,t}, \kappa_t', p_{I,t}, c_{E,t}) \neq 0$ for all $(c_{I,t}, \kappa_t', p_{I,t}, c_{E,t})$; (R-ii) $\frac{\Pi_3^{I,t}(c_{I,t}, \kappa_t', p_{I,t}, c_{E,t})}{\Pi_2^{I,t}(c_{I,t}, \kappa_t', p_{I,t}, c_{E,t})}$ is a monotone function of $c_{I,t}$ for all $(\kappa_t', c_{E,t})$; and (R-iii) $\overline{p} \geq p^{static\ monopoly}(\overline{c_I})$ and $\Pi^{I,t}(\underline{c_{I,t}}, \overline{\kappa}, \underline{p}, c_{E,t}) < \max_p \Pi^{I,t}(\underline{c_{I,t}}, \underline{\kappa}, p, c_{E,t})$ for all $(t, c_{E,t})$, then an equilibrium satisfying the D1 refinement will be fully separating.*

The signaling payoff function in this theorem is defined based on E's threshold, not its point belief, to allow for the fact that, with pooling, E's beliefs may not be a point. (R-iii) is a condition on the support of prices, as it says that I would always prefer to use some price above $\underline{p}$ even if doing this led to certain entry when setting $\underline{p}$ would prevent entry from happening. Once again, it is implied by Assumption 3. Essentially replicating the proofs of (MT-iii) and (MT-iv) above, we now show that conditions (R-i) and (R-ii) hold.

Condition (R-i): $\Pi_2^{I,t}(c_{I,t}, \kappa_t, p_{I,t}, c_{E,t}) = -\beta g(\kappa_t) \left\{ \mathbb{E}_t[V_{t+1}^I | c_{I,t}, c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}, c_{E,t}] \right\}$. This will not be equal to zero if $g(\cdot) > 0$ (true given Assumption 2 and the condition that an equilibrium level of κ_t' will satisfy $\underline{\kappa} < \kappa_t' < \overline{\kappa}$), and $\left\{ \mathbb{E}_t[V_{t+1}^I | c_{I,t}, c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}, c_{E,t}] \right\} > 0$ (follows from assumption I1^{t+1} and Lemma 2(b)).

Condition (R-ii): as before, we have

$$\frac{\Pi_3^{I,t}(c_{I,t}, \kappa_t, p_{I,t}, c_{E,t})}{\Pi_2^{I,t}(c_{I,t}, \kappa_t, p_{I,t}, c_{E,t})} = \frac{\left[q^M(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t}) \right]}{\left(-\beta g(\kappa_t) \left\{ \mathbb{E}_t[V_{t+1}^I | c_{I,t}, c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}, c_{E,t}] \right\} \right)}$$

Differentiation with respect to $c_{I,t}$ yields

$$\frac{\partial \frac{\Pi_3^{I,t}(c_{I,t},\kappa_t,p_{I,t},c_{E,t})}{\Pi_2^{I,t}(c_{I,t},\kappa_t,p_{I,t},c_{E,t})}}{\partial c_{I,t}} = \frac{\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}}{\beta g(\kappa_t)\mathbb{E}_t[V_{t+1}^I|c_{I,t},c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}]} + \ldots$$
$$\frac{\left[q(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})\right] \frac{\partial\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t},c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}]\right\}}{\partial c_{I,t}} (\beta g(\kappa_t))}{\left(\beta g(\kappa_t)\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t},c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}]\right\}\right)^2}$$

Sufficient conditions for $\frac{\partial \frac{\Pi_3^{I,t}(c_{I,t},\kappa_t,p_{I,t},c_{E,t})}{\Pi_2^{I,t}(c_{I,t},\kappa_t,p_{I,t},c_{E,t})}}{\partial c_{I,t}}$ to be < 0 (implying $\frac{\Pi_3^{I,t}(c_{I,t},\kappa_t,p_{I,t},c_{E,t})}{\Pi_2^{I,t}(c_{I,t},\kappa_t,p_{I,t},c_{E,t})}$ monotonic in $c_{I,t}$) are: $\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t},c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}]\right\} > 0$ (follows from assumption I1^{t+1} and Lemma 2(b));

$\frac{\partial\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t},c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}]\right\}}{\partial c_{I,t}} < 0$ (assumption I3^{t+1} and Corollary 3);

$\left[q(p_{I,t}) + \frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t} - c_{I,t})\right] \geq 0$ for all prices below the monopoly price (implied by quasi-concavity of the profit function); $g(\kappa_t^*(\widehat{c}_{I,t}, c_{E,t})) > 0$ (Assumption 2 and the previous result that $\underline{\kappa} < \kappa_t^*(\widehat{c}_{I,t}, c_{E,t}) < \overline{\kappa}$); and, $\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}} < 0$ (Assumption 3).

A.4.3 Properties of the Potential Entrant's Value Functions for Period t

We now show that, given these strategies (in particular the fact that I's pricing strategy is fully revealing), which depend on the assumed properties of value functions in period $t+1$, that the value functions at the start of period t will have these same properties. For the potential entrant we have to prove:

E1^t. $\phi_t^E(c_{E,t}, c_{I,t}) > V_t^E(c_{E,t}, c_{I,t})$; and

E2^t. $\phi_t^E(c_{E,t}, c_{I,t})$ and $V_t^E(c_{E,t}, c_{I,t})$ are uniquely defined functions of c_{It} and $c_{E,t}$, and do not depend on κ_{t-1} or any earlier values of κ;

E3^t. $\phi_t^E(c_{E,t}, c_{I,t})$ and $V_t^E(c_{E,t}, c_{I,t})$ are continuous and differentiable in both arguments; and

E4^t. $\frac{\partial[\phi_t^E(c_{E,t},c_{I,t})]}{\partial c_{I,t}} > \frac{\partial[V_t^E(c_{E,t},c_{I,t})]}{\partial c_{I,t}}$ and $\frac{\partial[\phi_t^E(c_{E,t},c_{I,t})]}{\partial c_{E,t}} < \frac{\partial[V_t^E(c_{E,t},c_{I,t})]}{\partial c_{E,t}}$

From the above, we have that

$$\phi_t^E(c_{I,t}, c_{E,t}) = \pi_E^D(c_{E,t}, c_{I,t}) + \beta \int_{\underline{c_I}}^{\overline{c_I}} \int_{\underline{c_E}}^{\overline{c_E}} \phi_{t+1}^E(c_{E,t+1}, c_{I,t+1}) \psi_I(c_{I,t+1}|c_{I,t}) \psi_E(c_{E,t+1}|c_{E,t}) dc_{E,t} dc_{I,t} \tag{14}$$

$$V_t^E(c_{I,t}, c_{E,t}) = \int_0^{\kappa^*} \int_{\underline{c_I}}^{\overline{c_I}} \int_{\underline{c_E}}^{\overline{c_E}} \left\{ \beta \phi_{t+1}^E(c_{E,t+1}, c_{I,t+1}) \psi_I(c_{I,t+1}|c_{I,t}) \psi_E(c_{E,t+1}|c_{E,t}) - \kappa \right\} g(\kappa) dc_{E,t} dc_{I,t} d\kappa + ... \tag{15}$$

$$\int_{\kappa^*}^{\overline{\kappa}} \int_{\underline{c_I}}^{\overline{c_I}} \int_{\underline{c_E}}^{\overline{c_E}} \beta V_{t+1}^E(c_{E,t+1}, c_{I,t+1}) \psi_I(c_{I,t+1}|c_{I,t}) \psi_E(c_{E,t+1}|c_{E,t}) g(\kappa) dc_{E,t} dc_{I,t} d\kappa$$

where $\kappa^*(c_{E,t}, c_{I,t})$ has been written as simply κ^* to save space and we are exploiting the fact that the unique equilibrium involves the entrant believing the true value of I's marginal cost when it takes its entry decision.

Continuity and differentiability of (14) and (15) follows from ϕ_{t+1}^E and V_{t+1}^E being continuous and differentiable (E3^{t+1}), and $\psi_I(c_{I,t+1}|c_{I,t})$ and $\psi_E(c_{E,t+1}|c_{E,t})$ being continuous and differentiable (Assumption 1) and $\kappa^*(c_{E,t}, c_{I,t})$ being continuous and differentiable as shown above. The fact that both (14) and (15) are uniquely defined and do not depend on κ_{t-1} or any earlier values of κ follows from inspection of these equations and, in particular, the fact that I's signaling strategy perfectly reveals its current cost so that E's entry threshold in period t does not depend on earlier information. As $\phi_{t+1}^E(c_{E,t+1}, c_{I,t+1}) > V_{t+1}^E(c_{E,t+1}, c_{I,t+1})$, (15) implies

$$V_t^E(c_{I,t}, c_{E,t}) < \beta \int_{\underline{c_I}}^{\overline{c_I}} \int_{\underline{c_E}}^{\overline{c_E}} \phi_{t+1}^E(c_{E,t+1}, c_{I,t+1}) \psi_I(c_{I,t+1}|c_{I,t}) \psi_E(c_{E,t+1}|c_{E,t}) dc_{E,t} dc_{I,t},$$

and therefore,

$$\phi_t^E(c_{I,t}, c_{E,t}) - V_t^E(c_{I,t}, c_{E,t}) > \pi_E^D(c_{E,t}, c_{I,t}) > 0$$

by our assumption on duopoly profits, so that $\phi_t^E(c_{E,t}, c_{I,t}) > V_t^E(c_{E,t}, c_{I,t})$.

To show that $\frac{\partial[\phi_t^E(c_{E,t},c_{I,t})]}{\partial c_{I,t}} > \frac{\partial[V_t^E(c_{E,t},c_{I,t})]}{\partial c_{I,t}}$, it is convenient to write

$$\phi_t^E(c_{I,t},c_{E,t}) - V_t^E(c_{I,t},c_{E,t}) = \pi_E^D(c_{E,t},c_{I,t}) + \beta \int_0^{\overline{\kappa}} \min\{\kappa, \mathbb{E}_t[\phi_{t+1}^E|c_{I,t},c_{E,t}] - \mathbb{E}_t[V_{t+1}^E|c_{I,t},c_{E,t}]\} g(\kappa) d\kappa$$

so that

$$\frac{\partial[\phi_t^E(c_{E,t},c_{I,t})]}{\partial c_{I,t}} - \frac{\partial[V_t^E(c_{E,t},c_{I,t})]}{\partial c_{I,t}} = \frac{\partial \pi_E^D(c_{E,t},c_{I,t})}{\partial c_{I,t}} + ...$$
$$\beta \frac{\partial \int_0^{\overline{\kappa}} \min\{\kappa, \mathbb{E}_t[\phi_{t+1}^E|c_{I,t},c_{E,t}] - \mathbb{E}_t[V_{t+1}^E|c_{I,t},c_{E,t}]\} g(\kappa) d\kappa}{\partial c_{I,t}} > 0$$

where the inequality follows from $\frac{\partial \pi_E^D(c_{E,t},c_{I,t})}{\partial c_{I,t}} > 0$ (Assumption 4), $0 < \kappa^* < \overline{\kappa}$ and $\frac{\partial \mathbb{E}_t[\phi_{t+1}^E|c_{I,t},c_{E,t}]}{\partial c_{I,t}} - \frac{\partial \mathbb{E}_t[V_{t+1}^E|c_{I,t},c_{E,t}]}{\partial c_{I,t}} > 0$ (E4^{t+1} and Corollary 1). $\frac{\partial[\phi_t^E(c_{E,t},c_{I,t})]}{\partial c_{E,t}} < \frac{\partial[V_t^E(c_{E,t},c_{I,t})]}{\partial c_{E,t}} < 0$ follows form the same logic, using $\frac{\partial \pi_E^D(c_{E,t},c_{I,t})}{\partial c_{E,t}} < 0$ (Assumption 4) and Corollary 2.

A.4.4 Properties of the Incumbent's Value Functions for Period t

For the incumbent we have to prove:

I1^t. $V_t^I(c_{I,t},c_{E,t}) > \phi_t^I(c_{I,t},c_{E,t})$;

I2^t. $V_t^I(c_{I,t},c_{E,t})$ and $\phi_t^I(c_{I,t},c_{E,t})$ are continuous and differentiable; and,

I3^t. $\frac{\partial V_t^I(c_{I,t},c_{E,t})}{\partial c_{I,t}} < \frac{\partial \phi_t^I(c_{I,t},c_{E,t})}{\partial c_{I,t}}$.

Condition I1^t:

$$V_t^I(c_{I,t},c_{E,t}) = \max_{p_{I,t}} q^M(p_{I,t})(p_{I,t} - c_{I,t}) + ... \tag{16}$$
$$\beta \begin{bmatrix} (1 - G(\kappa_t^*(\varsigma_{I,t}^{-1}(p_{I,t},c_{E,t}),c_{E,t})))\mathbb{E}_t[V_{t+1}^I|c_{I,t},c_{E,t}] \\ +G(\kappa_t^*(\varsigma_{I,t}^{-1}(p_{I,t},c_{E,t}),c_{E,t}))\mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}] \end{bmatrix}$$

$$\phi_t^I(c_{I,t},c_{E,t}) = \pi_I^D(c_{I,t},c_{E,t}) + \beta \mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}] \tag{17}$$

Now, given I1^{t+1} and Lemma 2(b),

$$\beta \left[\begin{array}{c} (1-G(\kappa_t^*(\varsigma_{I,t}^{-1}(p_{I,t},c_{E,t}),c_{E,t})))\mathbb{E}_t[V_{t+1}^I|c_{I,t},c_{E,t}]+ \\ G(\kappa_t^*(\varsigma_{I,t}^{-1}(p_{I,t},c_{E,t}),c_{E,t}))\mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}] \end{array} \right] > \beta\mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}]$$

for any $p_{I,t}$ (including the static monopoly price). But, as $q^M(p_{I,t})(p_{I,t}-c_{I,t}) > \pi_I^D(c_{I,t},c_{E,t})$ (Assumption 4) when the static monopoly price is chosen, it follows that $V_t^I(c_{I,t},c_{E,t}) > \phi_t^I(c_{I,t},c_{E,t})$ when a possibly different price is chosen by the incumbent.

Condition I2^t: continuity and differentiability of $V_t^I(c_{I,t},c_{E,t})$ and $\phi_t^I(c_{I,t},c_{E,t})$ follows from expressions (16) and (17), and the continuity and differentiability of the static and duopoly profit functions, the incumbent's equilibrium pricing function, the entry threshold function, $\kappa_t^*(c_{I,t},c_{E,t})$, the cdf of entry costs G, the cost transition conditional probability functions ψ_I and ψ_E, and the following period value functions $V_{t+1}^I(c_{I,t+1},c_{E,t+1})$ and $\phi_{t+1}^I(c_{I,t+1},c_{E,t+1})$ (I2^{t+1}).

Condition I3^t: $\frac{\partial V_t^I(c_{I,t},c_{E,t})}{\partial c_{I,t}} < \frac{\partial \phi_t^I(c_{I,t},c_{E,t})}{\partial c_{I,t}}$

$$\begin{aligned} \frac{\partial V_t^I(c_{I,t},c_{E,t})}{\partial c_{I,t}} = \frac{\partial \pi^M(p^*,c_{I,t},c_{E,t})}{\partial c_{I,t}} + \beta\frac{\partial \mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}]}{\partial c_{I,t}} - ... \\ \beta\frac{\partial \kappa^*(c_{I,t},c_{E,t})}{\partial c_{I,t}} g(\kappa_t^*(c_{I,t},c_{E,t}))\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t},c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}]\right\} + ... \\ \beta(1-G(\kappa^*(c_{It},c_{E,t})))\left[\frac{\partial \mathbb{E}_t[V_{t+1}^I|c_{I,t},c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t},c_{E,t}]}{\partial c_{I,t}}\right] \end{aligned}$$

$\frac{\partial \pi^M(p^*,c_{I,t},c_{E,t})}{\partial c_{I,t}} = -q^M(p^*) + \frac{\partial p^*(c_{I,t},c_{E,t})}{\partial c_{I,t}}\left\{q^M(p^*) + \frac{\partial q^M(p^*)}{\partial p}(p^*-c_{I,t})\right\}$. But from the unique equilibrium strategy of the incumbent (recall that $V_t^I(c_{I,t},c_{E,t})$ is the value to being an incumbent at the beginning of period t allowing for equilibrium play in that period),

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

so

$$\frac{\partial V_t^I(c_{I,t}, c_{E,t})}{\partial c_{I,t}} = -q^M(p^*) + \beta \frac{\partial \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}, c_{E,t}]}{\partial c_{I,t}} + ...$$
$$\beta(1 - G(\kappa^*(c_{It,} c_{E,t}))) \left[\frac{\partial \mathbb{E}_t[V_{t+1}^I | c_{I,t}, c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}, c_{E,t}]}{\partial c_{I,t}} \right]$$

and

$$\frac{\partial \phi_t^I(c_{I,t}, c_{E,t})}{\partial c_{I,t}} = \frac{\partial \pi^D(c_{I,t}, c_{E,t})}{\partial c_{I,t}} + \beta \frac{\partial \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}, c_{E,t}]}{\partial c_{I,t}}$$
$$= -q_I^D(c_{I,t}, c_{E,t}) + \frac{\partial \pi_I^D}{\partial a_E^D} \frac{\partial a_E^D}{\partial c_{I,t}} + \beta \frac{\partial \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}, c_{E,t}]}{\partial c_{I,t}} < 0$$

where the inequality follows from the assumption that $\frac{\partial \pi^D(c_{I,t}, c_{E,t})}{\partial c_{I,t}} < 0$ (Assumption 4). Therefore,

$$\frac{\partial V_t^I(c_{I,t}, c_{E,t})}{\partial c_{I,t}} - \frac{\partial \phi_t^I(c_{I,t}, c_{E,t})}{\partial c_{I,t}} = q_I^D(c_{I,t}, c_{E,t}) - q^M(p^*(c_{It,} c_{E,t})) - \frac{\partial \pi_I^D}{\partial a_E^D} \frac{\partial a_E^D}{\partial c_{I,t}} + ...$$
$$\beta(1 - G(\kappa^*(c_{I,t}, c_{E,t}))) \left[\frac{\partial \{\mathbb{E}_t[V_{t+1}^I | c_{I,t}, c_{E,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}, c_{E,t}]\}}{\partial c_{I,t}} \right] < 0$$

where the inequality follows from Assumption 4, as $q^M(p^*(c_{I,t}, c_{E,t})) > q^M(p^{\text{static monopoly}})$ because the limit price will be below the static monopoly price and demand slopes downwards (Assumption 3), and I3^{t+1} and Corollary 3.

A.5 Proof for Period T

We now turn to showing that the value functions defined at the start of period T have the required properties. Of course, this is trivial because the game ends after period T so that if I is a monopolist in period T it should just set the static monopoly price, and E should not enter for any positive entry cost. Therefore, $\phi_T^E(c_{E,T}, c_{I,T}) = \pi_E^D(c_{E,T}, c_{I,T})$, $V_T^E(c_{E,T}, c_{I,T}) = 0$, $\phi_T^I(c_{I,T}, c_{E,T}) = \pi_I^D(c_{I,T}, c_{E,T})$ and $V_T^I(c_{I,T}, c_{E,T}) = q(p^{\text{static monopoly}}(c_{I,T}))(p^{\text{static monopoly}}(c_{I,t}) - c_{I,t})$. Under our assumptions $\phi_T^E(c_{E,T}, c_{I,T}) > V_T^E(c_{E,T}, c_{I,T}), V_T^I(c_{I,T}, c_{E,T}) > \phi_T^I(c_{I,T}, c_{E,T})$ (Assumption 4) and $\frac{\partial \phi_T^E}{\partial c_{E,T}} < \frac{\partial V_T^E}{\partial c_{E,T}} = 0$, $\frac{\partial \phi_T^E}{\partial c_{I,T}} > \frac{\partial V_T^E}{\partial c_{I,T}} = 0$, $\frac{\partial V_T^I(c_{I,T}, c_{E,T})}{\partial c_{I,T}} < \frac{\partial \phi_T^I(c_{I,T}, c_{E,T})}{\partial c_{I,T}} < 0$.[60]

[60] $\frac{\partial V_T^I(c_{I,T}, c_{E,T})}{\partial c_{I,T}} - \frac{\partial \phi_T^I(c_{I,T}, c_{E,T})}{\partial c_{I,T}} = q_I^D(c_{I,T}, c_{E,T}) - q^M(p^{\text{static monopoly}}(c_{I,T}, c_{E,T})) - \frac{\partial \pi_I^D}{\partial a_E^D} \frac{\partial a_E^D}{\partial c_{I,T}} < 0$ by Assumption 4.

B List of Dominant Incumbent Markets By Carrier

In the following list (*) identifies markets in the subset of 65 markets where Southwest is observed for at least some periods as a potential, but not an actual, entrant. Carrier names reflect those at the end of the sample (so, for example, Northwest routes are listed under Delta).

American (AA): Nashville-Raleigh, Burbank-San Jose, Colorado Springs-St Louis(*), Las Vegas-San Jose, Los Angeles-San Jose(*), Reno-San Jose(*), Louisville-St Louis, San Jose-Orange County(*), St. Louis-Tampa

Alaska (AS): Boise-Portland, Boise-Seattle, Eugene-Seattle(*), Spokane-Portland(*), Spokane-Seattle, Oakland-Portland, Oakland-Seattle, Oakland-Orange Country(*), Palm Springs-Seattle(*), Palm Springs-San Francisco(*)

Continental (CO): Baltimore-Houston(Bush)(*), Cleveland-Palm Beach(*), Houston- Jackson, MS(*), Houston-Jacksonville(*), Houston-Orlando(*), Houston-Omaha(*), Houston-Palm-Beach(*), Houston-Raleigh(*), Houston-Seattle(*), Houston-Orange County(*), Houston-Tampa(*), Houston-Tulsa(*), Orlando-Omaha(*)

Delta (DL): Albany-Detroit(*), Albany-Minneapolis(*), Hartford-Minneapolis(*), Boise- Minneapolis(*), Boise-Salt Lake City, Buffalo-Detroit(*), Colorado Springs-Salt Lake City, Detroit-Milwaukee(*), Detroit-Norfolk, VA(*), Fresno-Reno(*), Fort Lauderdale-Minneapolis(*), Spokane-Minneapolis(*), Spokane-Salt Lake City, Jacksonville-LaGuardia(*), Los Angeles-Salt Lake City, LaGuardia-New Orleans(*), LaGuardia-Southwest Florida(*), Kansas City-Salt Lake City(*), Minneapolis-New Orleans(*), Minneapolis-Oklahoma City(*), Minneapolis-Omaha(*), Minneapolis-Providence(*), Minneapolis-Orange County(*), Minneapolis-Tulsa(*), Oakland-Salt Lake City, Portland-Salt Lake City, Reno-Salt Lake City(*), San Diego-Salt Lake City, Seattle-Salt Lake City(*), San Jose-Salt Lake City, Salt Lake City-Sacramento, Salt Lake City-Orange County(*)

United (UA): Hartford-Washington Dulles(*), Nashville-Washington Dulles(*),Boise-San Francisco(*), Eugene-San Francisco(*), Washington Dulles-Indianapolis(*), Washington Dulles- Jacksonville(*), Washington Dulles-LaGuardia(*), Washington Dulles-Raleigh(*), Washington Dulles-Tampa

US Airways (US): Albany-Baltimore, Hartford-Baltimore, Hartford-Philadelphia(*), Buffalo-Baltimore, Buffalo-LaGuardia(*), Buffalo-Philadelphia(*), Baltimore-Jacksonville, Baltimore-Orlando, Baltimore-Norfolk, Baltimore-Palm Beach, Baltimore-Providence, Baltimore-Tampa, Columbus-Philadelphia(*), Colorado Springs-Phoenix(*), Las Vegas-Omaha, Las Vegas-Pittsburgh, Las Vegas-Tulsa, LaGuardia-Pittsburgh(*), Manchester-Philadelphia(*), New Orleans- Philadelphia(*), Norfolk-Philadelphia(*), Omaha-Phoenix, Philadelphia-Pittsburgh, Philadelphia-Providence, Phoenix-Orange County(*), Sacramento-Orange County(*)

Other Carriers: Midwest Airlines (YX): Columbus-Milwaukee(*), Orlando-Milwaukee; Airtran (FL): Baltimore-Milwaukee; Midway Airlines (JI): Jacksonville-Raleigh(*); ATA (TZ): Chicago Midway-Philadelphia, Chicago Midway-Southwest Florida.

C Construction of Market Size

A simple approach to defining the size of an airline market is to assume that it is proportional to the arithmetic or geometric average population of the endpoint cities (e.g., Berry and Jia (2010)). However, the number of passengers traveling on a route also varies systematically with distance, time and the number of people who use the particular airports concerned.[61] Recognizing this fact, like Benkard, Bodoh-Creed, and Lazarev (2010) amongst others, we try to create a better measure of market size, that we use when estimating demand in Section 5 and also as one of the variables, in addition to average endpoint population, that can predict the probability of entry by Southwest in Section 4.

We estimate a generalized gravity equation using our full sample, where the expected number of passengers traveling on a route is a function of time, distance and the number of originating and final destination passengers at both of the endpoint airports as well as interactions between these variables and distance. The originating and destination variables are measured in the first quarter of our data (Q1 1993) in order to avoid potential problems arising from the fact that they will be affected by the airport entry of Southwest, and incumbents' responses to Southwest entry. We specify

$$\mathbb{E}\left[\text{Passengers}_{o,d,t}\right] = \exp\left\{\begin{array}{c} \beta_0 + \beta_1 Q_t + \beta_2 \log(\text{distance}_{o,d}) + \beta_2 \log(\text{distance}^2_{o,d}) + ... \\ \sum_{j=\{o,d\}} \beta_{3,j} \log(\text{originating}_{j,1993}) + \beta_{4,j} \log(\text{originating}^2_{j,1993}) + ... \\ \sum_{j=\{o,d\}} \beta_{5,j} \log(\text{destination}_{j,1993}) + \beta_{6,j} \log(\text{destination}^2_{j,1993}) + ... \\ \text{interactions between } \log(\text{distance}) \\ \text{and originating and destination variables} \end{array}\right\} \tag{18}$$

where o is the origin airport, d is the destination airport and Q_t are quarter dummies. $\text{Passengers}_{o,d,t}$ is the number of DB1 passengers with itineraries in either direction on the route, independent of whether they use direct or connecting service.[62] The specification is estimated using the Poisson Pseudo-Maximum Likelihood estimator, as suggested by Silva and Tenreyro (2006), because estimates from a log-linearized regression will be inconsistent when the residuals are heteroskedastic.

[61] This can reflect either the fact that customers in some cities may be able to choose between multiple airports, which may be more or less convenient, but also that some destinations, such as vacation destinations, receive more visitors than would be expected based on their populations.

[62] A return passenger counts as 1, and a one-way only passenger counts as 0.5.

The estimates on several coefficients are shown in Table C.1.

Table C.1: Selected Coefficients from the Gravity Equation Used to Estimate Market Size

	DB1 Passengers
log(Distance)	19.07***
	(0.313)
log(Distance)^2	-1.102***
	(0.0218)
log(Final Destination$_{o,1993}$)	0.028***
	(0.003)
log(Final Destination$^2_{o,1993}$)	-0.0017***
	(0.00017)
log(Final Destination$_{d,1993}$)	30.92***
	(0.148)
log(Final Destination$^2_{d,1993}$)	-1.655***
	(0.0076)
log(Originating$_{o,1993}$)	-21.21***
	(0.176)
log(Originating$^2_{o,1993}$)	1.274***
	(0.0091)
log(Originating$_{d,1993}$)	0.422***
	(0.0042)
log(Originating$^2_{d,1993}$)	-0.0221***
	(0.0002)
Observations	166,072
Pseudo-R^2	0.818

*** denotes significance at the 1% level.

With the estimates in hand, we calculate the predicted value of the number of passengers for each market-quarter and then form our estimate of market size by multiplying this estimate by 3.5, so that, on average, the market share of all carriers combined (as a share of the potential market) is between 25% and 40%. Based on this measure, the median-sized route in our 106 dominant incumbent sample is Salt Lake City-Orange County where Delta is the dominant incumbent (6,806 DB1 people, or 68,060 people accounting for the fact DB1 is a 10% sample).

D Effect of Southwest's Potential and Actual Entry on the Distribution of Prices

The following tables present the results of the GS regressions using the 25th, 50th or 75th percentiles of the price distribution on the incumbent to form the dependent variable, rather than the average fare.

Table D.1: Incumbent Pricing In Response to Southwest's Actual and Potential Entry: 25th Percentile of Prices

	Phase 1		*Phase 2*		*Phase 3*	
Fare						
	$t_0 - 8$	-0.039	t_0	-0.091^{**}	t_e	-0.424^{***}
		(0.031)		(0.037)		(0.074)
	$t_0 - 7$	0.002	$t_0 + 1$	-0.105^{**}	$t_e + 1$	-0.455^{***}
		(0.033)		(0.039)		(0.073)
	$t_0 - 6$	-0.019	$t_0 + 2$	-0.117^{**}	$t_e + 2$	-0.497^{***}
		(0.037)		(0.041)		(0.076)
	$t_0 - 5$	-0.029	$t_0 + 3$	-0.134^{***}	$t_e + 3$	-0.534^{***}
		(0.036)		(0.036)		(0.079)
	$t_0 - 4$	0.027	$t_0 + 4$	-0.085	$t_e + 4$	-0.547^{***}
		(0.038)		(0.0404)		(0.081)
	$t_0 - 3$	0.005	$t_0 + 5$	-0.099^{*}	$t_e + 5$	-0.523^{***}
		(0.036)		(0.042)		(0.083)
	$t_0 - 2$	-0.062^{*}	$t_0 + 6\text{-}12$	-0.170^{***}	$t_e + 6\text{-}12$	-0.502^{***}
		(0.034)		(0.049)		(0.082)
	$t_0 - 1$	-0.055^{*}	$t_0 + 13+$	-0.286^{***}	$t_e + 13+$	-0.494^{***}
		(0.031)		(0.056)		(0.089)
Yield						
	$t_0 - 8$	-0.014	t_0	-0.040^{**}	t_e	-0.169^{***}
		(0.012)		(0.016)		(0.04)
	$t_0 - 7$	0.016	$t_0 + 1$	-0.029^{*}	$t_e + 1$	-0.174^{***}
		(0.016)		(0.015)		(0.040)
	$t_0 - 6$	-0.001	$t_0 + 2$	-0.036^{**}	$t_e + 2$	-0.187^{***}
		(0.017)		(0.017)		(0.043)
	$t_0 - 5$	-0.005	$t_0 + 3$	-0.048^{***}	$t_e + 3$	-0.191^{***}
		(0.013)		(0.015)		(0.042)
	$t_0 - 4$	0.02	$t_0 + 4$	-0.030	$t_e + 4$	-0.195^{***}
		(0.016)		(0.020)		(0.043)
	$t_0 - 3$	0.01	$t_0 + 5$	-0.035^{*}	$t_e + 5$	-0.195^{***}
		(0.016)		(0.018)		(0.045)
	$t_0 - 2$	-0.019	$t_0 + 6\text{-}12$	-0.068^{***}	$t_e + 6\text{-}12$	-0.213^{***}
		(0.017)		(0.022)		(0.048)
	$t_0 - 1$	-0.018	$t_0 + 13+$	-0.115^{***}	$t_e + 13+$	-0.234^{***}
		(0.017)		(0.033)		(0.053)

Notes: Estimates of specification (6) when dependent variable is log of the 25th percentile passenger-weighted fare ("Fare") or this fare divided by the non-stop route distance ("Yield"). The adjusted R^2s are 0.75 ("Fare") and 0.78 ("Yield"). Other notes from Table 3 apply here.

Table D.2: Incumbent Pricing In Response to Southwest's Actual and Potential Entry: 50th Percentile of Prices

	Phase 1		*Phase 2*		*Phase 3*	
Fare						
	$t_0 - 8$	-0.029	t_0	-0.121^{***}	t_e	-0.524^{***}
		(0.034)		(0.039)		(0.090)
	$t_0 - 7$	-0.020	$t_0 + 1$	-0.131^{***}	$t_e + 1$	-0.615^{***}
		(0.042)		(0.047)		(0.090)
	$t_0 - 6$	-0.023	$t_0 + 2$	-0.129^{***}	$t_e + 2$	-0.650^{***}
		(0.04)		(0.042)		(0.097)
	$t_0 - 5$	-0.016	$t_0 + 3$	-0.144^{***}	$t_e + 3$	-0.722^{***}
		(0.039)		(0.042)		(0.104)
	$t_0 - 4$	-0.034	$t_0 + 4$	-0.163^{***}	$t_e + 4$	-0.685^{***}
		(0.041)		(0.042)		(0.104)
	$t_0 - 3$	-0.024	$t_0 + 5$	-0.175^{***}	$t_e + 5$	-0.628^{***}
		(0.0385)		(0.050)		(0.107)
	$t_0 - 2$	-0.107^{***}	$t_0 + 6$-12	-0.249^{***}	$t_e + 6$-12	-0.615^{***}
		(0.037)		(0.051)		(0.102)
	$t_0 - 1$	-0.097^{**}	$t_0 + 13+$	-0.364^{***}	$t_e + 13+$	-0.612^{***}
		(0.0386)		(0.061)		(0.109)
Yield						
	$t_0 - 8$	-0.018	t_0	-0.066^{***}	t_e	-0.281^{***}
		(0.017)		(0.024)		(0.065)
	$t_0 - 7$	0.007	$t_0 + 1$	-0.0491^{**}	$t_e + 1$	-0.314^{***}
		(0.022)		(0.028)		(0.064)
	$t_0 - 6$	0.004	$t_0 + 2$	-0.060^{***}	$t_e + 2$	-0.330^{***}
		(0.023)		(0.025)		(0.068)
	$t_0 - 5$	0.011	$t_0 + 3$	-0.070^{***}	$t_e + 3$	-0.352^{***}
		(0.023)		(0.024)		(0.070)
	$t_0 - 4$	-0.017	$t_0 + 4$	-0.074^{***}	$t_e + 4$	-0.352^{***}
		(0.024)		(0.024)		(0.072)
	$t_0 - 3$	-0.007	$t_0 + 5$	-0.074^{***}	$t_e + 5$	-0.347^{***}
		(0.025)		(0.024)		(0.075)
	$t_0 - 2$	-0.057^{**}	$t_0 + 6$-12	-0.143^{***}	$t_e + 6$-12	-0.367^{***}
		(0.025)		(0.033)		(0.075)
	$t_0 - 1$	-0.053^{**}	$t_0 + 13+$	-0.220^{***}	$t_e + 13+$	-0.400^{***}
		(0.026)		(0.050)		(0.086)

Notes: Estimates of specification (6) when dependent variable is log of the median passenger-weighted fare ("Fare") or this fare divided by the non-stop route distance ("Yield"). The adjusted R^2s are 0.73 ("Fare) and 0.82 ("Yield"). Other notes from Table 3 apply here.

Table D.3: Incumbent Pricing In Response to Southwest's Actual and Potential Entry: 75th Percentile of Prices

	Phase 1		*Phase 2*		*Phase 3*	
Fare						
	$t_0 - 8$	-0.053	t_0	-0.135^{***}	t_e	-0.476^{***}
		(0.034)		(0.046)		(0.091)
	$t_0 - 7$	-0.063	$t_0 + 1$	-0.170^{***}	$t_e + 1$	-0.597^{***}
		(0.039)		(0.045)		(0.092)
	$t_0 - 6$	-0.064	$t_0 + 2$	-0.193^{***}	$t_e + 2$	-0.615^{***}
		(0.041)		(0.046)		(0.098)
	$t_0 - 5$	-0.055	$t_0 + 3$	-0.176^{***}	$t_e + 3$	-0.697^{***}
		(0.042)		(0.046)		(0.106)
	$t_0 - 4$	-0.042	$t_0 + 4$	-0.194^{***}	$t_e + 4$	-0.707^{***}
		(0.042)		(0.047)		(0.102)
	$t_0 - 3$	-0.0333	$t_0 + 5$	-0.190^{***}	$t_e + 5$	-0.655^{***}
		(0.0377)		(0.052)		(0.106)
	$t_0 - 2$	-0.105^{***}	$t_0 + 6$-12	-0.242^{***}	$t_e + 6$-12	-0.672^{***}
		(0.040)		(0.061)		(0.101)
	$t_0 - 1$	-0.111^{***}	$t_0 + 13+$	-0.388^{***}	$t_e + 13+$	-0.636^{***}
		(0.039)		(0.069)		(0.109)
Yield						
	$t_0 - 8$	-0.029	t_0	-0.097^{***}	t_e	-0.342^{***}
		(0.022)		(0.03)		(0.079)
	$t_0 - 7$	-0.034	$t_0 + 1$	-0.098^{**}	$t_e + 1$	-0.403^{***}
		(0.023)		(0.033)		(0.077)
	$t_0 - 6$	-0.026	$t_0 + 2$	-0.113^{***}	$t_e + 2$	-0.422^{***}
		(0.025)		(0.032)		(0.083)
	$t_0 - 5$	-0.018	$t_0 + 3$	-0.099^{***}	$t_e + 3$	-0.456^{***}
		(0.026)		(0.032)		(0.086)
	$t_0 - 4$	-0.035	$t_0 + 4$	-0.115^{***}	$t_e + 4$	-0.468^{***}
		(0.025)		(0.033)		(0.086)
	$t_0 - 3$	-0.036	$t_0 + 5$	-0.118^{***}	$t_e + 5$	-0.460^{***}
		(0.023)		(0.037)		(0.087)
	$t_0 - 2$	-0.075^{***}	$t_0 + 6$-12	-0.179^{***}	$t_e + 6$-12	-0.488^{***}
		(0.027)		(0.044)		(0.084)
	$t_0 - 1$	-0.076^{***}	$t_0 + 13+$	-0.289^{***}	$t_e + 13+$	-0.518^{***}
		(0.027)		(0.051)		(0.097)

Notes: Estimates of specification (6) when dependent variable is log of the 75th percentile passenger-weighted fare ("Fare") or this fare divided by the non-stop route distance ("Yield"). The adjusted R^2s are 0.81 ("Fare") and 0.84 ("Yield"). Other notes from Table 3 apply here.

E First Stage of the Ellison and Ellison (2011) Analysis: Southwest's Route-Level Entry Probabilties

As outlined in Section 4.2, the EE approach is implemented in two stages. The first stage, which we describe in more detail here, involves the estimation of a probit model using the full sample of 1,872 markets to predict the probability of entry by Southwest at the route-level. There is one observation per market, and the dependent variable ($\text{Entry4}_{m,t}$) is equal to 1 if Southwest enters market m within four quarters of becoming a potential entrant at time t (recall that Southwest becomes a potential entrant when it has operations at both endpoints).

$$\Pr(\text{Entry4}_{m,t}|X,t) = \Phi(\tau_t + \alpha X_{m,t}) \tag{19}$$

where τ_t are a full set of quarter dummies. The explanatory variables X_m contain the following market characteristics:

- Distance: round-trip distance between the endpoint airports (also Distance^2);
- Long Distance: a dummy that is equal to 1 for markets with a round-trip distance greater than 2,000 miles;
- Average Pop.: geometric average population for the endpoint MSAs (also Average Pop.^{2});
- Market Size: our estimated market size based on our gravity model described in Appendix C (also Market Size^2). The size is measured in the quarter when Southwest becomes a potential entrant;
- Slot: a dummy that is equal to 1 if either endpoint airpot is a slot-controlled airport;
- Tourist: a dummy that is equal to 1 if either endpoint city is a leisure destination as defined by Gerardi and Shapiro (2009);
- Big City: a dummy that is equal to 1 if either endpoint city is a large city, following the population-based definition of Gerardi and Shapiro (2009);
- Southwest Alternate Airport: a dummy equal to 1 in cases where Southwest already serves one of the endpoint airports from an airport that is in the same city as the other endpoint

airport;

- HHI: the HHI, based on passenger numbers, for the route in the quarter that Southwest became a potential entrant;

For each of the endpoints separately, we also include:

- Primary Airport: a dummy equal to 1 for the largest airport (measured by passenger traffic in 2012) in a multiple airport city[63];
- Secondary Airport: a dummy equal to 1 for an airport other than the largest in a multiple airport city;
- Incumbent Presence: the average proportion of all passenger originations accounted for by the incumbents on route m at the airport in the quarter Southwest became a potential entrant (also Incumbent Presence^2);
- Southwest Presence: the proportion of all passenger originations accounted for by Southwest at the airport in the quarter it became a potential entrant (also Southwest Presence^2).

The results are reported in Table E.1.

[63] http://en.wikipedia.org/wiki/List_of_cities_with_more_than_one_airport.

Table E.1: Probit Model of Southwest's Entry

	Entry by Southwest Within Four Quarters	
Distance	-0.668***	
	(0.204)	
Distance^2	0.0385	
	(0.0344)	
Long Distance	-0.0414	
	(0.181)	
Average Pop.	-0.0952	
	(0.109)	
Average Pop.^{2}	0.0117*	
	(0.00637)	
Market Size	0.237***	
	(0.0404)	
Market Size^2	-0.00745***	
	(0.00165)	
Slot	-1.801***	
	(0.543)	
Tourist	1.003***	
	(0.174)	
Big City	-0.0134	
	(0.146)	
Southwest Alternate Airport	-0.185	
	(0.195)	
HHI	0.541***	
	(0.202)	
Airport-Specific Variables	Origin	Destination
Primary Airport	0.688***	0.558***
	(0.254)	(0.211)
Secondary Airport (origin)	0.542**	0.0383
	(0.237)	(0.233)
Incumbent Presence	2.174	-4.076
	(1.743)	(1.683)
Incumbent Presence^2	-2.085	6.253
	(1.683)	(7.521)
Southwest Presence	2.455**	0.187
	(0.983)	(1.045)
Southwest Presence^2	-2.245**	-0.0427
	(0.940)	(1.101)
Observations	1,872	
Pseudo-R^2	0.372	

Notes: Specification also includes dummies for the quarter in which Southwest becomes a potential entrant. Robust standard errors in parentheses. ***,**,* denote significance at the 1, 5 and 10% levels respectively. The origin airport is the endpoint with an IATA code that is earlier in the alphabet.

F Estimates of Demand and Marginal Cost for Calibration

This Appendix reports the estimates of carrier demand and marginal cost that are used in Section 5.

Table F.1: Nested Logit Demand Estimates

	OLS	2SLS
Price ($00s, $\widehat{\alpha}$)	-0.327***	-0.408***
	(0.012)	(0.037)
Inside Share ($\widehat{\lambda}$)	0.799***	0.762***
	(0.032)	(0.069)
Hub Carrier	0.184*	0.242***
	(0.030)	(0.034)
Selected Carrier Dummies		
American	-0.112**	-0.139**
	(0.054)	(0.060)
Continental	0.174**	0.263**
	(0.086)	(0.101)
Delta	-0.184***	-0.212***
	(0.043)	(0.045)
Northwest	0.296***	0.451***
	(0.052)	(0.086)
United	-0.358***	-0.330***
	(0.075)	(0.079)
US Airways	-0.027	0.048
	(0.047)	(0.058)
Southwest	-0.012	-0.082
	(0.041)	(0.050)
Observations	5,778	5,778
R^2	0.312	-

Notes: Specification also includes a linear time trend, quarter of year dummies, market characteristics (distance, distance^2, indicators for whether the route includes 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 text. Robust standard errors in parentheses. ***,** ,* denote statistical significance at the 1, 5 and 10% levels respectively.

Table F.2: Marginal Cost Evolution Estimates

	(1) OLS All Carriers	(2) 2SLS All Carriers	(3) 2SLS Southwest	(4) 2SLS Incumbents
MC $\widehat{\text{per mile}}_{j,m,t-1}$	0.847***	0.974***	0.975***	0.963***
	(0.1038)	(0.0123)	(0.0889)	(0.0461)
Observations	5,432	4,544	1,603	2,941
R^2	0.813	-	-	-

Notes: The dependent variable is MC $\widehat{\text{per mile}}_{j,m,t}$, carrier j's computed marginal cost 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 in parentheses. ***, **, * denote statistical significance at the 1, 5 and 10% levels respectively.