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

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Abstract

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

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1 Introduction

Economists have long been aware that incumbent firms with market power may want to take actions that deter new entry (Kaldor (1935) and Bain (1949)). Survey evidence supports the view that managers sometimes act in this way (Smiley (1988)). However, while models of entry deterrence are central to the theoretical Industrial Organization literature (e.g., chapters 8 and 9 of Tirole (1988)), empirical evidence that particular models explain observed firm behavior is limited. In our view, one reason for this is that it is often unclear what the stylized two-period models that dominate the literature predict should happen when firms interact repeatedly as happens in the real world where, for example, a potential entrant may wait for several years before entering. In this paper, we extend one particular model of entry deterrence, the classic Milgrom and Roberts (1982) (MR) model of limit pricing with asymmetric information, to a dynamic setting.[1] We then show that our model provides a plausible explanation for why, in the 1990s and 2000s, incumbent airlines often responded to the threat of entry by Southwest by lowering their prices, and then keeping them low, even before entry actually occurred. This pattern is part of the phenomenon commonly known as the "Southwest Effect".[2]

In the two-period MR model, an incumbent faces a potential entrant who is uninformed about some relevant aspect of the market, such as the incumbent's marginal cost. In equilibrium, the incumbent may deter entry by choosing a price that is low enough to credibly signal that the value of this variable is so low that the potential entrant's post-entry profits would not cover its entry costs. However, it is unclear *a priori* whether a more dynamic version of this model, where incumbents set prices multiple times, will be tractable[3] and what will happen to signaling incentives (for example, does the incumbent need to set low prices in every period or only in some initial set of periods?). We show that, when we allow the incumbent's private information to be positively serially correlated, but not perfectly persistent, over time, that the model is tractable with a unique Markov Perfect Bayesian equilibrium under a refinement when the incumbent's payoffs satisfy several conditions. When the incumbent's marginal cost evolves exogenously, the required conditions can be shown to always hold under quite weak, and easy-to-check, conditions on the primitives of the model. The unique equilibrium involves the incumbent using fully separating price strategies, which allows us to devise a computationally simple strategy for solving and calibrating the model. We also show how the consideration of dynamics can significantly increase the magnitude of limit pricing that occurs in equilibrium, so that prices are predicted to fall significantly

[1] The earlier limit pricing literature assumed that a low pre-entry price might deter entry because potential entrants would view it as implying that low prices would be set post-entry, even if arguments for why this would be rational were not explicitly developed (e.g., Modigliani (1958), Gaskins (1971), Kamien and Schwartz (1971), Baron (1973) and, for a critique, Friedman (1979)). MR addressed this issue by introducing asymmetric information between the incumbent and potential entrant. Matthews and Mirman (1983) and Harrington (1986) provide early developments of the MR framework. We note that we use the term dynamic limit pricing to refer to the fact that, in our model, the incumbent may set its price multiple times before the potential entrant enters. The term dynamic limit pricing has also sometimes been used to refer to the process by which an incumbent facing entry by multiple firms will change its price over time, partly to limit the growth of entrants (Gaskins (1971)).

[2] The term originates from a 1993 Department of Transportation study (Bennett and Craun (1993)) which noted that many contemporary pricing trends on short-haul routes could be attributed to the presence of Southwest on a route itself or its presence on routes serving the endpoint airports.

[3] Dynamic games with persistent asymmetric information have often been viewed as being too intractable to work with, at least using standard notions of equilibrium, in the applied literature (Doraszelski and Pakes (2007), Fershtman and Pakes (2012)).

even when the incumbent can only have a relatively small absolute effect on the probability of entry.

Having developed the model, we investigate whether it can explain the Southwest Effect. As documented by Goolsbee and Syverson (2008) (GS), incumbent airlines lower prices by as much as 20% on airport-pair routes when Southwest serves both endpoint airports without (yet) serving the route itself, and as suggested in Bennett and Craun (1993) and Morrison (2001), these price cuts have substantial welfare effects. For example, Morrison estimates that Southwest's presence as a potential competitor lowered consumers' annual expenditure on airfares by $3.3 billion in 1998. While this is a natural setting in which to consider limit pricing as these price reductions in response to potential competition are the largest documented in any industry (Bergman (2002)), we do not believe that anyone has closely examined whether a limit pricing story can explain what is observed in the data.

We present two forms of evidence focusing on a set of markets with a dominant incumbent, prior to Southwest's entry, to fit the assumptions of our model. First, we show that, as predicted by our model, there is a non-monotonic relationship between observed price changes and an exogenous measure of the probability of entry, with the largest price reductions occurring in markets where there is an intermediate probability that Southwest will enter. This pattern, which Ellison and Ellison (2011) (EE) argue is a testable prediction of a two-period model of entry deterrence, is also a prediction of our model. We show that explanations other than limit pricing for why prices fall in intermediate probability markets, involving, for example, strategic increases in capacity, declining load factors, or competition with connecting service on Southwest, are not consistent with the data. In contrast, we see that another strategy, increased code-sharing, that is also adopted when Southwest threatens entry (Goetz and Shapiro (2012)), occurs primarily in those markets where Southwest is most likely to enter, suggesting that it may reflect incumbents preparing to accommodate entry.

Second, we calibrate a parameterized version of our model. We estimate demand and marginal cost parameters using data from quarters where limit pricing should not be taking place, and we estimate the distribution of Southwest's entry costs using information on how the probability of entry varies across markets and over time, exploiting the fact that, in the equilibrium of our model, entry decisions will be the same as under complete information. With asymmetric information our model predicts a magnitude of price cuts and a relationship between price cuts and the probability of entry that are very similar to what we observe in the data. We use the calibrated model to perform two welfare calculations. Our first calculation quantifies the welfare effects of the pre-entry price cuts due to asymmetric information for our sample of markets. Even though our focus is on a relatively small number (109) of medium-sized and smaller markets we find substantial welfare effects: in present value terms, we find that limit pricing increases consumer surplus by over $600 million and total welfare by over $500 million (2009 dollars). Our second calculation quantifies the effects of granting Southwest small financial subsidies when it provides non-stop service, motivated by the fact that service subsidies are quite common in the industry. We predict that even small subsidies can increase welfare substantially, and at low cost to the government, with a large proportion of the gains coming in the smallest markets where subsidies can cause dominant incumbents to lower prices significantly just by making entry slightly more likely.

Our focus in most of the paper is on a relatively simple model where the incumbent has full information about the potential entrant, and the potential entrant is uninformed about the incumbent's exogenously evolving marginal cost. The final section of the paper briefly considers extensions which remain reasonably tractable and which can shed light on why we see limit pricing in airline markets and some additional features of the data. For example, one extension allows the incumbent's marginal cost to be an endogenous function of its pricing and capacity choices, and we assume that the incumbent's private information is about the level of demand from travelers using the route to make connections.[4] Given capacities, flows of connecting passengers affect a carrier's marginal cost of serving local passengers, as in Hendricks, Piccione, and Tan (1997). This model can also generate substantial price reductions due to limit pricing which, as in the basic model, vary non-monotonically with the probability of entry. In this model a carrier could try to use increased capacity investment to deter entry, in the spirit of Dixit (1980), in addition to limit pricing, but we find that, at least for the parameters that we use, the threat of entry does not cause capacity to increase. This is also consistent with the data. We also consider extensions that can help to explain why, in at least some markets in the data, the magnitude of the incumbent's price cuts appears to grow significantly over time, a phenomenon which our basic model can partly, but not completely, explain. One of these extensions involves the incumbent also learning about the preferences of the potential entrant from the entry decisions that it makes. This feature, which could not be included in a two-period model where the potential entrant only takes a single entry decision, is an additional innovation to the literature.

Our work draws on, and is related to, two broad literatures aside from the one that has studied market power in airlines and the Southwest Effect (we discuss this literature in Section 3). In characterizing what happens in a dynamic, finite horizon version of MR, we recursively apply the results of Mailath (1987), Mailath and von Thadden (2013) and Ramey (1996) in one-shot signaling models. Roddie (2012a) and Roddie (2012b) also take a recursive approach to solving a dynamic game of asymmetric information, focusing on the example of a quantity-setting game between two incumbents, one of whom has a privately-known marginal cost that evolves exogenously. As in these papers, we formally assume a finite-horizon structure, where we can use backwards induction to show existence and uniqueness properties. We allow the number of periods to go to infinity to give us a model where we can compute equilibria in an efficient manner. We differ from Roddie in considering an entry-deterrence game; in using different high-level conditions on incumbent payoffs to show existence and uniqueness of our equilibrium; and, in the exogenous marginal cost version of our model, showing how these conditions will be satisfied under a small number of easy-to-check conditions on static primitives of the model. Kaya (2009) and, in a limit pricing context, Toxvaerd (2014) consider repeated signaling models where the sender's type is fixed over time. This structure can lead to signaling only in the early periods of a game, whereas, with an evolving type, our model has repeated signaling in equilibrium.[5]

[4]Allowing connecting traffic to play a role is attractive for two reasons. First, most of the routes in our sample are heavily used by travelers making connections and, second, network flows are viewed as hard to understand without access to internal accounting data (Edlin and Farrell (2004) and Elzinga and Mills (2005), who consider predation cases where network flows are important). Bagwell and Ramey (1988) and Bagwell (2007) consider extensions to MR where the incumbent can (potentially) use both price and advertising to signal, and firms may differ in both patience and production costs. Spence (1977) compares price levels in a model where an incumbent limit prices (through an assumed price commitment) and a model where an incumbent can deter entry by investing in capacity.

[5]A model where the incumbent's type is fixed would have difficulty in explaining two aspects of our empirical application.

A second directly related literature has tried to provide empirical evidence of strategic investment. A common approach has looked for evidence of different investment strategies amongst firms (e.g., Lieberman (1987)) or effects of incumbent investment on subsequent entry (e.g., Chevalier (1995)) without specifying the exact mechanism involved. Masson and Shaanan (1982) try to provide evidence of limit pricing by pooling annual data on pricing from 37 different industries. Masson and Shaanan (1986) take a similar approach using data from 26 industries to argue that there is more evidence of incumbents using limit pricing than excess capacity to deter entry. While the empirical approach is very different, this conclusion is consistent with our results.[6] Closer to our approach is Seamans (2013) who, inspired by the approach of EE, argues that the pricing of incumbent cable TV systems is consistent with an MR model of entry deterrence as, in the cross-section, prices vary non-monotonically to the distance to the nearest potential telephone company entrant.[7]

Snider (2009) and Williams (2012) provide structural evidence in favor of airlines using capacity investment in order to predate on small new entrants on routes coming out of their hubs. Our evidence suggests that incumbents did not use capacity investment as a strategy to try to deter a much stronger potential entrant, Southwest. Both of these papers use infinite horizon dynamic structural models with complete information (up to i.i.d. payoff shocks) in the tradition of Ericson and Pakes (1995). One feature of these models is that there are often multiple equilibria. We differ from this literature by considering a dynamic model with asymmetric information and explicitly establishing conditions and a refinement under which the Markov Perfect Bayesian equilibrium that we look at is unique. Fershtman and Pakes (2012) consider an alternative way of incorporating persistent asymmetric information in a dynamic game, using an alternative concept of Experience Based Equilibrium, where players have beliefs about the payoffs from different actions, not the types of other players. When the structure of equilibrium beliefs is unknown ex-ante, this EBE approach may have computational advantages. However in our model, we can show uniqueness of a Markov Perfect Bayesian equilibrium where the entrant's beliefs will always be correct on the equilibrium path.[8] This allows us to provide a natural dynamic extension one of the classic two-period models of theoretical Industrial Organization.

The rest of the paper is organized as follows. Section 2 lays out our model of dynamic limit pricing when marginal costs are exogenous, characterizes the equilibrium and examines the predictions of the model. Section 3 describes our data, and discusses the potential applicability of our model to explaining the Southwest Effect. Section 4 provides the reduced-form (GS and EE-style) evidence in support of our

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 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.

[6] Strassmann (1990) used the Masson and Shaanan approach to try to identify evidence of limit pricing in airline markets looking at 92 heavily-traveled routes. She found evidence that high prices attracted entry, but no significant evidence that prices were lowered strategically in order to deter entry.

[7] In our analysis we look directly at whether price *changes* vary non-monotonically with the probability of entry once Southwest becomes a potential entrant.

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

limit pricing model. Section 5 presents our calibration of the model and quantifies the welfare effects of limit pricing and the welfare effects of counterfactual subsidies that would encourage Southwest to enter. Section 6 discusses some appealing extensions to the basic model. Section 7 concludes. Appendices contain theoretical proofs, additional examples and many details of our empirical work.

2 Model

In this section we develop our model of a dynamic entry deterrence game with asymmetric information. We focus on a game where the incumbent has a time-varying marginal cost of carrying passengers that evolves exogenously. This model is, in essence, a direct extension of MR, and, because a set of simple conditions on static primitives guarantee existence of a unique equilibrium, it is the most tractable game to consider. We develop our equilibrium concept, explain what is required for existence and uniqueness of a fully separating Markov Perfect Bayesian Equilibrium (MPBE), and provide some simple conditions on static payoffs and outcomes under which these requirements will be satisfied. Proofs of theoretical propositions are in Appendix A. Finally, we describe some properties of the model and compare them to those of the analogous two-period model.

2.1 A Dynamic Limit Pricing Model with Exogenous Marginal Costs

We consider a sequence of discrete time periods, $t = 1, 2, ...$, two long-lived firms and a common discount factor of $0 < \beta < 1$. To prove existence and uniqueness of an equilibrium in our model we use a finite structure, where the final period is T.[9] 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. Once E enters, it will also remain in the market forever.[10] The marginal costs of the firms are c_E and $c_{I,t}$. All of the theoretical results would hold if we allow $c_{E,t}$ to be serially correlated but publicly observed (see Gedge, Roberts, and Sweeting (2014) for the full presentation of the theory for this case). $c_{I,t}$ lies on a compact interval $[\underline{c_I}, \overline{c_I}]$ and evolves, exogenously, according to a first-order Markov process $\psi_I : c_{I,t-1} \rightarrow c_{I,t}$ with full support (i.e., $c_{I,t-1}$ can evolve to any point on the support in the next period). Note, however, that E may have a quite precise prior on $c_{I,t}$ given what it has observed previously. The conditional pdf is denoted $\psi_I(c_{I,t}|c_{I,t-1})$. We make the following assumptions.

Assumption 1 ***Marginal Cost Transitions***

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

[9]The finite structure also ensures that there is a unique equilibrium, equivalent to static Nash in every period, in the complete information game that follows entry when there is a unique equilibrium in the static duopoly pricing game, which will be the case for common demand specifications (e.g., linear, logit, nested logit) with single product firms and linear marginal costs.

[10]While we assume here that the incumbent and an entrant will remain in the market forever, this assumption is not necessary in that there can be a unique limit pricing equilibrium in the pre-entry game in an extended model where future exit is possible. In our dominant incumbent sample routes, there is only one route where Southwest enters and then exits before the end of our sample, while the incumbent remains in the market for at least two years after Southwest enters in 80% of cases.

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

To enter in period t, E has to pay a private information sunk entry cost, κ_t, which is an i.i.d. draw from a commonly-known time-invariant distribution $G(\kappa)$ (density $g(\kappa)$) with support $[\underline{\kappa} = 0, \overline{\kappa}]$.[11]

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 observed by both firms.

2.1.1 Pre-Entry Stage 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 sets a price $p_{I,t}$, and receives flow profit

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

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

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

   The incumbent can choose a price from the compact interval $[\underline{p}, \overline{p}]$.[12]

2. E observes $p_{I,t}$ and κ_t, and then decides whether to enter (paying κ_t if it does so). If it enters, it is active at the start of the following period.

3. I's marginal cost evolves according to ψ_I.

Assumption 3 ***Monopoly Payoffs***

[11] In MR's presentation, E's entry cost is publicly observed but its marginal cost is private information, although the reverse assumption would generate the same results. Given that we assume that I's marginal cost is serially correlated, it seems appropriate, as well as consistent with most of the literature on dynamic entry models, to assume that it is E's entry cost that is i.i.d. See Section 6 for a variant of our model where E has private information about G.

[12] All of our theoretical results would hold when the monopolist sets a quantity. The choice of strategic variable in the duopoly game that follows entry may matter, as will be explained below.

1. *$q^M(p_I)$, the demand function of a monopolist, is strictly monotonically decreasing in p_I, continuous and differentiable.*

2. *$\pi_I^M(p_I, c_I)$ has a unique optimum in price and for any $p_I \in [\underline{p}, \overline{p}]$ 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.*[13]

2.1.2 Post-Entry Stage Game

We assume that once E enters, marginal costs, which continue to evolve as before, are observed so there is no scope for further signaling, and we assume that a unique equilibrium in the static duopoly game is played. The assumption of complete information post-entry is obviously strong, and its plausibility will depend on exactly what is driving the evolution of the incumbent's marginal cost as some changes may be more transparent to direct competitors.[14]

Static per-period equilibrium profits are $\pi_I^D(c_{I,t})$ and $\pi_E^D(c_{I,t})$, and outputs $q_I^D(c_{I,t})$ and $q_E^D(c_{I,t})$. The choice variables of the firms, which could be prices or quantities, are denoted $a_{I,t}$ and $a_{E,t}$.

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

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

2. *$\pi_I^D(c_I)$ and $\pi_E^D(c_I)$ are continuous and differentiable in their arguments; and $\pi_I^D(c_I)$ ($\pi_E^D(c_I)$) is monotonically decreasing (increasing) in c_I.*

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

4. *$q_I^D(c_I) - q^M(p_I^{\text{static monopoly}}(c_I)) - \frac{\partial \pi_I^D(c_I)}{\partial a_E}\frac{\partial a_E^*}{\partial c_I} < 0$ for all c_I, where a_E^* is the equilibrium price or quantity choice of the entrant in the duopoly game.*

The fourth condition implies that a decrease in marginal cost is more valuable to a monopolist than a duopolist, and it is important in showing a single-crossing condition on the payoffs of an incumbent monopolist who can signal its costs.[15] The condition is easier to satisfy when the duopolists compete in prices (strategic complements), as $\frac{\partial \pi_I^D(c_I)}{\partial a_E}\frac{\partial a_E^*}{\partial c_I} > 0$ in this case, and when c_E is low relative to $\underline{c_I}$ (i.e., the potential entrant is always relatively efficient).[16] This makes sense in our empirical setting as Southwest is viewed as having had significantly lower costs than legacy carriers during our sample period.

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

[14] On-going work (see Sweeting and Tao (2017) for an example) examines dynamic oligopoly price and quantity-setting games with multi-sided asymmetric information using results from Mailath (1988). Signaling can generate substantial price changes in these games as well, but, without imposing linear demand, it is not possible to show that equilibrium strategies are unique (Mailath (1989) and Mester (1992)). This would substantially complicate the analysis in the current paper.

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

[16] In his presentation of the two-period MR model, Tirole (1988) suggests a condition that a static monopolist produces

2.1.3 Equilibrium

We assume that there is a unique Nash equilibrium in the post-entry complete information duopoly game. Our interest is in characterizing pre-entry play. Our basic equilibrium concept is Markov Perfect Bayesian Equilibrium (Roddie (2012a), Toxvaerd (2008)). In the finite horizon model, the specification of an MPBE requires, for each period:

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

where E's entry rule should be optimal given its beliefs about I's marginal cost and its expected post-entry payoffs, and its beliefs should be consistent with I's pricing strategy and the application of (the continuous random variable version of) Bayes Rule on the equilibrium path, and I's pricing rule must be optimal given what E will infer from I's price and how E will decide to enter. E's beliefs off the equilibrium path should support equilibrium play, and we will achieve this by assuming that E infers that I has the highest possible marginal cost when it sets a price that is outside the range of $\varsigma_{I,t}$. The Markovian restriction is that the only way that history is being allowed to matter is through how it affects E's beliefs about I's current marginal costs. These beliefs are payoff relevant because they affect E's expected future profits and its entry decision.

To establish the uniqueness of an MPBE in this model, we proceed recursively from the end of the model, characterizing the unique equilibrium in any single period and using that characterization to show uniqueness in the previous period. A set of conditions on payoffs imply that there is only one fully separating equilibrium, which will correspond to the Riley Equilibrium (Riley (1979)) where the incentive compatibility constraints consistent with full separation are satisfied at minimum cost to I in each period. We then show that similar conditions allow us to apply the so-called D1 refinement (Cho and Sobel (1990), Ramey (1996)), which restricts the inferences that a receiver can make if it observes off-the-equilibrium path actions, to eliminate pooling or partial pooling equilibria.[17,18]

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

Theorem 1 *Consider the following strategies and beliefs:*

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

In all periods $t < T$:

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.

[17]Specifically, D1 requires the receiver to place zero posterior weight on a signaler having a type θ_1 if there is another type θ_2 who would have a strictly greater incentive to deviate from the putative equilibrium for any set of post-signal beliefs that would give θ_1 an incentive to deviate.

[18]Our recursive approach means that when we apply D1 in period t, we are assuming that an off-the-equilibrium path action before t could not affect how an off-the-equilibrium path action in t is interpreted (Roddie (2012a)).

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

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

where $\mathbb{E}_t(V_{t+1}^E|\widehat{c}_{I,t})$ is E's expected value, at time t, of being a potential entrant in period $t+1$ (i.e., if it does not enter now) given equilibrium behavior at $t+1$, and $\mathbb{E}_t(\phi_{t+1}^E|\widehat{c}_{I,t})$ is its expected value of being a duopolist in period $t+1$ (which assumes it has entered prior to $t+1$).[19] *The threshold $\kappa_t^*(\widehat{c}_{I,t})$ is strictly increasing in $\widehat{c}_{I,t}$; (ii) I's pricing strategy, $\varsigma_{I,t} : c_{I,t} \rightarrow p_{I,t}^*$, will be the solution to a differential equation*

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

and an upper boundary condition $p_{I,t}^*(\overline{c_I}) = p^{\text{static monopoly}}(\overline{c_I})$. $\mathbb{E}_t[V_{t+1}^I|c_{I,t}]$ is I's expected value of being a monopolist at the start of period $t+1$ given current (t period) costs and equilibrium behavior at $t+1$. $\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]$ is its expected value of being a duopolist in period $t+1$; (iii) E's beliefs on the equilibrium path: observing a price $p_{I,t}$, E believes that I's marginal cost is $\varsigma_{I,t}^{-1}(p_{I,t})$.

This equilibrium exists, and these strategies 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 $\varsigma_{I,t}(c_{I,t})$ then it believes that the incumbent has marginal cost $\overline{c_I}$.

Proof. See Appendix A. ■

Our proof applies well-known results from the literature on one-shot signaling models. Mailath and von Thadden (2013)[20] provide conditions on a signaler's payoffs[21] under which there will only be one separating equilibrium, with the strategy characterized by a differential equation and a boundary condition. The key conditions are type monotonicity (a price cut is more costly for an incumbent with higher marginal costs), belief monotonicity (the incumbent always benefits when the entrant believes that he has lower marginal costs) and a single-crossing condition (a lower cost incumbent is always willing to cut the current price slightly more in order to differentiate itself from a higher cost type).

The more novel part of our results is that we show that our assumptions on static monopoly and duopoly quantities and payoffs are sufficient for the Mailath and von Thadden (2013) and Ramey (1996) requirements on dynamic payoffs to hold in *every period* of the game. This is a useful property because it allows us to verify existence and uniqueness before trying to solve the model.[22] In richer models, where marginal costs are endogenous (see Section 6), we can no longer rely on simple static conditions,

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

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

[21] The signaler's payoff function can be written as $\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$ 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 $\Pi^{I,t}(c_{I,t}, \kappa_t', p_{I,t})$ where κ_t' is the time-specific entry cost threshold used by the potential entrant.

[22] The static conditions are sufficient, not necessary, so our equilibrium may exist even if the conditions are violated.

and instead verify that payoffs satisfy the Mailath and von Thadden (2013) and Ramey (1996) at all of the points in the state-space throughout the game.

2.2 Equilibrium Properties

We now discuss some features of the equilibrium that are useful for understanding the empirical analysis that follows.

On the equilibrium path, E's entry decisions will be the same as in a complete information model. This property comes from our assumption that there is complete information post-entry, so that E cannot time its entry to affect I's beliefs, and from the property that, prior to entry, I's pricing strategy is fully separating. As a result, E correctly identifies I's marginal cost on the equilibrium path and should use the same entry strategy as under complete information.

This allows us to solve for E's entry strategy separately from I's pricing strategy, and this greatly facilitates computation, especially in the limiting infinite horizon version of the model where the incumbent's pre-entry pricing strategy is stationary and the same (up to small numerical differences) as in the early periods of a long, finite horizon game. We use the infinite horizon model, unless otherwise stated, when we present computations. Appendix B.1 details how this game is solved.

Determinants of price shading in the dynamic model and the relationship between the probability of entry and equilibrium shading. Under our assumptions, the incumbent's value is increased by maintaining its monopoly position ($\mathbb{E}_t[V^I_{t+1}|c_{I,t}] > \mathbb{E}_t[\phi^I_{t+1}|c_{I,t}]$). From (4), the incumbent's limit price will therefore be lower than its static monopoly price for all c_I less than $\bar{c}$, except in the final period, and we will call this lowering of price "price *shading*" in what follows.

The magnitude of shading will depend on all of the terms in the differential equation. It is useful to start by considering the analogue of (4) in a two-period model,

$$\frac{\partial p^*_{I,1}}{\partial c_{I,1}} = \frac{\beta \frac{\partial \Pr(\text{E enters in period 1})}{\partial c_{I,1}} M\{\mathbb{E}_t[\Pi^M_{I,2}|c_{I,1}] - \mathbb{E}_t[\Pi^D_{I,2}|c_{I,1}]\}}{M\left(s^M(p_{I,1}) + \frac{\partial s^M(p_{I,1})}{\partial p_{I,1}}(p_{I,1} - c_{I,1})\right)}, \tag{5}$$

where M is market size, and $\mathbb{E}_t[\Pi^M_{I,2}|c_{I,1}]$ and $\mathbb{E}_t[\Pi^D_{I,2}|c_{I,1}]$ denote expected second-period monopoly and duopoly profits per-consumer given I's period 1 marginal cost. The entry rule for E will be to enter if and only if its entry cost is less than $\kappa^*_1 = M\mathbb{E}_t[\Pi^D_{E,2}|c_{I,1}]$.

Holding the discount factor fixed, the pricing function will become steeper, implying greater shading, all else equal, when (i) there is a greater difference between I's static monopoly and duopoly profits; (ii) E's entry decision is more sensitive to the incumbent's marginal cost; and, (iii) the profit that the incumbent would gain in the first period if it increased its price (from a level below the static monopoly price) is small, which will depend on the curvature of the static profit function. As the static profit function will be flat at the static monopoly price, quite large price decreases may be incentive compatible as long as the curvature is not too great.

In (5) the Ms cancel, so that the way that market size will matter is through its effects on the E's entry decision. As $\frac{\partial \Pr(\text{E enters in period 1})}{\partial c_{I,1}} = g(\kappa^*_1(c_{I,1}))\frac{\partial \kappa^*_1(c_{I,1})}{\partial c_{I,1}}$, this will depend on the shape of the entry cost distribution. For example, if entry costs are normally distributed, then all else equal, the slope of the pricing function (and therefore the amount of shading) will be greatest when the probability of entry, in particular for $c_I = \overline{c_I}$, is around 0.5.[23] This will lead to a predicted U-shaped relationship between the one-period probability of entry and the price change we should expect to observe if E exogenously (i.e., independently of c_I) becomes a potential entrant. Of course, for other distributions the relationship between the probability of entry and the degree of shading will depend where in the distribution of entry costs the density g is maximized. The value of $\frac{\partial \kappa_1^*(c_{I,1})}{\partial c_{I,1}}$ will depend on how I's current marginal cost affects E's expected future profits, which will depend on the substitutability of their products and the serial correlation in I's marginal costs. As serial correlation increases, E's expected future profits will be more sensitive to $c_{I,1}$ and, all else equal, shading will increase.[24]

In the dynamic model the differential equation is the same except that $M\{\mathbb{E}_t[\Pi_{I,2}^M|c_{I,1}]-\mathbb{E}_t[\Pi_{I,2}^D|c_{I,1}]\}$ is replaced by $\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\}$, where V and ϕ are continuation values. If entry at the end of the next period is neither certain nor close to certain, the difference in continuation values may be much greater than the difference in static, one-period profits, because entry that is deterred in the current period may create a number of periods of monopoly in the future. This will increase the degree of shading, especially when entry probabilities are low, and can lead to substantial shading even if the effect that $c_{I,t}$ can have on entry is quite small. On the other hand, the non-monotonicity of the degree of shading in the entry probability should be preserved.

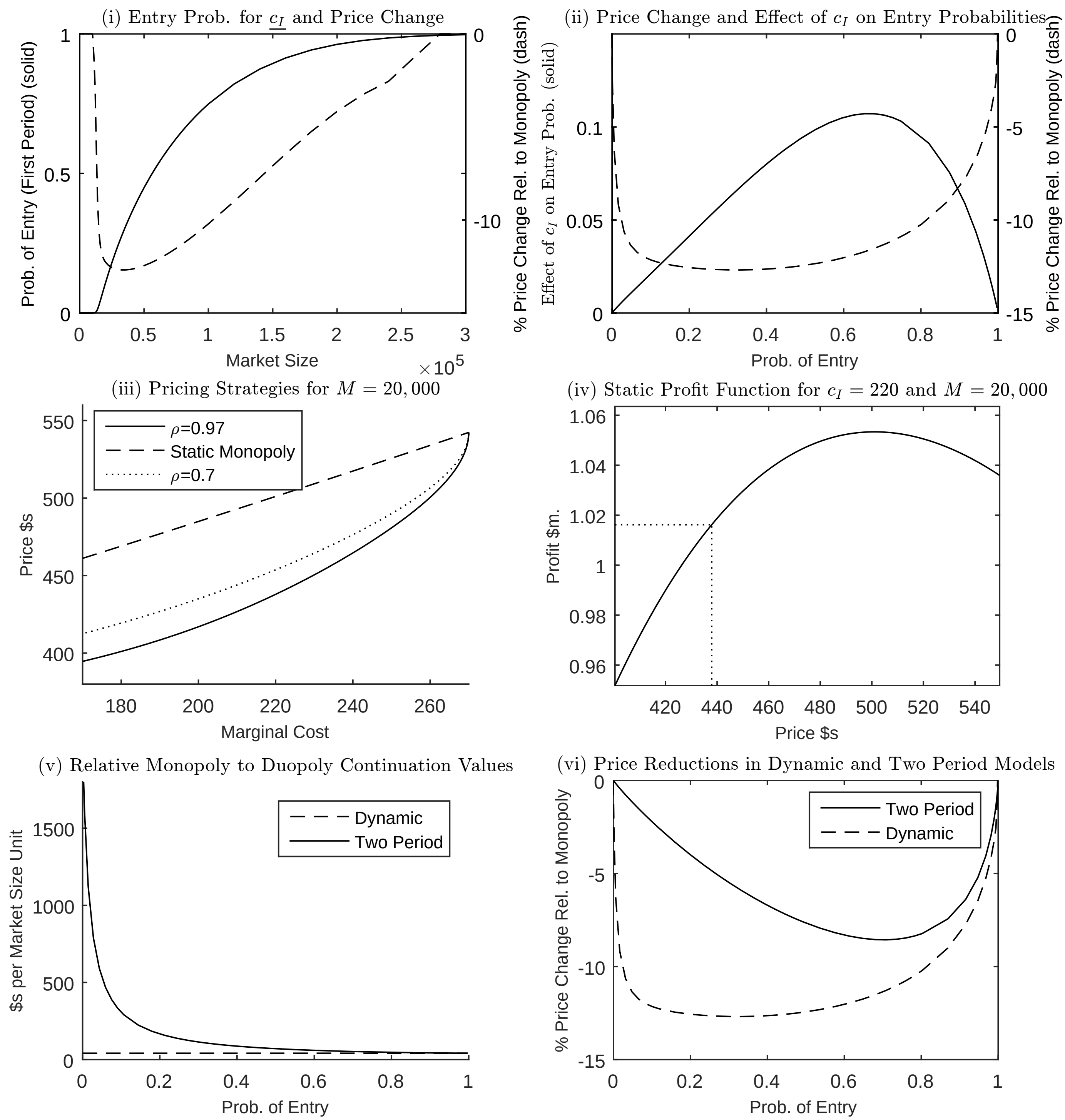
The six panels of Figure 1 illustrate this discussion. It is constructed using the demand parameters that we estimate as part of the calibration (see Section 5 and Appendix I). We also assume that c_E=\$150 and that c_I is between \$170 and \$270 and follows a (truncated) AR(1) process with serial correlation parameter $\rho = 0.97$, with normally distributed innovations that are mean zero and have standard deviation \$35. The entry cost has mean \$20 million and standard deviation \$2 million. The discount factor is 0.98. We assume that E's arrival as a potential entrant is independent of the value of c_I so that we calculate average price changes assuming that c_I is drawn from its steady state distribution.

Panel (i) shows the probability of entry when $c_I = \underline{c_I}$ and the average price change, as a % of the static monopoly price (so think of this as negative shading), in the first period that E arrives as a potential entrant, in markets with sizes varying from 1,000 to 300,000 people. There is a clear monotonic relationship between market size and the probability of entry, and a clear non-monotonic relationship between market size and the degree of shading. Panel (ii) shows the implied relationship between the entry probability at $c_I = \underline{c_I}$ (x-axis), the difference in the entry probabilities for $c_I = \overline{c_I}$ and $c_I = \underline{c_I}$ (left-axis) and the degree of shading (right-axis). There is a non-monotonicity between the

[23]As the denominators in (4) and (5) have their smallest value when c_I is close to $\overline{c_I}$, the effect of g being maximized is greatest when the probability of entry for $c_I = \overline{c_I}$ is close to 0.5, although the average degree of shading will depend on the value of g throughout the range of costs.

[24]An intuition in the other direction that has been mentioned to us is that when there is more serial correlation, I will have less new information to signal and so there should be less shading. While it is correct that equilibrium signaling may cease after a number of periods when c_I is fixed (Toxvaerd (2014)), this intuition does not apply when c_I simply becomes more serially correlated because, as is standard in fully separating equilibria, I's pricing strategy, described by (4) and the upper boundary condition, does not depend directly on the precision of the receiver's prior. Instead, the pricing schedule is determined by a type's need to prevent higher cost types from being willing to copy it, whatever the probability that E attaches to these types ex-ante as long as all types are possible.

Figure 1: Relationship Between Market Size, Entry Probabilities and Shading in the Dynamic Limit Pricing Model.



entry probability and the degree of shading, and the degree of shading can be large when the effect that c_I has on the entry probabilities is quite small. For example, for $M = 20,000$ and $\rho = 0.97$, the incumbent's cost can only reduce the entry probability from 0.129 to 0.107, but there is a 12.3% reduction in the incumbent's average price. The degree of shading is maximized, at just under 13% of static profit maximizing prices, when the entry probability for $c_I = \underline{c_I}$ is 0.303.

For $M = 20,000$, panel (iii) shows the equilibrium limit pricing schedules when $\rho = 0.97$ and when $\rho = 0.7$. There is more shading when $\rho = 0.97$ and this holds for all of the other market sizes as well. For $c_I = \$220$, the incumbent sets a price that is \$63 less than the static monopoly price. We can verify that this strategy is better than deviating to using the static monopoly price with a simple calculation. As panel (iv) shows the loss in current profit from charging the limit price is \$37,200. On the other hand, the difference in the incumbent's expected monopoly and duopoly continuation values is \$5.8 million, and charging the limit price reduces the entry probability from 0.128 to 0.118. As $(0.128 - 0.118) \times 5.8 > 0.037$, choosing the limit price increases the firm's payoff.

Panel (v) compares the difference in continuation values per market size unit, with and without entry, in the dynamic and two-period games as the entry probability varies. In the two-period game the difference in continuation values is simply the difference between expected static monopoly and duopoly profits, and, as market size varies, these payoffs are fixed per consumer because equilibrium prices and market shares do not vary with market size conditional on market structure. In the dynamic model the difference in continuation values depends on the probability of entry in future periods. When the probability of entry is very high, the difference between dynamic continuation values is essentially just the difference between the static profits. However, at very low entry probabilities the difference can be up to 50 ($= \frac{1}{1-0.98}$) times greater, creating stronger incentives to signal. To further illustrate this point, panel (vi) shows shading in the dynamic and two-period models when we use the same entry probabilities but just change whether the incumbent considers only next period's profits or the continuation values when setting its limit price.[25] Consistent with our discussion above, there is much less shading in equilibrium in the two-period model, unless entry probabilities are high. This difference matters for our empirical application because we observe large price cuts in markets where entry does not occur for quite long periods of time.

3 Data and Sample Selection

We now turn to our empirical analysis, which examines how dominant incumbent airlines lower prices when faced by the threat of entry by Southwest. While we face the standard problems that we cannot observe what an incumbent has in mind when it sets its price or how a potential entrant interprets the incumbent's price, we can show that the pattern of price changes across markets is consistent with our model, both in a reduced-form and when we calibrate the model without using any information on how

[25] I.e., for the static model we find the price strategy implied by (5) but using the entry probabilities for c_I that are stationary values in the infinite horizon dynamic model. We use this approach to compare the models in this way because there is no natural way to rescale the normal entry cost distribution to get entry probabilities that vary in a similar way with market size.

prices respond to the threat of entry. In this section we briefly discuss the empirical setting, the data and our selection of a set of markets that best match the assumptions of our model.

3.1 Empirical Application

With its large number of distinct airport-pair or city-pair markets that are usually served by at most a small number of carriers, the deregulated airline industry has provided a natural setting for investigating the economics of entry (Berry (1992)), the sources of market power and the effects of mergers (Borenstein (1989), Borenstein (1990), Kim and Singal (1993), Benkard, Bodoh-Creed, and Lazarev (2010)), and price discrimination (Borenstein and Rose (1995), Lazarev (2013)), amongst other topics. Several studies (e.g., Morrison and Winston (1987)) show that ticket prices tend to be lower when there are more potential competitors (defined as carriers serving one or both endpoints, but not yet serving the route)[26], but "the most dramatic effects from potential competition arise in the case of Southwest Airlines, which has long been the dominant low-cost carrier" (Kwoka and Shumilkina (2010), p. 772). The well-known studies of GS and Morrison (2001) estimate that potential competition from Southwest lowers prices by as much as 33% and 19-28%, respectively.[27] While these are the largest estimates of potential competition in any industry (Bergman (2002)), no clear explanation for why incumbents lower prices when Southwest is a potential competitor, but not an actual entrant, has been provided. GS show that price declines are smaller on routes where Southwest announces its entry before it begins operating at the airport, which they tentatively interpret as evidence in favor of an entry deterrence, rather than an entry accommodation explanation, although the difference from the remaining routes in their sample is not statistically significant. They do show incumbents tend not to increase capacity when lowering prices, and they speculate that incumbents may be trying to increase their customers' loyalty, possibly through frequent-flyer programs, in order to reduce the demand that Southwest might receive post-entry (GS, p. 1629). In contrast to this existing literature, our contribution is to show that a limit pricing story provides an empirically plausible explanation for why incumbents lower prices when entry is threatened.

To be consistent with our model, where I is a monopolist, we focus on a set of airport-pair markets where there is a dominant incumbent (as defined below).[28] Almost all of these markets involve at least one hub or focus city for the incumbent, and it was in these markets that Bennett and Craun (1993) originally identified the Southwest Effect. On these routes, the incumbent carrier will usually serve

[26] For example, Morrison and Winston (1987) find that an additional potential competitor lowered prices by $0.0015/passenger mile (1987 dollars) compared with $0.0044/passenger mile for an actual competitor. Kwoka and Shumilkina (2010) find the largest effect of potential entry involving firms other than Southwest that we have seen in the literature, focusing on the effect of the 1987 merger of US Air and Piedmont. In cases where one of the merging airlines operated and the other was a potential entrant prior to the merger, prices rose by 5-6% relative to a control group where one of the carriers operated and the other one was not present at all.

[27] The fact that incumbent prices fall on routes that Southwest does not yet serve has also been frequently noted in the press. For example, "Consider what happened in the two years since Southwest began flying to T.F. Green Airport in Warwick, RI ... competing airlines ... lowered fares - and not only to the cities where Southwest was flying", article by Laurence Zuckerman, 'As Southwest Invades East, Airline Fares Heading South', Oklahoma City Journal Record, February 8, 1999.

[28] GS also use airport-pairs, and if we used city-pairs, the number of dominant incumbent markets where Southwest becomes a potential entrant would be smaller. Morrison (2001) estimates that Southwest has substantially smaller effects on fares when it only serves nearby airports, and not the same airport, as either an actual or a potential competitor.

many passengers making connections, as well as local passengers, so that the incumbent's marginal (opportunity) cost of selling a seat to a local passenger will depend on flows of connecting traffic that may be hard for rival carriers, especially ones that are not serving the route themselves, to observe without the incumbent's internal data (Edlin and Farrell (2004), Elzinga and Mills (2005)). We believe that this is one reason why the incumbent's marginal cost should be viewed as private information and we develop this idea more formally in Section 6.[29] In addition, monopoly hub routes are typically viewed as being critical to a carrier's profitability making it plausible that incumbents would be willing to engage in significant short-run price cuts to defend them.[30] While our assumption that Southwest's marginal cost is observed is primarily motivated by the desire to keep the model as tractable as possible, it is consistent with the fact that Southwest uses a homogeneous fleet and operates a network that is much less dependent on hubs.

In our empirical work we will exploit the fact that these dominant incumbent markets are likely to differ in how attractive they are for Southwest to enter. Consistent with GS's logic about pre-announced entry, there are clearly some routes, including to Southwest's focus airports such as Las Vegas or Chicago Midway, that Southwest is almost certain to enter immediately when it enters an airport. At the other extreme there will be markets that are too small for Southwest to likely ever want to enter. In between, there will be some markets that are marginal for Southwest where information about how the incumbent may price in response to entry may affect the decision to enter. Comments from Southwest representatives are consistent with the carrier deciding to enter markets based on its perceptions of how profitable they will be at the time that the entry decision is made.[31]

While we believe that our model is informative about the Southwest Effect, we note several features of airline markets that our model does not capture. For example, carriers sell tickets at many different prices on a single route as part of a revenue management strategy, whereas we model the carrier as setting a single price. We do show empirically, however, that the incumbent lowers prices in a similar way across the fare distribution. Our model also ignores the fact that a potential entrant might be able to infer some information about marginal costs from prices set on other routes, and it also abstracts away from the fact that incumbents might be concerned about potential entrants other than Southwest,

[29]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 one quarter, and our theoretical and simulation 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.

[30]For example, when Southwest entered Philadelphia in 2004, the US Airways CEO David Siegel told employees "Southwest is coming for one reason: they are coming to kill us. They beat us on the West Coast, and they beat us in Baltimore. If they beat us in Philadelphia, they're going to kill us." (Business Travel News, March 25, 2004, "Philadelphia Could be US Airways' Last Stand").

[31]For example, "It's all based on customer demand. We're always evaluating markets to see if they are **overpriced** and underserved" (quote by Southwest spokesperson Brandy King, cited in an article "Southwest to Offer Flights between Sacramento and Orange County, CA" by Clint Swett, Knight Ridder Tribune Business News, 6 Mar 2002) (emphasis added). Also, "Southwest does not have any hard and fast criteria dictating when it enters a market. The method is a cautious, reactive approach designed to take advantage of opportunities as they arrive" (description of March 13, 2008 comments by Brook Sorem, Southwest's manager of Schedule Planning, reported in an World Airport Week article "What Can Airports Do to Attract Southwest Airlines?", March 24, 1998). Herb Kelleher, one of the founders and longtime Chairman and CEO of Southwest, also admitted to having at least six different strategic plans for how Southwest might develop in the Northeast United States, after its initial entry into Providence, R.I. (from Wall Street Journal article by Scott McCartney, "Turbulence Ahead: Competitors Quake as Southwest is Set to Invade the Northeast", October 23, 1996).

as several of these exist for most of the routes that we consider. However, given that Southwest was the largest low-cost carrier during our sample period and it was well known for setting low prices, it is plausible that incumbents would be especially keen to deter its entry.

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).[32]

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 direct passengers on the route in DB1, and we consider it to be a *potential entrant* once it serves at least one route out of each of the endpoint airports.[33]

Based on our potential entrant definition there are 1,542 markets where Southwest becomes a potential entrant after the first quarter of our data and before Q4 2009, a cutoff which is one year before the end of our sample data so that we can look at whether Southwest enters the following year. Southwest enters 337 of these markets during the period of our data. We will call these 1,542 markets our "full sample", but we will focus most of our analysis on a subset of markets where one carrier is a *dominant incumbent* before Southwest enters. As we want to identify sustained dominance in a market, rather than a market share that is only temporarily high, 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[34], and in 80% of those quarters it must account for 80% of direct traffic on the market and at least 50% of total traffic.[35]

[32]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 in the first part of our data, and prior to 2002 regional affiliates, such as Air Wisconsin operating as United Express, were not required to report T100 data. See footnote 41 for some related comments.

[33]While this definition means that we may consider Southwest to have entered a market when its non-stop schedule has only five flights per week, this is a more stringent criterion than the one used by GS and, in practice, there are very few observations near the threshold (the 75^{th} percentile of the number of Southwests flights in a quarter is 1, and the 77^{th} is 181.)

[34]This quarter percentage threshold corresponds to close to the 25^{th} percentile of the proportion of periods that an incumbent is active, and the 50^{th} percentile is 100%.

[35]We apply this definition treating carriers that merge as a single carrier before and after the merger. For example, we define Delta/Northwest as dominant on the Minneapolis-Oklahoma City route as Northwest was dominant before their

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 population (m.)	2.509	1.918	2.834	1.923	3.218	2.112
Round-trip distance (miles)	2,525.11	1352.57	1,257.57	743.08	1,344.5	798.75
Constructed market size measure	33,018	46,459	65,684	68,743	52,387	62,864
Origin or destination is a:						
primary airport	0.186	0.389	0.312	0.496	0.262	0.443
secondary airport	0.316	0.465	0.321	0.469	0.369	0.486
big city	0.643	0.479	0.844	0.364	0.877	0.331
leisure destination	0.108	0.311	0.110	0.314	0.092	0.292
slot controlled airport	0.039	0.192	0.064	0.246	0.108	0.312
Number of markets	1,542		109		65	

We identify 109 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 route is one of the ones that Southwest enters as soon as it serves both endpoints), and in a few of them the dominant incumbent only becomes active once 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 these routes that can identify how the Southwest entry threat changes a dominant incumbent's behavior, although we include all 109 routes in the "dominant incumbent" regressions to more precisely identify the coefficients on the time effects and other controls.[36] The 109 and 65 markets are listed in Appendix C.

Table 1 provides some summary statistics on routes in the different samples. Dominant incumbent markets tend to be shorter with endpoint airports that are more likely to be primary airports in large cities.[37] All of the markets in our dominant firm sample are shorter than the longest routes that Southwest flies non-stop (such as Las Vegas-Providence), so its entry should be feasible.[38] The standard deviations show that both samples are quite heterogeneous with respect to these market characteristics. We also construct a variable measuring market size, which we will use when estimating demand and computing welfare in Section 5 and as an additional variable for predicting the probability that Southwest enters a market. The reason for constructing this measure is that the number of people

merger and Delta was dominant afterwards. The 80% and 50% thresholds are also chosen so that there are few observations close to them. For example, the 75$^{\text{th}}$ percentile for direct traffic share is 1% and the 90$^{\text{th}}$ percentile is 91%.

[36] 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.

[37] We follow Gerardi and Shapiro (2009) in defining the largest 30 MSAs, excluding some tourist destinations, such as Orlando, as "big cities" and in defining a set of cities in Florida, Las Vegas, Charleston, SC and New Orleans as "leisure" destinations'. We define JFK, LaGuardia and Newark in the New York area, Washington National and Chicago O'Hare as slot controlled, 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.

[38] 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.

traveling between two airports varies systematically with the distance between the airports as well as the total number of passengers using the endpoint airports in a way that endpoint MSA populations do not capture.[39] As explained in Appendix D, we construct our market size measure using predicted values from a generalized gravity equation, and to prevent our measure being affected by Southwest becoming a (potential) entrant or the incumbent's response to this, we define our explanatory variables, apart from a time trend, based on the first quarter of 1993, at the start of our sample.

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.

Market-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 statistics are, however, consistent with (i) Southwest's actual entry reducing prices and the incumbent's market share dramatically, so that an incumbent should be willing to make investments to deter or delay entry if it can; and (ii) incumbent's lowering their prices when entry is threatened, consistent with limit pricing being one of these investments.[40]

The last sections of the table show the amount of capacity (measured by seats performed), the total number of passengers carried on the segment, and the load factor (number of passengers carried divided by the number of seats). All numbers are based on data from T100. One explanation for why an incumbent might lower its fares in Phase 2 is that its planes are emptier, perhaps because customers choose to fly to other destination on Southwest, reducing its marginal costs of selling a seat. Contrary to this explanation, we observe an increase in average load factors between Phases 1 and 2 in the delayed entry markets. We report an estimate of the proportion of passengers traveling the route to make connections.[41] For both incumbents and Southwest, the majority of passengers carried on these routes are making connections, a point we will return to in Section 6. We also report a measure of the proportion of local passengers who are carried by the incumbent under a code-sharing arrangement, based on observations after 1998, when we are first able to identify these passengers are ones who have different ticketing and operating carriers in DB1.[42] Goetz and Shapiro (2012) find that

[39]We use a nested logit specification for our demand model. While the nesting parameter can potentially adjust for a mis-specification of market size which is common across markets, it cannot account for mis-specification which varies according to the length of a particular route or across airports in a particular MSA.

[40]The proportional changes in average prices and yields across phases are different because Southwest is more likely to enter shorter markets. We look at both metrics below, although, for brevity, we focus more on yields as per mile metrics are more standard in the industry.

[41]The number of connecting passengers is estimated by taking 10 times the number of passengers traveling the route in DB1 from the total number of passengers reported in T100. These estimates should be interpreted as rough approximations because some regional affiliates do not report T100 numbers throughout the sample; some DB1 non-connecting passengers might travel on a one-stop service with no change of places via another airport and so not be included in T100; and sampling error may give rise to randomness in the DB1 passenger estimates. This limits our ability to perform a detailed analysis of connecting traffic even thought it may play an important role in making it more difficult for potential entrants to judge a carrier's marginal costs.

[42]A code-sharing arrangement allows specific non-operating (marketing) carriers to sell tickets on a flight operated by

Table 2: Summary Statistics: Dominant Incumbent Sample

	Phase 1: $t < t_0$ All markets		Phase 1: $t < t_0$ Delayed entry markets		Phase 2: $t_0 \leq t < t_e$		Phase 3: $t \geq t_e$	
Variable	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.	Mean	Std. Dev.
Incumbent Pricing								
Yield (average fare per mile)	0.516	0.331	0.526	0.340	0.451	0.323	0.311	0.167
Average fare	476.49	135.30	514.08	144.76	426.20	117.80	261.86	60.65
Southwest Pricing								
Yield		-		-	0.293	0.152	0.235	0.072
Average fare		-		-	391.01	118.69	214.46	62.52
Passenger Shares								
Incumbent	0.802	0.201	0.752	0.220	0.841	0.121	0.469	0.202
Southwest		-		-	0.018	0.032	0.479	0.216
Incumbent Capacity and Traffic								
Capacity (seats performed)	75,760	52,459	72,785	49,012	69,606	47,003	90,877	52,314
Segment passengers	46,072	32,141	44,174	29,814	48,343	31,618	64,385	38,585
(incl. connecting passengers)								
Load factor	0.612	0.104	0.618	0.105	0.710	0.121	0.705	0.081
Proportion passengers connecting	0.836	0.113	0.847	0.109	0.830	0.115	0.773	0.106
Code-share measure	0.074	0.176	0.107	0.215	0.248	0.326	0.192	0.264
Southwest Capacity and Traffic								
Capacity (seats performed)		-		-		-	80,751	62,207
Segment passengers		-		-		-	52,713	39,195
(incl. connecting passengers)								
Load factor		-		-		-	0.651	0.083
Proportion passengers connecting		-		-		-	0.701	0.100
Code-share measure		-		-		-	0.015	0.078
Number of markets	109		65		65		59	

incumbents are more likely to code-share with other carriers when Southwest threatens entry, and we also see code-sharing increasing in Phases 2 and 3 in our data.

4 Evidence of Limit Pricing in the Dominant Incumbent Sample

This section presents reduced-form evidence that a limit pricing model can explain why incumbents cut prices when Southwest becomes a potential entrant. To do so, we extend the analysis of GS by trying to discriminate between alternative explanations, focusing on dominant incumbent markets that best fit the assumed market structure in almost all models of strategic investment.

4.1 Price Changes When Southwest Becomes a Potential Entrant

We start by confirming that the price reductions identified by GS, who used all markets where Southwest became a potential entrant, are also present in our dominant incumbent sub-sample. The regression specification is

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

where $\gamma_{j,m}$ are market-carrier fixed effects and τ_t are quarter fixed effects. Only observations for the dominant incumbent are included in the regression, but the control variables X include the number of other carriers serving the market (separate counts for direct and connecting service) as well as interactions between the jet fuel price[43] 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 for 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 the market 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 ticket price and the

another carrier, and the flight itself will usually be given a flight number for each of the code-sharing carriers. Continental and Northwest, and United and US Airways engaged in fairly extensive code-sharing in some quarters during our data. Of course, carriers that are not code-sharing may still sell a ticket on another carrier's flight as part of an 'interlining' agreement. Therefore the fact that a proportion is not equal to zero is not indicative that a full code-sharing agreement was in place. However, we observe much higher proportions for carrier combinations with known code-sharing agreements.

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

yield as alternative price measures. Average prices fall by 10-14% when Southwest becomes a potential entrant. 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 these estimates is that prices appear to fall more the longer a market is in Phase 2, i.e., if Southwest does not actually enter. For example, the t_0+ 6-12 and t_0+ 13+ coefficients are significantly larger in absolute value than the other t_0 coefficients. We discuss the ability of our model to explain this pattern, and extensions that can also generate this finding, in Section 6. Another feature, also found in GS, is that prices start declining two quarters *before* Southwest becomes a potential entrant. While in some settings one would be concerned that a pre-treatment change might reflect some other development that might cause both prices to fall and Southwest to become a potential entrant, in our setting, this pattern is consistent with our model once one takes into account that Southwest typically announces its entry into airports several months before it actually starts to operate flights.[44] As Southwest will be making decisions about how to build out its network as soon as it has decided to enter an airport, we would expect incumbents to start making strategic investments, including setting limit prices, as soon as they know that airport entry will occur.

4.2 Non-Monotonic Relationship Between Probability of Entry and Price Changes

We now show that Phase 2 price declines are likely driven by the dominant incumbent trying to deter entry. Our approach, which follows the same logic as EE, looks at whether there is non-monotonic relationship between an exogenous proxy for the probability that Southwest will enter a market once it becomes a potential entrant and the magnitude of the Phase 2 price decline. The intuition for this approach is that incumbents, faced by a potential entrant, are unlikely to invest much in entry deterrence investments in markets where entry is either very unlikely or almost certain, but they may have strong incentives to invest in markets where the probability of entry is somewhere in between. We illustrated this property for our dynamic limit pricing model in Section 2. In contrast, costly investment motivated by entry accommodation (i.e., a desire to make post-entry competition more profitable for the incumbent) should be greatest in markets where entry is most likely. We use a two-stage empirical strategy to test for the implied non-monontonicity of price changes, as evidence of entry deterring investment. In the first stage, a simple model of the entry probability based on observable, exogenous market-level variables is estimated to construct a single index of the attractiveness of the market to the potential entrant. Critically, this provides us with a variation in the probability of entry that should not

[44]For example, Southwest announced its entry into Philadelphia on October 28, 2003, and began operations on May 9, 2004. It announced entry into Boston on February 19, 2009 and began operations on August 16, 2009. We were able to identify the exact dates when Southwest publicly announced and began service for 24 of the airports in our dominant firm sample that Southwest entered after 1993, using data from http://swamedia.com/channels/By-Category/pages/openings-closings and newspaper reports. The average gap is 140 days, and it is obviously possible that incumbent carriers will get some inside information about Southwest's arrival before its public announcements.

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

		Phase 1		*Phase 2*		*Phase 3*
<u>Fare</u>						
	$t_0 - 8$	-0.046	t_0	-0.089^{***}	t_e	-0.438^{***}
		(0.028)		(0.029)		(0.064)
	$t_0 - 7$	-0.022	$t_0 + 1$	-0.117^{***}	$t_e + 1$	-0.549^{***}
		(0.027)		(0.035)		(0.070)
	$t_0 - 6$	-0.048	$t_0 + 2$	-0.127^{***}	$t_e + 2$	-0.554^{***}
		(0.030)		(0.033)		(0.076)
	$t_0 - 5$	-0.050	$t_0 + 3$	-0.126^{***}	$t_e + 3$	-0.602^{***}
		(0.032)		(0.032)		(0.079)
	$t_0 - 4$	-0.021	$t_0 + 4$	-0.142^{***}	$t_e + 4$	-0.618^{***}
		(0.031)		(0.033)		(0.082)
	$t_0 - 3$	-0.015	$t_0 + 5$	-0.139^{***}	$t_e + 5$	-0.610^{***}
		(0.027)		(0.040)		(0.080)
	$t_0 - 2$	-0.059^{**}	$t_0 +$ 6-12	-0.201^{***}	$t_e +$ 6-12	-0.583^{***}
		(0.026)		(0.050)		(0.080)
	$t_0 - 1$	-0.065^{***}	$t_0 + 13+$	-0.308^{***}	$t_e + 13+$	-0.580^{***}
		(0.024)		(0.052)		(0.084)
<u>Yield</u>						
	$t_0 - 8$	-0.025^{*}	t_0	-0.045^{***}	t_e	-0.250^{***}
		(0.015)		(0.017)		(0.050)
	$t_0 - 7$	-0.007	$t_0 + 1$	-0.046^{**}	$t_e + 1$	-0.294^{***}
		(0.015)		(0.022)		(0.053)
	$t_0 - 6$	-0.022	$t_0 + 2$	-0.056^{***}	$t_e + 2$	-0.295^{***}
		(0.016)		(0.020)		(0.057)
	$t_0 - 5$	-0.014	$t_0 + 3$	-0.056^{***}	$t_e + 3$	-0.312^{***}
		(0.017)		(0.019)		(0.058)
	$t_0 - 4$	-0.013	$t_0 + 4$	-0.069^{***}	$t_e + 4$	-0.323^{***}
		(0.016)		(0.021)		(0.060)
	$t_0 - 3$	-0.009	$t_0 + 5$	-0.067^{***}	$t_e + 5$	-0.330^{***}
		(0.015)		(0.024)		(0.059)
	$t_0 - 2$	-0.035^{**}	$t_0 +$ 6-12	-0.111^{***}	$t_e +$ 6-12	-0.325^{***}
		(0.016)		(0.029)		(0.059)
	$t_0 - 1$	-0.036^{**}	$t_0 + 13+$	-0.178^{***}	$t_e + 13+$	-0.348^{***}
		(0.015)		(0.034)		(0.066)

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 statistical significance at the 1, 5 and 10% levels respectively. Number of observations is 4,159 and the adjusted R^2s are 0.78 ("Fare") and 0.85 ("Yield"). Phases are defined in the text.

depend on the prices set by the incumbent. In the second stage, the monotonicity of the relationship between this index and the incumbent's investment (or changes in the incumbent's investment when entry is threatened) is examined.

For our first stage, we estimate a probit model of Southwest's entry using the full sample of markets. An observation is a route and the dependent variable is equal to one if Southwest entered within four quarters of becoming a potential entrant, where we are implicitly assuming that Southwest will typically choose to enter the most attractive markets from an airport first.[45] In our model the probability of entry once Southwest is a potential entrant will depend on the incumbent's cost and potentially other factors that the incumbent can control that may be regarded as possibly being functions of the incumbent's pricing behavior. However, for our analysis here we only want to identify only exogenous variation in the probability of entry. Therefore, the explanatory variables that we include are either obviously exogenous route characteristics (such as distance, endpoint city populations and whether an airport is slot-constrained) or, in the case of variables that measure functions of passenger flows (e.g., airport presence or market concentration), they are calculated based on observations more than four periods *before* Southwest became a potential entrant.[46] Further details of the variables included and the estimated coefficients are given in Appendix E.

Consistent with previous research (Boguslaski, Ito, and Lee (2004)), our model can explain a reasonable degree of variation (pseudo-R^2 0.40) in Southwest's entry decisions in the full sample, with Southwest more likely to enter shorter, larger and more concentrated markets, as intuition would predict. For the subset of 65 markets where we can identify price effects, the predicted within-four-quarter entry probabilities vary from $3\text{x}10^{-5}$ to 0.99, with the 20^{th}, 40^{th} and 60^{th} and 80^{th} percentiles at 0.03, 0.17, 0.39 and 0.64.

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

$$\begin{aligned}\text{Price Measure}_{j,m,t} &= \gamma_{j,m} + \tau_t + \alpha X_{j,m,t} + \ldots \\ &\beta_0 SWPE_{m,t} + \beta_1 \widehat{\rho_m} \times SWPE_{m,t} + \beta_2 \widehat{\rho_m}^2 \times SWPE_{m,t} + \epsilon_{j,m,t} \qquad (7)\end{aligned}$$

where $\widehat{\rho_m}$ is the predicted one year probability of entry 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 probit estimates $\widehat{\rho_m}$, as well as heteroskedasticity and first-order serial correlation in the

[45] We measure entry over a short fixed interval so that we do not need to account for the fact that we observe markets that are exposed to the possibility of entry for different numbers of periods. In the data, Southwest enters close to 70% of the routes that it enters during our sample within one year of becoming a potential entrant, and 7% and 5% of routes over the next two years. See Sections 5 and 6 for more discussion of the hazard rate of entry and how this affects limit pricing incentives.

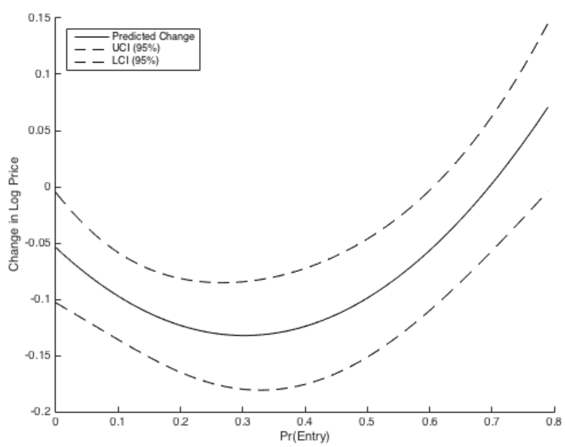
[46] If we do not have four periods before Southwest becomes a potential entrant, we use the average over the Phase 1 periods that we do have in the data.

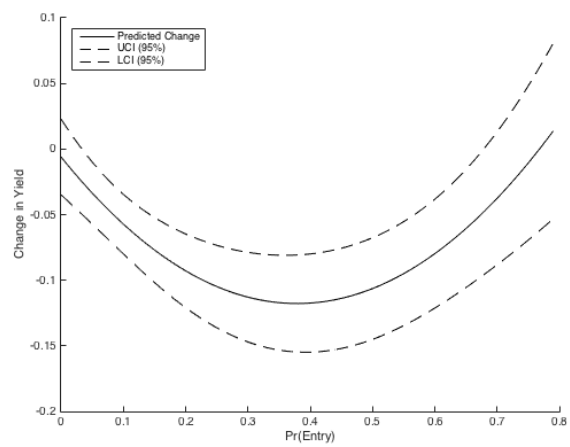
residuals.[47] If the incumbent is using a limit pricing strategy, or some other deterrence strategy that causes prices to fall, then we would expect $\widehat{\beta_0} \approx 0$, $\widehat{\beta_1} < 0$ and $\widehat{\beta_2} > 0$. On the other hand, an entry accommodation explanation for falling prices 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.

Given our identification strategy, one might be concerned that there is some other factor, possibly unobserved, that varies non-monotonically with the entry probability and could also affect price changes (factors that just affect price levels should be dealt with by the fixed effects). We partially address this issue in Appendix F where we use a "balance table" to examine how observed variables, including some variables that are not included in our first-stage probit, vary with the probability of entry by splitting the dominant incumbent markets into three terciles based on $\widehat{\rho_m}$. Average values for the intermediate probability markets lie between those for the low and high probability markets for most variables, and for the remaining variables the differences between the groups are not statistically significant.

Figure 2 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) price measures. The coefficients for yield are reported in column (1) of Table 4. Consistent with a deterrence explanation, but not an accommodation explanation, on average, price changes are U-shaped with the large and statistically significant price declines for intermediate probabilities of Southwest entry, and smaller and less significant effects for high or low probabilities.

Figure 2: Predicted Incumbent Price and Yield Changes in Phase 2 as a Function of Southwest's Predicted Probability of Entry.

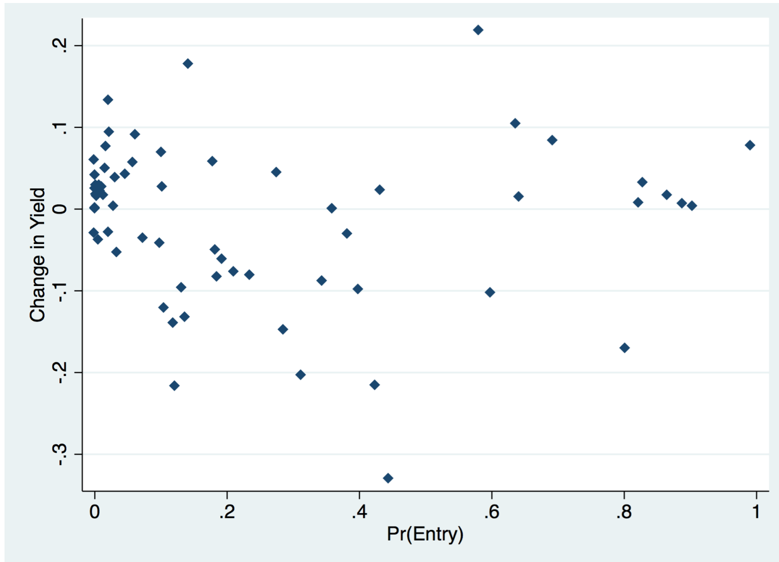




Our use of a quadratic specification is a simple way to test for non-monotonicity given that we have a relatively small sample of markets from which to identify the price effects. In order to show that this choice of specification is not driving a misleading result, Figure 3 plots the estimated change in yield

[47] To do this, we specify the derivatives of the first-stage log-likelihood as an additional set of moment conditions and adapt the methodology used 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.

Figure 3: Estimated Phase 2 Price Changes Market-by-Market as a Function of Southwest's Predicted Probability of Entry



for each of the dominant incumbent markets separately against the estimated entry probability (the figure using log of the average fare looks very similar).[48] These market-specific effects are estimated by replacing the three $SWPE_{m,t}$ terms in specification (7) with $SWPE_{m,t}\times$market m dummy interactions, with the plotted points being the point estimates of the coefficients on these interactions. While there is heterogeneity in how prices change for a given predicted entry probability, which could reflect either different cost realizations for incumbents and/or the fact that we are using only an imperfect proxy for Southwest's entry probability, we see that prices do not typically decrease in markets with high or very low entry probabilities, while prices decline in most of the markets in between.

The rest of Table 4 presents the coefficient estimates for yield regressions when we make a number of changes to investigate the robustness and the interpretation of the results in column (1). In columns (2) and (3) we try to address any remaining concerns about the possible endogeneity of the variables included in the probit by, respectively, excluding those variables (HHI and the presence related variables) that are based on passenger flows in periods that lead up to Southwest becoming a potential entrant and excluding the dominant incumbent markets from the sample used to estimate the first-stage probit. These changes actually increase the significance of the U-shaped price decline.

In column (4) we add a set of interactions between the Phase 2 dummy variable and airport-specific fixed effects in the second-stage specification, so that the quadratic is identified from variation in entry probabilities across routes at given airports.[49] The estimated quadratic coefficients are also larger in this case. In lower specification (5) we test whether there is a detectable non-monotonicity between price changes and the entry probability towards the end of Phase 1, on the grounds that if there is

[48]One market with a yield change of -0.6 and an entry probability of 0.12 is excluded from the figure to preserve a reasonable spread of the observations on the diagram.

[49]For example, a dummy for Las Vegas in Phase 2 that is equal to 1 for any route during Phase 2 which has Las Vegas as an endpoint, so that there will be two airport dummies equal to one for each Phase 2 observation.

Table 4: Ellison and Ellison Reduced-Form Analysis: Second-Stage Estimates for Incumbent Yield

	(1) Baseline	(2) Exclude Pass. Flow Vars. from 1st Stage	(3) Excl. Dom. Inc. Mkts. from 1st Stage	(4) Incl. Phase 2 ×Airport Fixed Effects
$SWPE_{mt}$	-0.0060	0.0040	0.0023	-
	(0.015)	(0.014)	(0.014)	
$\widehat{\rho_m} \times SWPE_{mt}$	-0.589***	-0.685***	-0.747***	-1.000**
	(0.122)	(0.146)	(0.145)	(0.478)
$\widehat{\rho_m}^2 \times SWPE_{mt}$	0.778***	0.929***	1.060***	1.056**
	(0.164)	(0.201)	(0.222)	(0.479)

	(5) Allow for Quadratic for $t_0 - 8$ to $t_0 - 2$		(6) Allow for Separate Effects with Phase 2 Duration		(7) Control for Conv. of WN Connections
	Phase 1 Effect	Phase 2 Effect	First 12 Qtrs	After 12 Qtrs.	
Constant	-0.0333***	-0.0174	-0.0187	0.0046	0.0075
	(0.015)	(0.016)	(0.014)	(0.018)	(0.014)
$\widehat{\rho_m} \times ...$	0.0186	-0.599***	-0.328***	-1.084***	-0.337***
	(0.119)	(0.130)	(0.120)	(0.163)	(0.137)
$\widehat{\rho_m}^2 \times ...$	0.0755	0.819***	0.450***	1.505***	0.535***
	(0.152)	(0.177)	(0.160)	(0.245)	(0.163)

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. All specifications include route fixed effects and the additional controls listed in Table 3, and specification (7) has controls for the convenience of connecting on Southwest. In specification (5) the constant, $\widehat{\rho_m}$ and $\widehat{\rho_m^2}$ are interacted with a dummy variable for Phase 1 and a dummy variable for Phase 2. In specification (6) they are interacted with dummies for the first 12 quarters of Phase 2 and later quarters. In specification (7) they are interacted with dummies for Phase 2, as in the first four specifications. ***, ** and * denote statistical significance at the 1, 5 and 10% levels respectively. All specifications are estimated using 3,867 incumbent-market-quarter observations.

a non-monotonic relationship then we might think that something else is causing prices to change in intermediate probability markets that happens to occur at around the same time that Southwest becomes a potential entrant (for example, some airports may make changes that lower all carriers' costs and which also encourage Southwest to enter). As we think that Southwest's arrival has some effect on prices before it begins operations we look at the $t_0 - 8$ to $t_0 - 2$ quarters, and allow for a separate quadratic effect. We find no evidence of a non-monotonic relationship in Phase 1, while the Phase 2 relationship remains very close to the baseline.

As mentioned above, the magnitude of the Phase 2 price decline seems to increase over time. In lower specification (6) we therefore test whether the non-monotonicity is a feature of the data both in the first three years after Southwest becomes a potential entrant and in later quarters. The quadratic coefficients are economically and statistically significant for both sets of time periods.[50]

One possible non-strategic explanation for Phase 2 price declines is that once Southwest serves both endpoints, it is able to provide *actual* competition, because it can provide connecting service that is a

[50]For example, if $\rho = 0.4$ then the expected yield decrease will be 0.08 for the first 12 quarters and 0.2 for subsequent quarters, compared with an average Phase 1 yield of 0.53 for these markets.

partial substitute for the incumbent's direct service.[51] Several pieces of evidence suggest that this does not explain our results.

First, as seen in Phase 2, on average Southwest captures a very small share (less than 2%) of traffic in Phase 2, compared with either the Phase 2 market share of the incumbent (over 80%) or Southwest's post-entry Phase 3 share, and Southwest's average Phase 2 fares are quite high ($391 compared to $426 for the incumbent). It seems unlikely that the incumbent's optimal, static Phase 2 price would change so much in response to this small competitive presence, given that other carriers were already able to provide connecting service on our routes. As reported in Appendix F, the share of traffic that Southwest achieves during Phase 2 is not particularly high in markets with intermediate entry probabilities: in fact, Southwest's Phase 2 share tends to be highest in markets with the smallest entry probabilities.

Second, the fact that the incumbent's prices start to decline two quarters before Southwest actually starts being active at both endpoints, which is consistent with a strategic investment story, is not consistent with prices falling due to actual competition, at least if we assume that consumers do not substitute intemporally (e.g., delaying travel in anticipation that Southwest's reasonably high connecting fares will soon be available).

Third, connecting service on Southwest is likely to be most attractive for price sensitive, leisure travelers. Assuming that these customers will also tend to buy the cheapest fares on the incumbent (for example, because they buy restricted tickets far in advance of departure), one would expect actual competition to drive the largest price reductions on these low priced fares. As shown in Appendix G, prices decline significantly for the 25^{th}, the 50^{th} and the 75^{th} percentiles of the price distribution, and for each of them we observe a statistically and economically U-shaped price decline with respect to the estimated probability of entry. While it seems unlikely that limited low-end actual competition would produce this result, it is consistent with a limit pricing story.[52]

Fourth, we can provide additional evidence by directly controlling for the convenience of connecting service on Southwest. To do so, we augment the baseline specification, in lower specification (7) of Table 4, by including interactions between the Phase 2 dummy and additional dummies that split our dominant incumbent markets into quintiles based on the proportional increase in the distance that a traveler would have to fly (relative to the nonstop distance) if she made a connection via the most convenient Southwest focus airport (Baltimore, Chicago Midway, Las Vegas or Phoenix). While this change does reduce the magnitude of the quadratic coefficients they remain significant and, counter-intuitively, the coefficients on the new variables indicate that yields fall most on routes where connections on Southwest are least convenient.

[51] The limited literature on connecting service (in general, not specifically focused on Southwest) indicates that it provides only a partial constraint on the market power of a carrier that provides direct service (Reiss and Spiller (1989), Dunn (2008)).

[52] For example, Pires and Jorge (2012) consider a model where an incumbent has a common marginal cost across several markets and only one market is threatened by entry. They show that in a limit price, signaling equilibrium, the incumbent lowers prices in all markets.

4.3 Evidence that Alternative Deterrence Strategies Do Not Explain Non-Monotonic Price Declines

These results strongly suggest that the Phase 2 price declines reflect attempts by incumbents to deter entry. However, other models of entry deterring strategic investments, that do not involve signaling, could also predict non-monotonic price declines in Phase 2, so we now evaluate whether there is clear evidence that one or more of these alternative models can explain the pattern identified in the previous sub-section. While we do not find strong evidence in favor of alternative theories explaining the non-monotonicity we should note that we do not interpret this to mean that incumbent may not be using other strategies, in addition to limit pricing, to either deter entry or to affect post-entry competition in their favor.

The first explanation that we consider is that incumbents might add capacity, as suggested by Snider (2009) and Williams (2012) in the context of alleged predation on small low-cost carriers by hub carriers. Increased capacity investment might commit an incumbent to more aggressive pricing in response to Southwest's entry, and therefore make entry less attractive, as suggested by Dixit (1980), but it would also tend to reduce the incumbent's optimal monopoly price in Phase 2 by reducing the opportunity cost of selling seats by causing the incumbent's load factor to fall.[53] We investigate whether capacity is increasing in the intermediate probability markets, by using the log of the incumbent's capacity on the route (measured by T100 'seats performed') as the dependent variable in specification (7). As seen in column (1) of Table 5 and the top-left panel of Figure 4, the incumbent's capacity does not, on average, significantly increase when Southwest becomes a potential entrant for any entry probability. In addition, traffic and load factors tend to increase in intermediate probability of entry markets, so that the (static) opportunity cost of selling seats should not be falling (columns (2) and (3) of Table 5 and the top-right and bottom-left panels of Figure 4). Traffic and load factors only fall in high probability of entry markets where we do not observe significant price decreases.

Another explanation for falling Phase 2 prices in intermediate probability of entry markets is that incumbents use lower prices, not to signal to Southwest, but to build the loyalty of their customers, possibly by encouraging them to accumulate points in a frequent-flyer program (FFP). This strategy could either be used to try to deter entry, by reducing Southwest's post-entry demand, or, in expectation of entry, to try to increase the incumbent's post-entry demand. The data appear inconsistent with an accommodation explanation because prices do not fall in markets where Southwest's entry is most certain. We think that attempts to build loyalty are unlikely to be the primary explanation for the observed price because the types of travelers who are most likely to be benefit from increased frequent-flyer points are business travelers, but we do not observe that prices drop only for the expensive fares (likely purchased close to departure) that these travelers are likely to buy. More targeted rewards, such as extra miles on certain routes, would likely be more effective at generating loyalty than a broad price reduction. The literature on frequent-flyer programs (Uncles, Dowling, and Hammond (2003)) has also found that business travelers often switch between programs on different carriers suggesting that their

[53] One could also imagine that Southwest's presence at the endpoint airports would reduce the number of people using the incumbent carrier's flights to make connections, reducing its marginal costs for non-strategic reasons.

Table 5: Ellison and Ellison Reduced-Form Analysis: Second-Stage Estimates with Non-Price Dependent Variables

Dependent Variable	(1) Log Capacity	(2) Log Passengers	(3) Log Load Factor	(4) Proportion Code-share
$SWPE_{m,t}$	0.056	0.129***	0.074***	0.0003
	(0.044)	(0.046)	(0.053)	(0.0024)
$\widehat{\rho_m} * SWPE_{m,t}$	0.178	0.704**	0.526***	0.056**
	(0.316)	(0351)	(0.112)	(0.029)
$\widehat{\rho_m}^2 * SWPE_{m,t}$	-0.788	-1.826***	-1.038***	-0.024
	(0.476)	(0.558)	(0.312)	(0.046)
Observations	3,393	3,393	3,393	2,406

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. The number of observations reflect differences in the coverage and reporting in the DB1 and T100 data during our sample period. ***, ** and * denote statistical significance at the 1, 5 and 10% levels respectively.

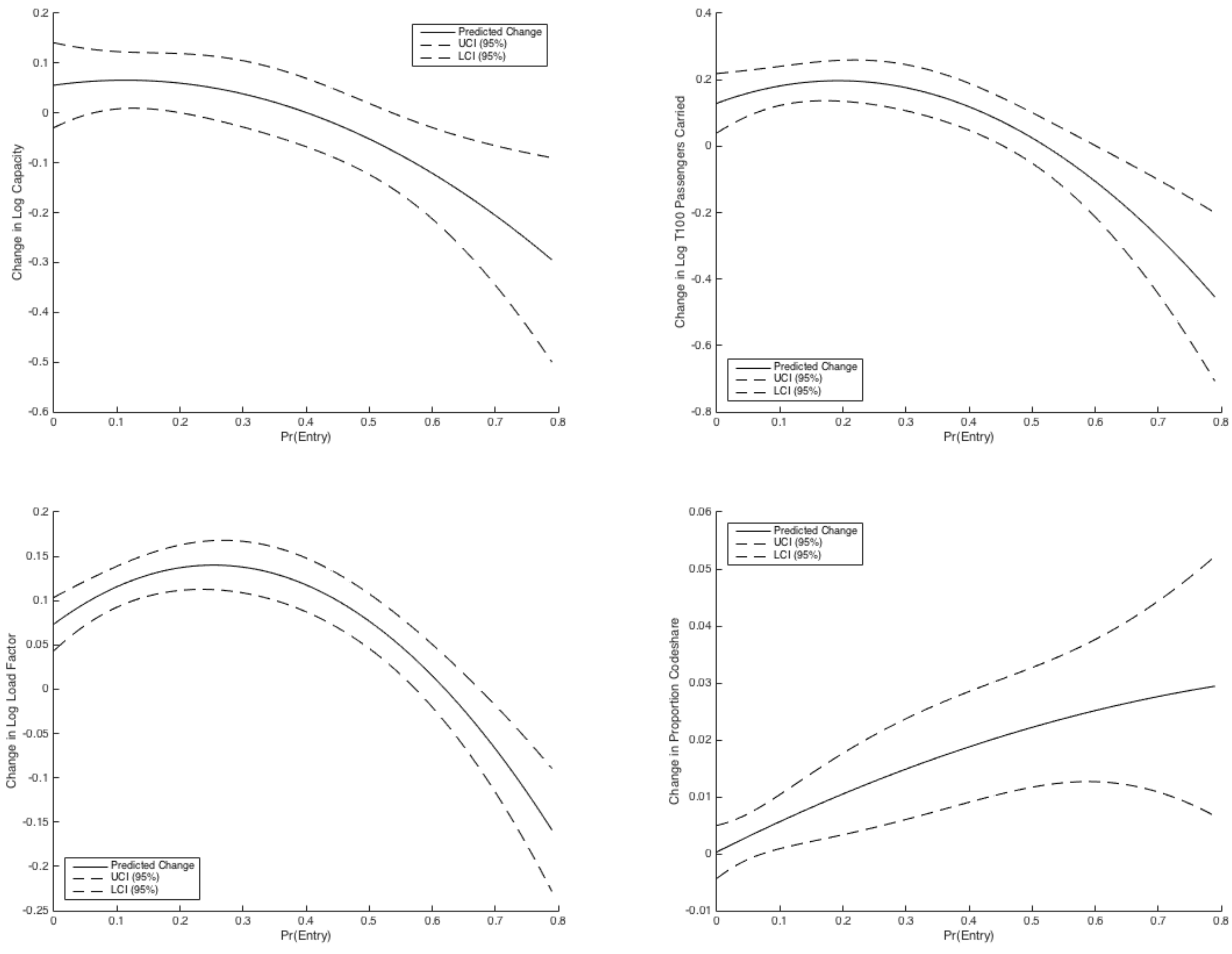
future loyalty would be far from guaranteed even if lower prics could induce them to fly more before Southwest enters. Appendix H also presents an analysis of whether lower incumbent prices appear to increase its future demand, and we do not find any evidence in favor of this hypothesis, although we also acknowledge some of the limitations of our analysis, such as the fact that it is using aggregate data with no information on how many frequent-flyers travel on different routes. That said, we would not rule out the possibility that the desire to build customer loyalty plays some minor role in explaining why carriers cut prices.

Finally, as noted in Section 3.2, we observe that incumbents increase how many passengers they carry under code-sharing arrangements when faced by possible and actual entry. Establishing code-sharing relationships might be a way for an incumbent to increase its own demand and reduce Southwest's demand if Southwest enters. In order to investigate what motivates code-sharing, we use the proportion of passengers carried under code-share arrangements as the dependent variable in column (4) of Table 5. The estimates (see the bottom-right panel of Figure 4) indicate that the proportion of code-shared passengers increases monotonically with entry for the range of probabilities observed in the data, suggesting that code-sharing might be an accommodating strategy that incumbents adopt when entry is very likely.

5 Calibration

While the reduced-form evidence is consistent with our model, it is natural to ask if our model predicts significant price declines when Southwest becomes a potential entrant if we use parameters that are consistent with demand, pricing and entry decisions in our markets. We now calibrate our model, without targeting any moments that reflect Phase 2 price declines, to show that this is the case. We use

Figure 4: 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).



the calibrated model to quantify the welfare effects of potential competition and of subsidies that might be offered to encourage Southwest to enter. We use the infinite horizon version of our model primarily for computational tractability.

5.1 Parameter Estimation

We proceed in two stages. In the first stage we estimate demand and marginal cost parameters using data from our dominant incumbent markets during Phases 1 and 3 (i.e., when we do not expect limit pricing to be taking place). In the second stage we estimate the entry cost parameters for Southwest by matching a panel of entry probabilities during Phase 2. We briefly outline the procedure here, with full details given in Appendix I.

5.1.1 Demand and Marginal Cost Parameters

We model the demand of passengers to fly the route using a one-level nested logit, differentiated products structure, where the nests are simply 'fly' and 'do not fly'. Flights on carriers other than the dominant incumbent and Southwest are included with not flying at all in the outside good, although we allow the number of other nonstop carriers to affect the mean utility of the outside good. Demand is estimated using data from Phase 1 (before Southwest is a potential entrant) and Phase 3 (after Southwest has entered, if it enters the route). The parameters indicate that Southwest and the incumbent are fairly close substitutes (in Phase 3 the average own price elasticity for the incumbent is 3.14), although incumbents have slightly higher quality.

We use the estimated demand system and the first-order conditions associated with static, complete information profit-maximization for quarters in Phases 1 and 3 to infer the carriers' marginal costs in each quarter. We estimate an AR(1) process for how marginal costs per mile evolve

$$mc_{j,t} = \rho^{AR} mc_{j,t-1} + (1-\rho^{AR}) \frac{\underline{c_j} + \overline{c_j}}{2} + \varepsilon_{j,t} \tag{8}$$

The estimated AR(1) coefficient is around 0.97. We choose the standard deviation of the innovations, which are assumed to be normally distributed, to match the interquartile range of the innovations in the data.

Before estimating entry costs, we make some adjustments to the estimated demand and marginal cost model. First, we homogenize across markets by setting the non-price component of carrier qualities and the range of marginal costs to be the same in all of the markets in our data. We explain below how we adjust market sizes to account for how factors such as distance affect Southwest's entry.

Second, we set the qualities of both carriers and the marginal costs of Southwest to be fixed over time. While we can allow these variables to vary over time in our model if they are publicly observed, this increases the computational burden without yielding any significant insights. The marginal cost of Southwest is set at \$167, and we allow the marginal cost of the incumbent to vary between \$242 and \$282. Given that the standard deviation of the marginal cost innovations is equal to \$36, this implies that the incumbent's marginal costs can move rapidly from being low to high, or vice-versa, on their support, which means that incentives to engage in limit pricing are not necessarily large. Our demand and marginal cost parameters imply that the incumbent's prices should fall by just over 40%, relative to static monopoly prices, if Southwest enters, which is only slightly smaller than the decline observed in the data.

5.1.2 Entry Parameters

We calibrate the distribution of entry costs by matching a panel of entry probabilities predicted by our model to hazard rates of entry estimated from the data. To construct the hazard rates, we estimate a Weibull hazard model for Southwest's entry decision as a function of the variables included in our EE first-stage probit model using our full sample of data. The Weibull hazard structure allows us to capture the fact that hazard rates of entry (i.e., the probability that Southwest enters in quarter q conditional on not entering previously) fall with the time elapsed since Southwest became a potential entrant. The explanatory variables are defined based on data before Southwest became a potential entrant to deal with endogeneity concerns. We use the estimated coefficients on the market-level variables to create a new, "rescaled" market size measure, which accounts for the fact that many factors, such as distance, market concentration and whether the route serves a leisure destination, have significant effects on the probability of entry beyond the effect of our market size variable.[54] Appendix I contains examples of this transformation.

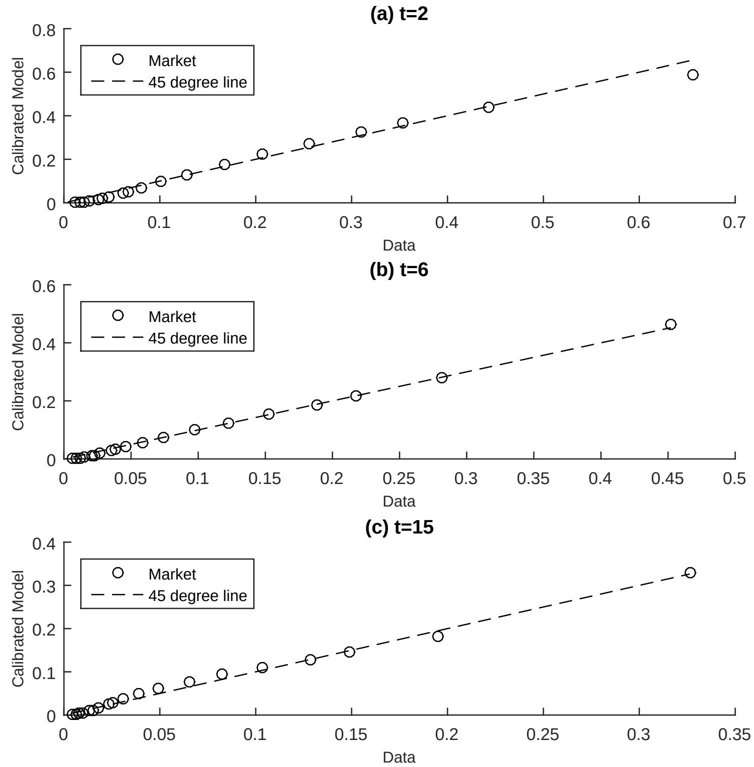
We match the hazard rates of entry with predicted values from an augmented version of the model presented in Section 2 (the changes are described in the next paragraph) using a nested fixed point procedure where we minimize the sum of squared differences between the quarter-by-quarter Weibull-estimated hazard rates for every fifth dominant incumbent market (when they are ordered by rescaled market size) and those implied by the model for given parameters, and an assumed discount factor of 0.98. This procedure is computationally feasible because the equivalence of equilibrium entry decisions under asymmetric and complete information allows us to solve for entry strategies without solving for limit pricing strategies at each iteration.

The model is augmented by allowing the mean of the entry cost distribution to increase over time and for the initial mean to vary with our rescaled market size measure. These changes are necessary to be able to fit the entry probabilities in the data, and it is sensible as we interpret our estimated entry cost to include the value of expected future fixed costs which, in our model, Southwest is committing to pay when it enters.[55] Fixed costs are likely to include a share of Southwest's capacity costs and these are likely to rise with the size of the market. The estimated relationship between mean entry costs and market size is approximately linear in the range of market sizes in our data, with an initial mean for the smallest market in our data of approximately \$2.75 million. The calibrated standard deviation of entry costs, which is assumed to be the same across markets and over time, is just under \$200,000. Allowing

[54]The estimated effect of factors such as distance in the hazard model will reflect the impact of distance on demand and marginal costs, and we would be double counting these effects if we both adjusted market size and allowed for distance to affect demand and marginal costs. This explains why we homogenize demand and marginal costs before calibrating the entry cost parameters.

[55]Without this flexibility we are unable to match the entry probabilities for small and large markets, and how they change over time, simultaneously.

Figure 5: Match of Empirical Entry Probabilities and the Probabilities Predicted by the Calibrated Model for the 21 Markets Used in the Calibration



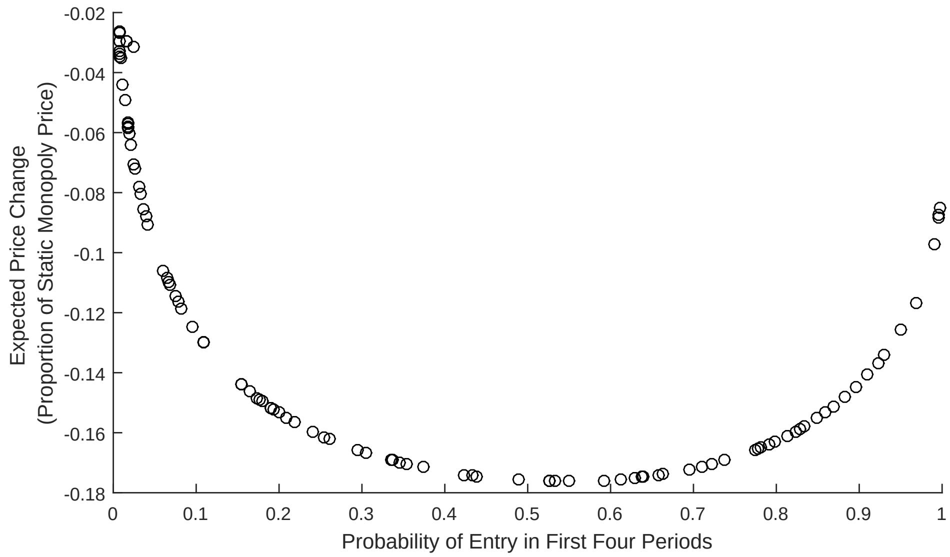
for entry costs to increase over time is consistent with the fact that airports often provide generous financial incentives, such as reduced landing fees and subsidized marketing, to airlines to expand their route network when they first enter an airport. It could also be consistent with Southwest's managers having limited attention and being most aware of opportunities for expansion when they are initially developing service at an airport. In practice, we only need small increases in entry costs (of less than 1% over six years for most markets) to explain the data.

Figure 5 shows the match between the hazard rates of entry in the data and in those in the model for the second, sixth and fifteenth quarters after Southwest becomes a potential entrant. The fit is very good across the distribution of market sizes.

5.2 Predicted Limit Pricing

Given the calibrated parameters, we solve for equilibrium limit pricing strategies in every period using the method described in Appendix B. Figure 6 shows the relationship between the probability that Southwest enters in the first four quarters that it is a potential entrant and the expected change in the incumbent's price, relative to the static monopoly price, in these same quarters before entry happens. This is comparable to the reduced-form relationship identified in Figure 2. The pattern is clearly U-shaped with large predicted price declines of up to 17% in intermediate probability of entry markets. Given that we did not use any information on Phase 2 pricing in calibrating the model, the fact we are able to replicate the qualitative and quantitative pattern in the data is significant evidence in favor of

Figure 6: Probability of Southwest Entry in First Four Quarters and Predicted Price Changes in the Calibrated Model for All Dominant Incumbent Markets



the ability of the model to plausibly explain why incumbents cut prices.

We use the model to perform two more substantive calculations. The first one provides estimates of the welfare effects of limit pricing in our dominant incumbent markets by comparing outcomes with asymmetric information and complete information about the incumbent's marginal costs. The results are shown in Table 6 for three example markets and when we add all of the dominant incumbent markets together.[56]

Starting with the Hartford-Minneapolis market, which is a relatively unattractive market for Southwest, our model predicts that the threat of entry by Southwest would have reduced the incumbent's prices by around \$23 (or 4.4%) because the probability that Southwest will enter is low. However, using a quarterly discount factor of 0.98, this price change still implies substantial consumer benefits of threatened Southwest entry. We calculate that consumers who would have traveled if the incumbent set the static monopoly price save \$4.89 million dollars (in present discounted value terms, 2009 dollars) because of reduced prices while the incumbent remains a monopolist.[57] As the lower fares also cause some additional consumers to travel, the increase in consumer surplus is slightly larger. Of course, lower prices reduce the incumbent's profits but this effect is much smaller, because a small decrease in the

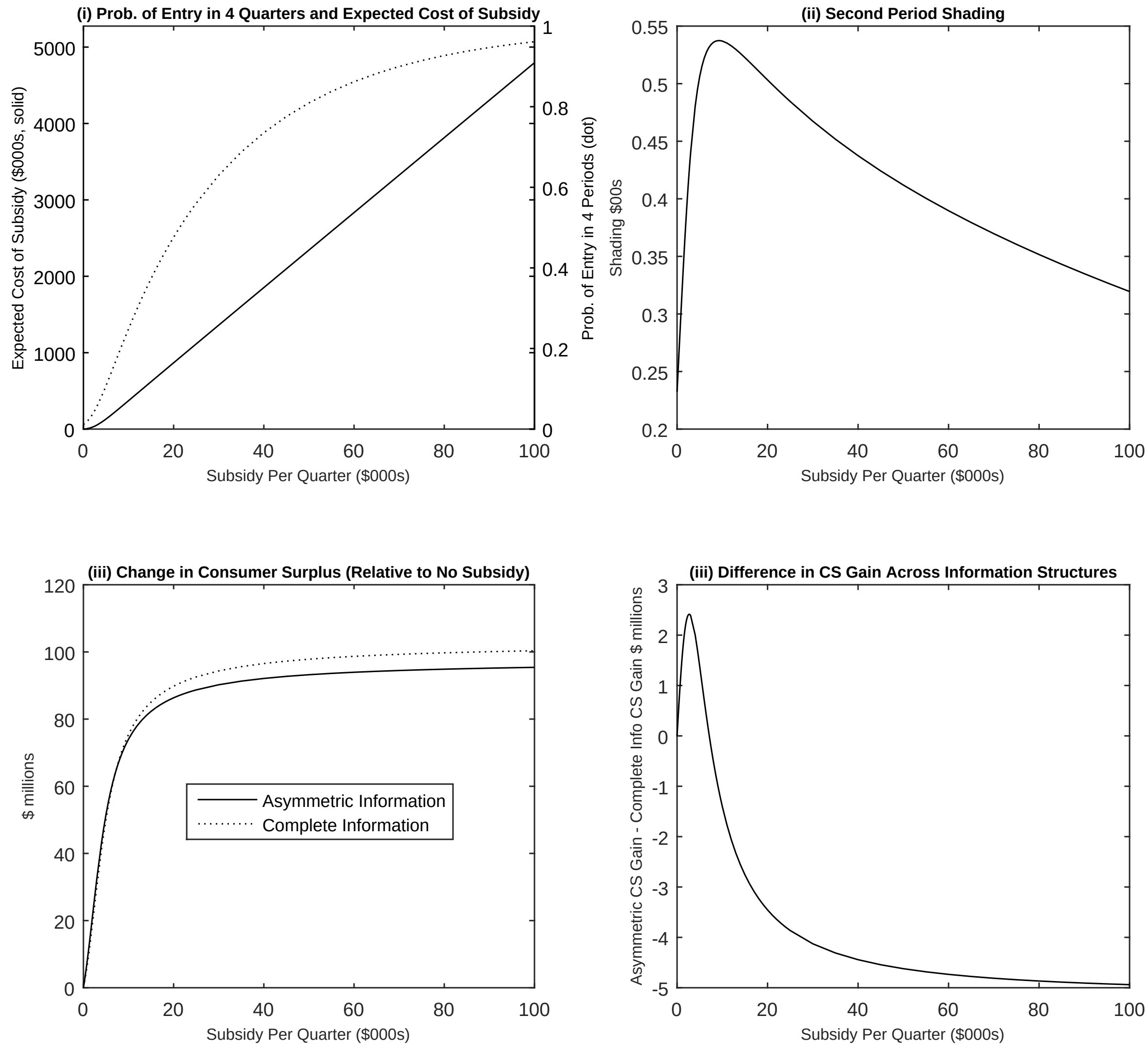
[56]To calculate welfare changes for consumers and the incumbent, we use our "true" market size measure, not the rescaled measure that we used when estimating the potential entrant's entry decisions. This is consistent with viewing the additional factors that affect the rescaled market size measure as being factors that affect Southwest's entry costs. In terms of timing we assume that Southwest arrives as a potential entrant once the incumbent has chosen its static monopoly price in the first period and can choose to enter immediately. The incumbent will then limit price from the second period if it is still a monopolist.

[57]I.e., this is the difference in fares paid between an environment with asymmetric information and one with complete information, multiplied by the predicted number of passengers flying under complete information, where entry decisions and post-entry outcomes will be the same in both.

Table 6: Welfare Effects of Limit Pricing and Counterfactual Fixed Cost Subsidies

Market	Hartford-Minneapolis	Manchester, NH-Philadelphia	Las Vegas-San Jose	All Dominant Incumbent Markets
Market Rank (by rescaled market size)	20	65	105	
Actual Market Size	33,822	45,287	137,571	total: 5.7 million
Model Predictions				
2nd Period				
Prob. of Entry (if no entry in 1st period)	0.003	0.097	0.580	mean: 0.150
Shading ($, % relative to static monopoly price)	$23.24, 4.4%	$91.10, 17.1%	$61.35, 11.5%	mean: $63.25, 11.9%
20th Period				
Probability of Entry (if no entry previously)	0.002	0.047	0.250	mean: 0.049
Shading ($, % relative to static monopoly price)	$19.50,3.7%	$72.18,13.7%	$118.62,22.2%	mean: $55.26, 10.4%
Welfare Effects of Limit Pricing (relative to complete information)				
Probability of Entry Within 4 Quarters	0.011	0.346	0.968	mean: 0.355
PDV of Reduced Prices ($ms)	4.89	6.34	0.88	total: 572.54
PDV of Change in Consumer Surplus ($ms)	4.98	7.27	0.99	total: 631.33
PDV of Change in Incumbent Profits ($ms)	-0.23	-1.43	-0.16	total: -94.16
Impact of a $1,000 Per Quarter Subsidy				
Probability of Entry within 4 Quarters	0.021	0.379	0.969	mean: 0.374
2nd Period Shading ($, %)	$31.16, 5.8%	$89.62, 16.8%	$60.98, 11.4%	mean: $64.31, 12.1%
PDV of the Cost to Government ($ms)	0.008	0.039	0.048	total: 3.436
Welfare Changes Under Complete Information				
PDV of Change in Consumer Surplus ($ms)	8.277	4.252	0.094	total: 624,57
PDV of Change in Incumbent Profits ($ms)	-4.529	-2.327	-0.051	total: -341.81
Changes Under Asymmetric Information				
PDV of Consumer Surplus Gain ($ms)	9.702	3.354	0.070	total: 595.12
PDV of Change in Incumbent Profits ($ms)	-4.714	-2.158	-0.047	total: -339.26

Figure 7: Predicted Effect of Fixed Cost Subsidies for Southwest on Entry, Incumbent Shading and Consumer Surplus in the Hartford-Minneapolis Market



monopolist's price away from its static profit-maximizing price does not have a first-order effect on the incumbent's profits, even though it has a first-order effect on consumer surplus.

Our model predicts much greater price changes when entry is threatened in the Manchester-Philadelphia market, but because the probability of entry rises with the size of the market, and limit pricing ceases as soon as entry occurs, the present discounted value of the benefits from limit pricing only increases by around 30% compared with the Hartford-Minneapolis market. For the largest markets, such as Las Vegas - San Jose, the entry probability is very high (in fact, the most common outcome is that entry happens at once so that there are no quarters where limit pricing is observed) so that the welfare effects of limit pricing are limited. However, because most of our dominant incumbent markets are quite small, so that limit pricing persists for some time, the present discounted value of limit pricing for consumers is over $630 million, which is a substantial effect.

We also use our model to investigate the welfare effects of granting a subsidy to Southwest to provide service on a route. It is not unusual for airports or local governments to provide carriers with financial incentives to begin serving routes. For example, Columbus offers marketing subsidies of up to $100,000 and one year with no landing fees in a widely-praised program designed to encourage entry on a targeted set of routes.[58] The subsidy we consider would pay Southwest $1,000 every quarter once it enters, corresponding to a present discounted value of $50,000.

The lower section of Table 6 shows the effects of the subsidy on the probability of entry, the amount of shading, consumer surplus and the profits of the incumbent. We compare the effects of the subsidy program under complete information, where the effects only come from raising the probability of actual entry by the incumbent, and under asymmetric information. Whether the increase in consumer surplus is greater under complete or asymmetric information depends on the sign and the magnitude of two effects. First, as consumer surplus prior to actual entry is higher under asymmetric information, the gain from increasing the probability of actual entry will tend to be greater under complete information, and this effect will be greater when there is more shading. Second, the subsidy can affect how much shading the incumbent does prior to entry.

In the Hartford-Minneapolis market, the increased probability of entry causes shading to increase (for example, from an average of $23 to $31 dollars in the first period that the incumbent can engage in limit pricing) and because the probability of entry is still low, the increase in consumer surplus is greater under asymmetric information. The magnitude of the welfare changes is also substantial. Under asymmetric information, the present discounted value of consumer surplus increases by $9.7 million and the value of incumbent profits falls by $4.7 million, and these are achieved at an expected cost to the government of just under $8,000.[59] To illustrate how the level of subsidy affects the size of the increase in consumer surplus, Figure 7 shows how, for the Hartford-Minneapolis market, the probability of entry, shading and the gain in consumer surplus change when we increase per-quarter subsidies from $0 to $100,000 per quarter. At the upper end of this range, it is almost certain that entry will happen quickly, and an increase in the subsidy will reduce shading. Therefore the welfare benefits of subsidies will be greater under complete information. At low entry probabilities, an increase in the subsidy can increase equilibrium shading so that the subsidy can increase consumer surplus by a greater amount under asymmetric information.

For intermediate size markets, such as Philadelphia-Manchester, the subsidy continues to have large positive welfare effects, although they are larger under complete information than under asymmetric

[58] "What's Behind Your Airport's New Nonstop Route?" by Jen Kinney, February 9, 2017, published at https://nextcity.org/daily/entry/airports-new-routes-announced-economics (accessed June 1, 2017). Details of a number of subsidy programs that Columbus operates can be found at https://www.dropbox.com/s/l8kpxtqfo9v6lbw/CMH_incentive_EXPANSION%5B2010%5D.pdf?dl=0 (accessed June 1, 2017). Most actual subsidy programs only give money to the first carrier that serves a route, not additional carriers. One could view our results as suggesting that subsidies that at least encourage the possibility of additional entry could yield significant benefits.

[59] In this market, the difference between the average (undiscounted) per-quarter consumer surplus under monopoly and duopoly is $1.2 million, so that increasing the (discounted) number of future periods of duopoly by seven or eight quarters can give rise to a substantial increase in consumer surplus. Note that the proportional relationship between the change in consumer surplus and the change in incumbent profits is different to the one in our previous calculations because we are now considering effects of a change in the probability of duopoly, and changes in the incumbent's price from a level that does not maximize its static profits.

information because entry is less valuable when the incumbent is already lowering its price significantly. In contrast, in the largest markets entry is almost certain without the subsidy, and the subsidy is effectively just a transfer to Southwest with any increases in consumer surplus roughly equal to the cost of the subsidy.

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

6 Extensions to the Basic Model

The previous analysis has focused on a simple model where the incumbent's marginal cost is private information and evolves exogenously. While this is a simple model to compute and analyze, it has two limitations. First, it does not capture some important characteristics of the airline industry, such as the fact that carriers must invest in capacity. The mechanism through which factors such as connecting traffic may cause an incumbent to behave as if its marginal cost is private information is also unclear. We address these issues by sketching an extension to our model, and we show that this more complicated model continues to generate significant limit pricing. Second, we have not analyzed whether the simple model can explain why, on average, prices fall over time in Phase 2. We discuss this issue and formulations of the model that can help to explain it.

6.1 Limit Pricing with Connecting Traffic and Capacity Investment

Our first extension allows for endogenous capacity investment and an asymmetry of information about how many people are interested in flying on the incumbent as part of a longer trip (i.e., connecting passenger demand). Recall that the majority of passengers that the incumbent carries on our routes are connecting passengers (Table 2) and that the economics of network flows are usually viewed as being fairly opaque (Edlin and Farrell (2004)). Here we outline the model and describe its implications for pricing and capacity investment for a given set of parameters.[60]

6.1.1 Specification and Parameterization

On a given route, carriers use their available capacity (measured by seats) to serve two mutually exclusive types of travelers: local customers (L), who are only traveling between the endpoints, and non-local (connecting) customers (NL) who are making longer journeys. We assume that the incumbent and an entrant would compete for local customers, but that they serve distinct markets for connecting customers.[61] The incumbent's connecting demand is not observed by the potential entrant, but the

[60]We leave estimation of this model to future research, which would need to overcome the data issues described in footnote 41 and the much greater computational burden associated with this model.

[61]We have in mind that people connecting on Southwest may tend to be going to different places than people connecting on legacy carriers, and that, in either case, connecting customers will typically have a number of different connecting

profitability of entry can be affected by it in two ways: first, the incumbent's marginal cost will increase in its capacity utilization so that high connecting demand will lead to it setting higher local prices, for a given level of capacity; and, second, the connecting demand of the two carriers can be positively correlated. For both reasons, the incumbent may want to signal that its connecting demand is low to deter entry. We assume that the incumbent's connecting prices are not observed by the potential entrant, but that it can observe the incumbent's local price.[62] We are interested in how local prices may change when entry is threatened.

Demand. We assume that local demand has exactly the same form, with the same parameters, as in Section 5. We focus on a local market of size 52,361, which is the mean rescaled market size in our dominant carrier sample. We assume that, whether entry has occurred or not, the incumbent faces non-local demand of

$$q_{I,t}^{NL}(p_{I,t}^{NL},\theta_{I,t}^{NL}) = \theta_{I,t}^{NL}\frac{\exp(\beta_I^{NL}-\alpha^{NL}p_{I,t}^{NL})}{1+\exp(\beta_I^{NL}-\alpha^{NL}p_{I,t}^{NL})} \tag{9}$$

where $p_{I,t}^{NL}$ is the incumbent's chosen price (here we are simplifying by assuming that a single connecting price is chosen). $\theta_{I,t}^{NL}$, which acts like the market size variable in a standard discrete choice analysis of firm demand, lies on a compact interval $[\underline{\theta_I^{NL}},\overline{\theta_I^{NL}}]$, and is not observed by a potential entrant, although it is observed post-entry. Reflecting the changing travel options available to connecting passengers, it evolves according to a stationary, first-order AR(1) process

$$\theta_{I,t}^{NL} = \rho^{NL}\theta_{I,t-1}^{NL} + (1-\rho^{NL})\frac{\underline{\theta_I^{NL}}+\overline{\theta_I^{NL}}}{2} + \varepsilon_t \tag{10}$$

where the normal distribution of ε_t is truncated to keep the parameter on the support. We assume that $\beta_I^{NL} = 0.727$ (the same as for local demand), $\underline{\theta_I^{NL}} = 150,000$, $\overline{\theta_I^{NL}} = 250,000$, $\rho^{NL} = 0.9$[63] and the standard deviation of ε is 15,000. $\alpha^{NL} = 0.0066$ (for a price in dollars), which is 50% larger than its value for local demand. We assume that, if it enters, the entrant will have non-local demand

$$q_{E,t}^{NL}(p_{E,t}^{NL},\theta_{E,t}^{NL}) = (\theta_E^{NL}+\tau\theta_{I,t}^{NL})\frac{\exp(\beta_E^{NL}-\alpha^{NL}p_{E,t}^{NL})}{1+\exp(\beta_E^{NL}-\alpha^{NL}p_{E,t}^{NL})} \tag{11}$$

where, in our baseline, $\tau = 0.25$ and $\theta_E^{NL} = 16,667$, so that, on average, $(\theta_E^{NL}+\tau\theta_{I,t}^{NL})$ is roughly one-third of the value of $\theta_{I,t}^{NL}$.[64] $\beta_E^{NL} = 0.627$ (once again, the same as for local demand).

options involving other routes so it will not be the case that the incumbent and the entrant compete head-to-head for connecting traffic. One supporting piece of evidence for this assumption is that the average incumbent connecting fare in Phase 3 (once Southwest has entered), \$381.77, is almost the same as in Phase 2, \$388.99, when Southwest is just a potential entrant on the route. This suggests that Southwest's entry onto the route does not affect an incumbent's connecting demand too much.

[62] In practice, so many connections use a particular segment that the entrant would have to monitor hundreds of connecting prices and then infer how these were being affected by demand on a particular segment.

[63] When we estimate an AR(1) using the incumbent's realized connecting traffic (measured with caveats discussed in Section 3.2), we find a serial correlation parameter between 0.85 and 0.9. Of course, realized connecting traffic will depend on costs on other segments and operational considerations as well as underlying demand, so it should be recognized that this statistic does not exactly correspond to the serial correlation that we assume in our model.

[64] Of course, the entrant may carry more connecting passengers than this proportion would suggest because its costs tend to be lower.

Carrier Costs. Carriers have observable capacities, $K_{j,t}$ and carrier j's period t costs are equal to

$$C_j(q_{j,t}^L, q_{j,t}^{NL}, K_{j,t}) = \gamma_j^K K_{j,t} + \gamma_{j,1}^L q_{j,t}^L + \gamma_{j,1}^{NL} q_{j,t}^{NL} + \gamma_{j,2} \left(\frac{q_{j,t}^{NL} + q_{j,t}^L}{K_{j,t}} \right)^{\upsilon} (q_{j,t}^L + q_{j,t}^{NL}) \tag{12}$$

so that there are soft capacity constraints and marginal costs increase in the load factor. This specification also implies that if entry lowers the incumbent's demand then its marginal costs will tend to fall as well. We assume that $\gamma_{I,1}^L = 45$, $\gamma_{I,1}^{NL} = \gamma_{E,1}^L = \gamma_{E,1}^{NL} = 0, \gamma_{j,2} = 100$ and $\nu = 10$, so the marginal costs of carrying additional passengers are only high when the load factor is high. $\gamma_I^K = \$180$ and $\gamma_E^K = \$120$ per seat. Therefore, the entrant tends to have an advantage through lower marginal and capacity costs. This advantage plays a role in making sure that the single-crossing condition, which is required for a unique equilibrium, holds.

We also assume that the incumbent has to pay additional costs when it changes its capacity,

$$C_{I,t}^A(K_{I,t}, K_{I,t+1}) = \zeta(K_{I,t+1} - K_{I,t})^2 + \mathcal{I}(K_{I,t+1} \neq K_{I,t}) \times \eta_{I,t} \tag{13}$$

where the first term is a deterministic convex adjustment cost, with $\zeta = 0.25$ in the baseline, and the second component is a fixed adjustment cost, which is an i.i.d. draw from an exponential distribution with a mean, in the baseline, of \$50,000. We assume that the entrant does not have any adjustment costs for capacity. This is partly for computational simplicity, but it also reflects the fact that operational constraints at an incumbent's hub may mean that it is more difficult for it to reschedule capacity.

Timing. We assume a finite horizon structure. Within each period t prior to entry, timing is as follows.

1. I observes $\theta_{I,t}^{NL}$ and $K_{I,t}$.
2. I chooses its prices $p_{I,t}^L$ and $p_{I,t}^{NL}$, receives ticket revenues and pays the cost of transporting passengers, and the linear capacity cost.
3. E observes its entry cost, which is an i.i.d. draw from a commonly known distribution, $p_{I,t}^L$ and $K_{I,t}$, and decides whether to enter, paying the entry cost if does so.
4. If E has entered, both firms simultaneously choose their capacities for $t+1$, and pay any relevant adjustment costs. If E has not entered, I makes its capacity choice.
5. $\theta_{I,t}^{NL}$ evolves to its value $\theta_{I,t+1}^{NL}$.

After entry, we assume that $\theta_{I,t}^{NL}$ is publicly observed by both firms, but that otherwise the timing is unchanged, except that step 3 is removed and both firms choose their prices simultaneously in step 2.

Discount Factor. For the calculations reported below, we assume a discount factor of 0.95, so that we can identify strategies that are essentially stationary once we have gone back 50 or 60 periods.[65]

[65] We stop the recursion when, looking across the entire state space, no price changes by more than 1 cent and no entry probability changes by more than 1e-4.

6.1.2 Equilibrium

The equilibrium in this model is comprised of beliefs and an entry rule for the potential entrant, a pre-entry pricing strategy for the incumbent and post-entry pricing strategies for both firms, and also capacity investment strategies. For this richer model there is no simple static condition that ensures that there will be a unique signaling equilibrium under refinement, so we numerically verify the conditions required for existence and uniqueness during the solution process, which is described in Appendix B.2.

Several features of this model are worth highlighting. The incumbent has incentives to signal that its connecting demand is low, which it can only do by setting a low local price. Capacity cannot be used as a signal because we assume that $K_{I,t}$ is chosen before $\theta_{I,t}^{NL}$ is known to the incumbent, and $K_{I,t+1}$ is chosen after the entry decision has been made. On the other hand, the incumbent could try to deter entry by building up excess capacity to the extent that adjustment costs mean that it will not immediately reduce its capacity once entry occurs. On the other hand, there is also an incentive to lower capacity in order to soften competition if entry does occur.[66] Capacity choices may also interact with limit pricing in subtle ways. For example, an incumbent can lower the cost of cutting the local price by increasing capacity, but because capacity is observed, a capacity increase may also require the incumbent to lower local prices even more for its signal to be credible. In this model, the cost of lowering the local price by a given amount is reduced by the fact that the incumbent can simultaneously increase $p_{I,t}^{NL}$, reducing $q_{I,t}^{NL}$, so that its marginal costs do not increase too much. Of course, this feature also implies that greater price reductions are required for the signal to be credible.

6.1.3 Results

Figure 8 shows the relationship between the probability that entry occurs within four periods, the expected percentage first period price change and the expected percentage change in capacity over the first four periods (assuming that entry does not occur). The changes are measured relative to the prices and capacities charged in the last period before the entry threat is introduced, based on 1,000 simulations.[67] As we are holding market size fixed, the entry probability is varied by adding a fixed amount, which can vary from $-\$12$ million to \$5 million to the entrant's per-period profits.[68] Entry cost draws are assumed to be distributed normally with mean \$20 million and standard deviation \$4 million, and we assume that this distribution does not change over time in order to have a manageable computational burden.

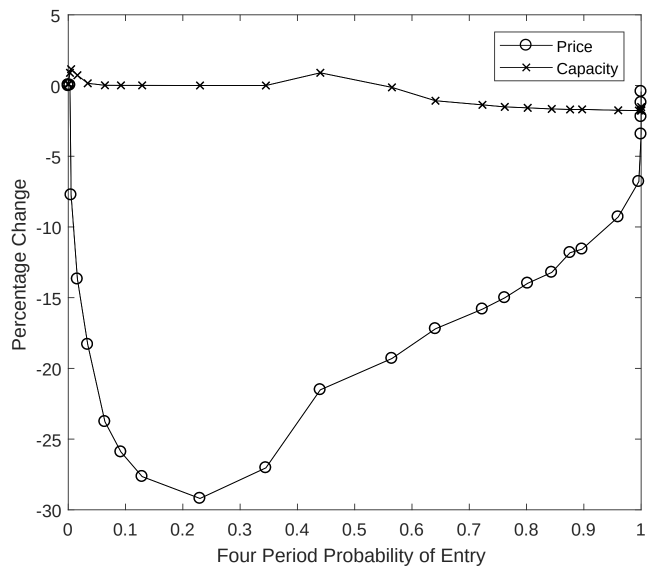
The results are striking. The incumbent responds to the threat of entry by reducing prices significantly, unless entry is almost certain. There is a clear non-monotonic relationship between the

[66] Adjustment costs also affect incentives to signal, because, if they are low, the potential entrant knows that even if the incumbent has either a high or low pre-entry marginal cost, it would be able to adjust it rapidly once entry occurs.

[67] These statistics are calculated using a two-stage process. In the first stage, we solve for equilibrium strategies in the game presented above and in a variant where entry is assumed to be blockaded. In the second stage, we first use strategies from the blockaded game to simulate 1,000 paths for capacities, prices and $\theta_{I,t}^{NL}$ for 100 periods starting from randomly chosen initial states. The states at the end of these paths are used as starting points for a further set of simulations, for 20 periods, using converged strategies from the early periods of the game where the entry threat is present. We then compare changes in prices and capacities with prices and capacities from the period before the entry threat is introduced.

[68] We vary entry probabilities in this way because, if market size is varied, we would also need to vary the grids used for connecting traffic and carrier capacities in an appropriate way.

Figure 8: Predicted Price and Capacity Changes When Entry is Threatened in a Model with Endogenous Marginal Costs and Endogenous Capacity Investment



probability of entry and the magnitude of the price change. On the other hand, capacity changes are very small, with slight increases at very low entry probabilities and declines for higher entry probabilities. Note that this lack of capacity changes does not reflect the existence of excessively large adjustment costs, because, on average, the incumbent's capacity drops by 0.5% or more in a single period when entry occurs.[69] This basic pattern is consistent with the results of the empirical analysis (for example, Figure 4 and Table 5) in the sense that there are large price reductions in intermediate probability of entry markets and no significant changes in capacity in low or intermediate probability of entry markets. In the data, capacity in high probability of entry markets declines slightly. This may reflect the fact that in these markets, which typically involve a Southwest focus airport, the incumbent anticipates a significant loss of both local and connecting (which we did not allow for in the model) passengers when Southwest's entry occurs.

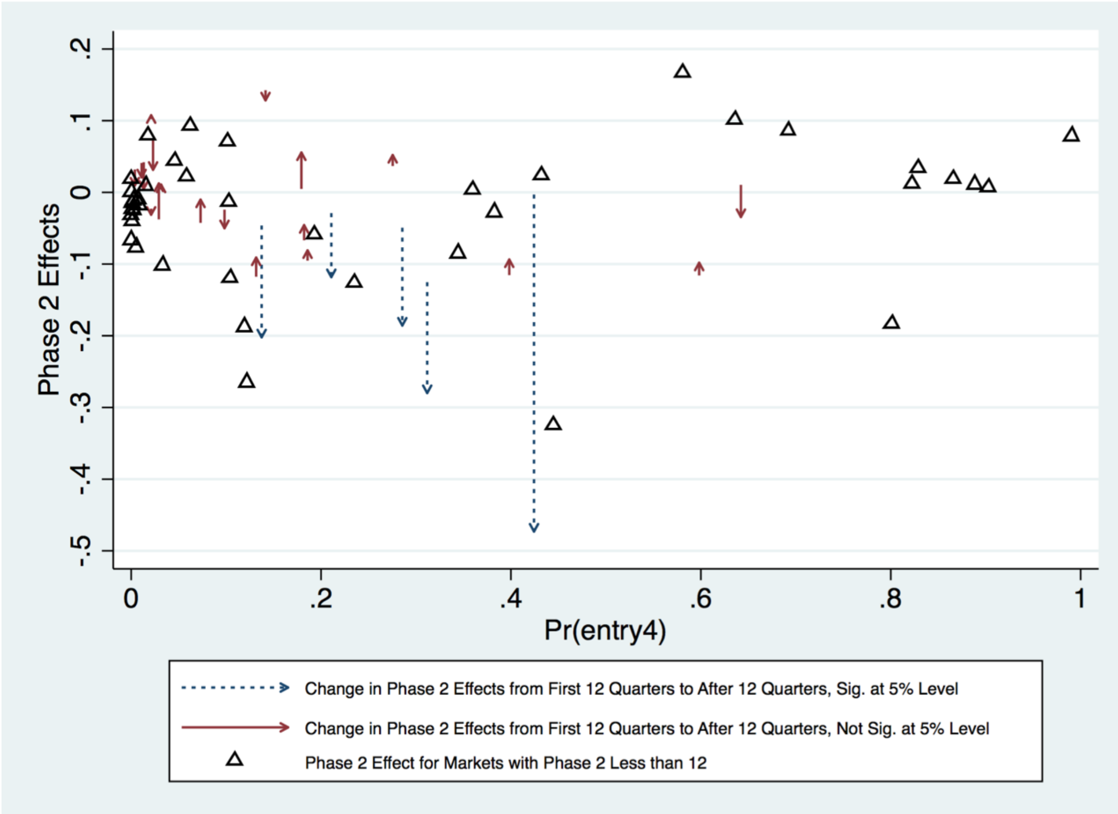
6.2 Limit Pricing and Increasing Price Reductions over Time

Recall that the estimates in Tables 3 and 4 show that, on average, yields continue to decline the longer markets remain in Phase 2 (i.e., when entry is threatened but does not occur). We now consider this pattern, and potential explanations, in more detail.

A closer analysis reveals that this pattern is driven by some large yield decreases in a small number of intermediate probability of entry markets. This is illustrated in Figure 9, which is similar to Figure 3, but which distinguishes between incumbent yield changes within twelve quarters of Southwest becoming a potential entrant and later quarters. Markets that do not have more than twelve Phase 2 quarters

[69]We have examined what happens when adjustment costs are lowered. Capacity changes are also small in this case. It is not surprising that the incumbent does not try to deter entry by investing in capacity when adjustment costs are low, because there is no reason for the potential entrant to expect the incumbent to keep its capacity high if it enters.

Figure 9: Yield Changes During Phase 2 For Markets in the Dominant Firm Sample



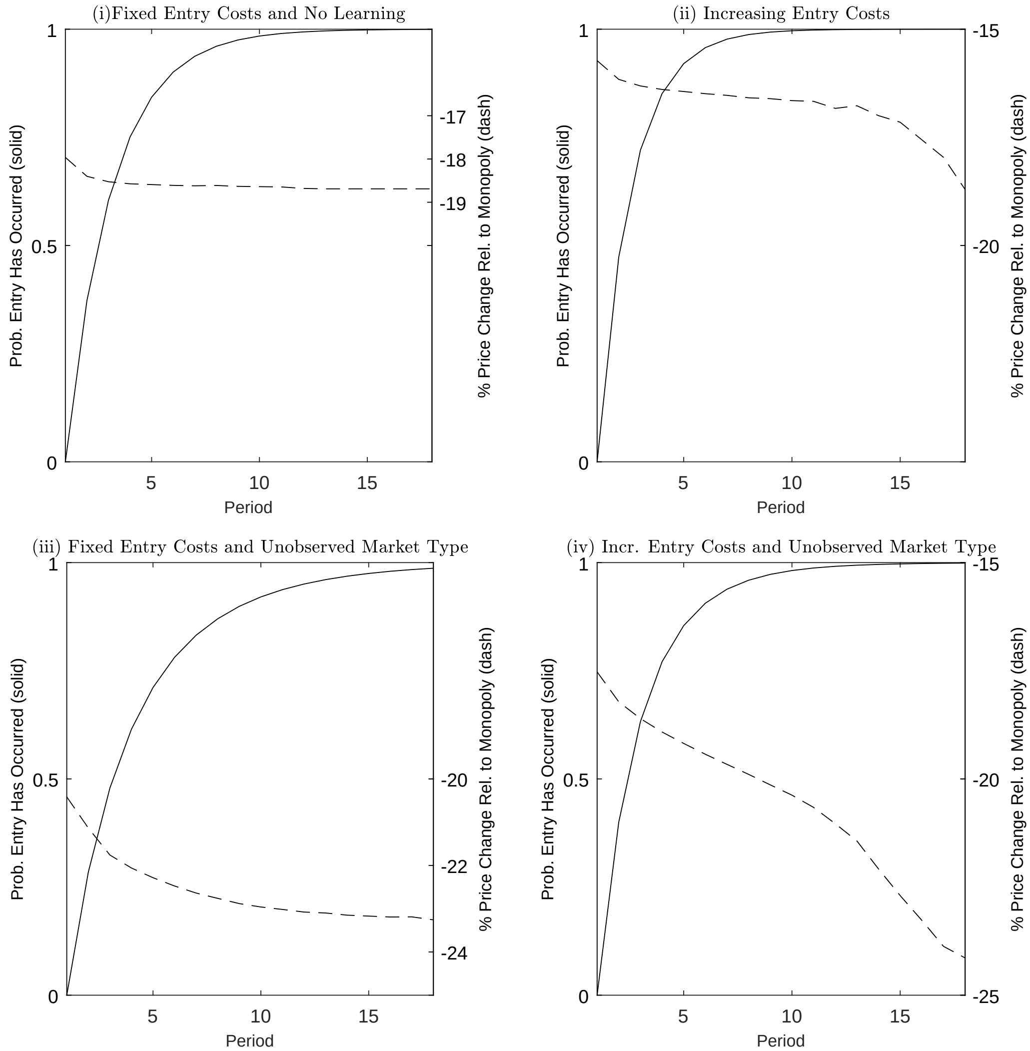
(either because Southwest enters, the sample ends or the incumbent ceases to meet the criteria for dominance) are marked by triangles. Yield changes for markets with more than twelve Phase 2 quarters are represented by arrows with the yield change (relative to Phase 1) after more than 12 quarters at the arrow's tip and the initial price decline at the other end.

We observe that there are large, statistically and economically significant price declines *during Phase 2* in five intermediate entry probability markets, and no statistically significant increases. This suggests that we should not look for a mechanism that would cause prices to fall in all markets. Broadly speaking, there are two different kinds of explanations that are worth considering. The first type of explanation is that, once entry is threatened, incumbents make investments that lower their marginal costs. These investments may complement limit pricing as an entry deterrence strategy. One example might be US Airways's 1998 introduction of its MetroJet-branded service on many routes from Baltimore-Washington International (BWI) in response to Southwest's growth at the airport.[70] US Airways executives indicated that MetroJet had significantly lower costs than its parent, which had previously flown the same routes, so that its optimal monopoly and limit prices would have fallen.[71] However, we note that this type of

[70]Note that MetroJet cannot explain any of the significant price changes in Figure 9 because only one BWI route in the dominant firm sample remains in Phase 2 for more than twelve quarters, and that route (to Houston Intercontinental, IAH) was a route where Southwest had a low predicted probability of entry reflecting Southwest's limited presence at IAH.

[71]US Airways CEO David Siegel was quoted in Business Travel News on October 28, 2001 as saying "We tried small fixes [to combat the growth of Southwest], and we know those don't work. MetroJet was about an eight-cent [per seat-mile] carrier and we know what happened to MetroJet."

Figure 10: Price Changes over Time in A Model With Limit Pricing, Incumbent Learning and Increasing Entry Costs



investment cannot explain all of the Phase 2 price declines in our data: it took US Airways 5 years to introduce MetroJet after Southwest entered BWI whereas we observe price declines as soon as Southwest threatens entry. It is also worth noting that MetroJet was terminated in late 2001, having never been profitable.

The second type of explanation is that decreasing prices can arise in a limit pricing model without any change in static demand or marginal cost primitives. Recall that in our model price declines tend to be maximized when the probability of entry is quite low (see Figure 1). Therefore, if the probability of entry perceived by the incumbent is initially reasonably high but falls over time, then the amount of shading may increase. In our calibrated model this can occur because of the increase in entry costs, as can been seen from considering the Las Vegas-San Jose market in Table 6. Expected shading almost doubles, from 11.5% to 22.2% of the static monopoly price, from the second to the twentieth period, if entry does not occur.

This type of entry cost increase can be complemented by other features that can be incorporated into the model.[72] One example is learning by the incumbent about how likely the potential entrant is to enter. To be specific, suppose that a market is either attractive or unattractive for entry (maybe because of how much connecting traffic will be supplied to its network if it enters the route), but that this is not observed by the incumbent, which initially attaches equal probability to each market type. If entry does not initially occur, the incumbent will update its beliefs using Bayes Rule, and will expect a lower probability of entry which could cause it to lower its price. In this model there is two-way learning, which cannot be a feature of a two-period model where there is only one opportunity for the potential entrant to enter the market, but the model remains tractable as long as it is assumed that post-entry competition is not affected by how the potential entrant times its entry decision.

For a given set of parameters, Figure 10 illustrates the effect of introducing learning into the model.[73] In panel (i), we assume that mean entry costs do not increase over time and that the incumbent knows how attractive the market is for the potential entrant, although the potential entrant does not know the incumbent's marginal cost so that there is still limit pricing. Given the parameters, there is significant limit pricing and a *small* increase in the magnitude of the price decline over time as the entry process tends to lead the incumbent being more likely to have a low marginal cost. In panel (ii) we introduce an increasing mean entry cost (the increase is \$100,000 per period for twenty periods, when initial mean entry costs are \$48 million). This lowers the initial degree of shading, because it increases the initial probability of entry, but it causes the degree of shading to increase over time.[74] In panel (iii), we introduce our unobserved market type. We lower the potential entrant's per-period profits in an unattractive market by \$200,000, which is 15% of its average profit. This lowers the probability of entry, and it also causes shading to increase over time as the incumbent revises its beliefs. For example, if entry has not occurred after 5 periods, the incumbent's posterior is, on average, that the market is unattractive with probability 0.89. However, most of the increase in shading happens fairly quickly, reflecting the fact that only a small number of periods is required for the incumbent to become pretty confident about how attractive the market is to Southwest.[75] Finally, in panel (iv), we combine incumbent learning and increasing entry costs, and together these factors combine to produce a sustained increase, of over 7 percentage points of the expected static monopoly price, in the degree of shading. Therefore, limit pricing combined with both learning and small increases in entry costs may provide an explanation for the increasing price reductions observed in the data.

[72] It could also be complemented by investments that reduce the incumbent's marginal cost, as in the MetroJet example.

[73] As in our other examples, passenger demand has a nested logit structure, with a price coefficient of $\alpha = 0.4$ (prices are measured in hundreds of dollars) and the nesting parameter is 0.75. The incumbent's marginal cost can range from \$160 to \$280, and the innovation process is the same as the one used in the calibration. The entrant's marginal cost is \$150. Entry costs are normally distributed with an initial mean of \$48 million and a standard deviation of \$1.25 million. Market size is 50,000.

[74] The slight shakiness in the pattern is due to simulation error.

[75] Of course we would expect the attractiveness of a real market to potentially evolve over time, so that the incumbent may remain more uncertain than our model allows.

7 Conclusion

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

We show how the introduction of dynamics can lead to larger price reductions than in the canonical two-period model (Milgrom and Roberts (1982)), especially in markets where the probability of entry is not too high. In the application, this feature can explain why incumbent carriers keep prices low when Southwest remains a potential, but not an actual, entrant for quite long periods of time, and our model can also explain why incumbents cut prices even before Southwest has actually started operating at the endpoint airports. We provide new reduced-form evidence that a limit pricing explanation can explain why prices fall, by analyzing where the price declines are greatest, and also providing evidence against alternative explanations, such as prices being cut to boost future demand or being a side-effect of either entry-deterring capacity investments or changes in load factors. When we calibrate our model without using any information on price changes when entry is threatened, we find that the model predicts price changes across markets that are qualitatively and quantitatively similar to those in the data. An extended version of our model, that allows for marginal costs to be endogenous functions of carriers' capacity investments, can not only predict price declines that are consistent with the data, but it is also able to explain why capacity changes very little in intermediate probability of entry markets.

While we have explored one type of asymmetric information model and one application, we believe that there are many areas in which to explore how asymmetric information may impact firm behavior. For example, it is often claimed that predatory pricing is motivated by incumbents wanting to signal information on their costs or their intentions to both the current competitor and potential future competitors, and it would be interesting to compare how well this type of signaling story compares quantitatively against non-informational models of predation where the dominant incumbent makes observable investments (for instance, in capacity (Snider (2009), Williams (2012)), or learning-by-doing (Besanko, Doraszelski, and Kryukov (2014))) that commit it to lower future costs. We would also like to explore whether there are assumptions under which a model with several incumbents could also have a tractable equilibrium with significant limit pricing behavior. This would allow us to expand our analysis in this paper to a broader set of industries and markets.

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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., $\mathbb{E}_t[V_{t+1}^E|\widehat{c}_{I,t}]$. We will use several conventions.

1. $\phi_t^E(c_{I,t})$ denotes E's expected present discounted future value when it is a duopolist at the beginning of period 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, $\phi_t^E(c_{I,t})$ is uniquely defined.

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

3. $V_t^I(c_{I,t})$ 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 $c_{I,t}$. The entry cost, κ_t, is not known when the value is defined, so that 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 the strategies of both firms in future periods.

4. $V_t^E(c_{I,t})$ denotes E's expected present discounted future value when it is a potential entrant at the beginning of period 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 because it both defines the value of both firms at the same moment each period (the beginning) and economizes on the amount of notation. κ_t is not known when the value is defined, so that 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 $c_{I,t}$, or the entrant's beliefs about $c_{I,t}$, should be understood. For example, $\mathbb{E}_t[V_{t+1}^E|\widehat{c}_{I,t}]$ is the expected value of E as a potential entrant at the start of period $t+1$ given a belief that $c_{I,t}$ is exactly $\widehat{c}_{I,t}$. As in this example, when E has a point belief 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 $f(x)$ is a strictly positive function, $g(x|w)$ is a strictly positive conditional pdf on $x, w \in [\underline{x}, \overline{x}]$. Further suppose that (i) for a given value of w $\exists x' \in (\underline{x}, \overline{x})$ such that $\frac{\partial g(x'|w)}{\partial w} = 0$, $\frac{\partial g(x|w)}{\partial w} < 0$ for $\forall x < x'$ and $\frac{\partial g(x|w)}{\partial w} > 0$ for $\forall x > x'$; and, (ii) $k \equiv \int_{\underline{x}}^{\overline{x}} f(x) \frac{\partial g(x|w)}{\partial w} dx$. If $\forall x$, $\frac{\partial f(x)}{\partial x} > 0$ then $k > 0$. On the other hand, if $\forall x$, $\frac{\partial f(x)}{\partial x} < 0$ then $k < 0$.*

Proof.

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

■

There are several useful corollaries of Lemma 1.

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

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

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

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

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

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

$$\mathbb{E}_t[\phi^E_{t+1}|q(\widetilde{c_{I,t}})] - \mathbb{E}_t[V^E_{t+1}|q(\widetilde{c_{I,t}})] =$$

$$\int_{\underline{c_I}}^{\overline{c_I}}\int_{\underline{c_I}}^{\overline{c_I}} \left\{ \begin{array}{c} \left[\phi^E_{t+1}(c_{I,t+1}) - V^E_{t+1}(c_{I,t+1})\right] \times ... \\ \psi_I(c_{I,t+1}|\widetilde{c_{I,t}})q(\widetilde{c_{I,t}}) \end{array} \right\} dc_{I,t+1} d\widetilde{c_{I,t}} > 0$$

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

$$\mathbb{E}_t[V^I_{t+1}|c_{I,t}] - \mathbb{E}_t[\phi^I_{t+1}|c_{I,t}] =$$

$$\int_{\underline{c_I}}^{\overline{c_I}} \left[V^I_{t+1}(c_{I,t+1}) - \phi^I_{t+1}(c_{I,t+1})\right] \psi_I(c_{I,t+1}|c_{I,t}) dc_{I,t+1} > 0$$

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

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

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

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

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

A.4.1 Potential Entrant Strategy in Period t

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

Specifically, E will enter if and only if

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

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

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

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 increasing in $\widehat{c}_{I,t}$. $\kappa_t^* > \underline{\kappa} = 0$ follows from combining E1^{t+1} and Lemma 2(a). $\kappa_t^*(\widehat{c}_{I,t})$ will be continuous and differentiable if $\phi_{t+1}^E(c_{I,t+1})$ and $V_{t+1}^E(c_{I,t+1})$ are continuous and differentiable (E3^{t+1}), and ψ_I is continuous and differentiable (Assumption 1). $\kappa_t^*(\widehat{c}_{I,t})$ is strictly increasing in $\widehat{c}_{I,t}$ if $\frac{\partial \mathbb{E}_t[\phi_{t+1}^E|\widehat{c}_{I,t}]}{\partial \widehat{c}_{I,t}} - \frac{\partial \mathbb{E}_{t-1}[V_{t+1}^E|\widehat{c}_{I,t}]}{\partial \widehat{c}_{I,t}} > 0$, which follows from E4^{t+1} and Corollary 1.

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' $\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$ 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, and $p_{I,t}$ is the price that I sets.

Theorem [Based on Mailath and von Thadden (2013)] *If (MT-i) $\Pi^{I,t}(c_{I,t}, c_{I,t}, p_{I,t})$ has a unique optimum in $p_{I,t}$, and for any $p_{I,t} \in [\underline{p}, \overline{p}]$ where $\Pi_{33}^{I,t}(c_{I,t}, c_{I,t}, p_{I,t}) > 0$, there $\exists k > 0$ such that $\left|\Pi_3^{I,t}(c_{I,t}, c_{I,t}, p_{I,t})\right| > k$ for all $c_{I,t}$; (MT-ii) $\Pi_{13}^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) \neq 0$ for all $(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$; (MT-iii) $\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) \neq 0$ for all $(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})$; (MT-iv) $\frac{\Pi_3^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})}{\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t})}$ is a monotone function of $c_{I,t}$ for all $\widehat{c}_{I,t}$ and all $p_{I,t}$ below the static monopoly price; (MT-v) $\overline{p} \geq p^{\text{static monopoly}}(\overline{c_I})$ and $\Pi^{I,t}(\underline{c_{I,t}}, \underline{c_{I,t}}, \underline{p}) < \max_p \Pi^{I,t}(\underline{c_{I,t}}, \overline{c_{I,t}}, p)$, then 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 $p_{I,t}^*(\overline{c_I}) = p^{\text{static monopoly}}(\overline{c_I})$.

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

I1^{t+1}. $V_{t+1}^I(c_{I,t+1}) > \phi_{t+1}^I(c_{I,t+1})$;

I2^{t+1}. $V_{t+1}^I(c_{I,t+1})$ and $\phi_{t+1}^I(c_{I,t+1})$ are continuous and differentiable; and,

I3^{t+1}. $\frac{\partial V_{t+1}^I(c_{I,t+1})}{\partial c_{I,t+1}} < \frac{\partial \phi_t^I(c_{I,t+1})}{\partial c_{I,t+1}}$

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

$$\Pi^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) = q^M(p_{I,t})(p_{I,t} - c_{I,t}) + ...$$
$$\beta((1 - G(\kappa_t^*(\widehat{c}_{I,t})))\mathbb{E}_t[V_{t+1}^I | c_{I,t}] + G(\kappa_t^*(\widehat{c}_{I,t}))\mathbb{E}_t[\phi_{t+1}^I | c_{I,t}])$$

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

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

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

$$\Pi_{13}^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) = -\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}} \tag{14}$$

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

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

$$\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) = -\beta g(\kappa_t^*(\widehat{c}_{I,t}))\frac{\partial \kappa_t^*(\widehat{c_{I,t}})}{\partial \widehat{c}_{I,t}} \left\{\mathbb{E}_t[V_{t+1}^I | c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}]\right\} \tag{15}$$

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

Condition (MT-iv): Using equations (14) and (15) we have

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

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

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

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

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

$\frac{\partial\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}]-\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}}{\partial c_{I,t}}<0$ (assumption I3^{t+1} and Corollary 2);

$\left[q(p_{I,t})+\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t}-c_{I,t})\right]\geq 0$ for all prices below the monopoly price (implied by strict quasi-concavity of the profit function); $g(\kappa_t^*(\widehat{c}_{I,t}))>0$ (Assumption 2 and the previous result that $\underline{\kappa}<\kappa_t^*(\widehat{c}_{I,t})<\overline{\kappa}$); $\frac{\partial \kappa_t^*(\widehat{c}_{I,t})}{\partial \widehat{c}_{I,t}}>0$ (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* $\Pi^{I,t}(c_{I,t},\kappa_t',p_{I,t})$ *where* κ_t' *is E's entry threshold. If conditions (R-i)* $\Pi_2^{I,t}(c_{I,t},\kappa_t',p_{I,t})\neq 0$ *for all* $(c_{I,t},\kappa_t',p_{I,t})$*; (R-ii)* $\frac{\Pi_3^{I,t}(c_{I,t},\kappa_t',p_{I,t})}{\Pi_2^{I,t}(c_{I,t},\kappa_t',p_{I,t})}$ *is a monotone function of* $c_{I,t}$ *for all* κ_t'*; and (R-iii)* $\overline{p}\geq p^{\text{static monopoly}}(\overline{c_I})$ *and* $\Pi^{I,t}(\underline{c_{I,t}},\overline{\kappa},\underline{p})<\max_p \Pi^{I,t}(\underline{c_{I,t}},\underline{\kappa},p)$ *for all 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): $\Pi_2^{I,t}(c_{I,t},\kappa_t,p_{I,t})=-\beta g(\kappa_t)\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}]-\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}$. The right-hand side 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 $\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}]-\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}>0$ (follows from assumption I1^{t+1} and Lemma 2(b)).

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

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

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

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

Sufficient conditions for $\frac{\partial\frac{\Pi_3^{I,t}(c_{I,t},\kappa_t,p_{I,t})}{\Pi_2^{I,t}(c_{I,t},\kappa_t,p_{I,t})}}{\partial c_{I,t}}$ to be <0 (implying $\frac{\Pi_3^{I,t}(c_{I,t},\kappa_t,p_{I,t})}{\Pi_2^{I,t}(c_{I,t},\kappa_t,p_{I,t})}$ monotonic in $c_{I,t}$) are: $\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}]-\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}>0$ (follows from assumption I1^{t+1} and Lemma 2(b));
$\frac{\partial\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}]-\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}}{\partial c_{I,t}}<0$ (assumption I3^{t+1} and Corollary 2);
$\left[q(p_{I,t})+\frac{\partial q^M(p_{I,t})}{\partial p_{I,t}}(p_{I,t}-c_{I,t})\right]\geq 0$ for all prices below the monopoly price (implied by quasi-concavity of the profit function); $g(\kappa_t^*(\widehat{c}_{I,t}))>0$ (Assumption 2 and the previous result that $\underline{\kappa}<\kappa_t^*(\widehat{c}_{I,t})<\overline{\kappa}$); 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. $\phi_t^E(c_{I,t})>V_t^E(c_{I,t})$;

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

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

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

From the above, we have that

$$\phi_t^E(c_{I,t}) = \pi_E^D(c_{I,t}) + \beta \int_{\underline{c_I}}^{\overline{c_I}} \phi_{t+1}^E(c_{I,t+1})\psi_I(c_{I,t+1}|c_{I,t})dc_{I,t+1} \tag{16}$$

$$\begin{aligned} V_t^E(c_{I,t}) = & \int_0^{\kappa^*(c_{I,t})} \int_{\underline{c_I}}^{\overline{c_I}} \left\{\beta\phi_{t+1}^E(c_{I,t+1})\psi_I(c_{I,t+1}|c_{I,t}) - \kappa\right\} g(\kappa)dc_{I,t+1}d\kappa + ... \\ & \int_{\kappa^*(c_{I,t})}^{\overline{\kappa}} \int_{\underline{c_I}}^{\overline{c_I}} \beta V_{t+1}^E(c_{I,t+1})\psi_I(c_{I,t+1}|c_{I,t})g(\kappa)dc_{I,t+1}d\kappa \end{aligned} \tag{17}$$

where we are exploiting the fact that the entrant has correct beliefs about I's marginal cost when taking its entry decision in equilibrium.

Continuity and differentiability of (16) and (17) follows from ϕ_{t+1}^E and V_{t+1}^E being continuous and differentiable (E3^{t+1}), $\psi_I(c_{I,t+1}|c_{I,t})$ being continuous and differentiable (Assumption 1) and $\kappa^*(c_{I,t})$ being continuous and differentiable as shown above. The fact that both (16) and (17) 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 $\phi_{t+1}^E(c_{I,t+1}) > V_{t+1}^E(c_{I,t+1})$, (17) implies

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

and therefore,

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

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

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

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

so that

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

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

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

For the incumbent we have to prove:

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

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

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

Condition I1^t:

$$V_t^I(c_{I,t}) = \max_{p_{I,t}} q^M(p_{I,t})(p_{I,t} - c_{I,t}) + ... \tag{18}$$

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

$$\phi_t^I(c_{I,t}) = \pi_I^D(c_{I,t}) + \beta \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}] \tag{19}$$

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

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

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

Condition I2^t: continuity and differentiability of $V_t^I(c_{I,t})$ and $\phi_t^I(c_{I,t})$ follows from expressions (18) and (19), and the continuity and differentiability of the static and duopoly profit functions, the incumbent's equilibrium pricing function, the entry threshold function, $\kappa_t^*(c_{I,t})$, the cdf of entry costs G, the cost transition conditional probability function ψ_I, and the following period value functions $V_{t+1}^I(c_{I,t+1})$ and $\phi_{t+1}^I(c_{I,t+1})$ (I2^{t+1}).

Condition I3^t:

$$\frac{\partial V_t^I(c_{I,t})}{\partial c_{I,t}} = \frac{\partial \pi^M(p^*, c_{I,t})}{\partial c_{I,t}} + \beta \frac{\partial \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]}{\partial c_{I,t}} - ...$$

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

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

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

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

so

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

and

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

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

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

where the inequality follows from Assumption 4, as $q^M(p^*(c_{I,t})) > q^M(p^{\text{static monopoly}})$ because the limit price will be below the static monopoly price and demand slopes downwards (Assumption 3), and I3^{t+1} and Corollary 2.

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 then it should just set the static monopoly price, and E should not enter for any positive entry cost. Therefore, $\phi_T^E(c_{I,T}) = \pi_E^D(c_{I,T})$, $V_T^E(c_{I,T}) = 0$, $\phi_T^I(c_{I,T}) = \pi_I^D(c_{I,T})$ and $V_T^I(c_{I,T}) = q(p^{\text{static monopoly}}(c_{I,T}))(p^{\text{static monopoly}}(c_{I,T}) - c_{I,T})$. Under our assumptions $\phi_T^E(c_{I,T}) > V_T^E(c_{I,T})$, $V_T^I(c_{I,T}) > \phi_T^I(c_{I,T})$, $\frac{\partial \phi_T^E}{\partial c_{I,T}} > \frac{\partial V_T^E}{\partial c_{I,T}} = 0$, $\frac{\partial V_T^I(c_{I,T})}{\partial c_{I,T}} < \frac{\partial \phi_T^I(c_{I,T})}{\partial c_{I,T}} < 0$.[76]

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

B Computational Methods for Solving Dynamic Limit Pricing Models

In this Appendix we explain how we solve our dynamic limit pricing model. We first explain how we solve the game where marginal costs evolve exogenously, considering both the finite horizon and the limiting infinite horizon models. We then discuss how we solve the extended model where capacity choices and marginal costs are endogenous.

B.1 Model with Exogenous Marginal Costs

This subsection explains how we solve models with exogenously evolving incumbent marginal costs, which are used both in illustrating properties of the model and in our calibration. We begin with the case where the distribution of entry costs is time invariant.

B.1.1 Preliminaries

We start by specifying a 25-point grid of values for the incumbent's marginal cost (results are almost identical using 50 or 100 points) and a 1000-point grid of values for the incumbent's price, where the highest value is above the static monopoly price of the incumbent with the highest possible marginal cost and the lowest price is much lower than the monopoly price associated with the lowest possible marginal cost. For each value on the cost grid we solve for:

- I's profits and prices as a static monopolist;
- I and E's profits in static duopoly ($\pi_j^D(c_I)$); and,
- the gradient of I's static monopoly profits with respect to its price for each price on the price grid, $\frac{\partial \pi_I^M(p_I,c_I)}{\partial p_I} = q^M(p_I) + \frac{\partial q^M(p_I)}{\partial p_I}(p_I - c_I)$.

We also verify that the sufficient condition for single-crossing

$$\left(q_I^D(c_I, c_E) - q^M(p_I^{\text{static monopoly}}(c_I)) - \frac{\partial \pi_I^D(c_I, c_E, p_E)}{\partial p_E} \frac{\partial p_E^*}{\partial c_I} < 0 \right)$$

for all c_I.

B.1.2 Entry Strategies

E has a stochastic optimal stopping problem where its decision is to enter, as once it enters it simply receives the associated flow of static duopoly profits for the rest of the game. In a finite horizon structure, signify its entry strategy as $\kappa_t^*(c_I)$ where we are exploiting the fact that, in equilibrium, it will know the true value of I's marginal cost, and we specify E's values as a potential entrant and as a duopolist in the final period of the game as $V_T^E(c_I) = 0$ and $\phi_T^E(c_I) = \pi_E^D(c_I)$. These values are measured once c_I has evolved to its final time period value.

We can now go to the penultimate time period ($T-1$). We use the assumed form of the transition processes for c_I to calculate the value of $\mathbb{E}_{T-1}[\phi_T^E|c_{I,T-1}]$ for each value of $c_{I,T-1}$ on the cost grid. The integration is done using the trapezium rule. As $\mathbb{E}_{T-1}[V_T^E|c_{I,T-1}]=0$, $\kappa^*_{T-1}(c_{I,T-1})=\beta\mathbb{E}_{T-1}[\phi_T^E|c_{I,T-1}]$. We compute $g(\kappa^*_{T-1})$ and $\frac{\partial\kappa^*_{T-1}(c_{I,T-1})}{\partial c_{I,T-1}}$ for each grid point. We can use the implied entry probabilities to compute the entrant's expected values at the beginning of period $T-1$, i.e.,

$$\phi_{T-1}^E(c_{I,T-1})=\pi_E^D(c_{I,T-1})+\beta\mathbb{E}_{T-1}[\phi_T^E|c_{I,T-1}]$$
$$V_{T-1}^E(c_{I,T-1})=\beta G(\kappa^*_{T-1}(c_{I,T-1}))\mathbb{E}_{T-1}[\phi_T^E|c_{I,T-1}]+....$$
$$\beta(1-G(\kappa^*_{T-1}(c_{I,T-1})))\mathbb{E}_{T-1}[V_T^E|c_{I,T-1}]-\int_0^{\kappa^*(c_{I,T-1})}\kappa g(\kappa)d\kappa$$

where the integration to calculate the expected value of the entry cost conditional on entry being optimal can be done analytically when the distribution of entry costs is normal.

We can now proceed to $T-2$ and all earlier periods. We use exactly the same procedure apart from recognizing that

$$\kappa^*_{T-2}(c_{I,T-2},c_{E,T-2})=\beta\{\mathbb{E}_{T-2}[\phi_{T-1}^E|c_{I,T-2},c_{E,T-2}]-\mathbb{E}_{T-2}[V_{T-1}^E|c_{I,T-2},c_{E,T-2}]\},\tag{20}$$

as there is positive value associated with being a potential entrant at $T-1$.

When we solve the limiting infinite horizon case, we simply continue the recursion until the values of ϕ_t^E, V_t^E and κ_t^* have converged for all values on the cost grid.

B.1.3 Limit Pricing Strategies

In a finite horizon game, we solve for the incumbent's value functions and its limit pricing strategies recursively.

In the final time period, the incumbent will set the optimal static price, so that $V_T^I=\pi_I^{*M}(c_I)$ and $\phi_T^I=\pi_I^D(c_I)$. In the penultimate period, we calculate $\mathbb{E}_{T-1}[V_T^I|c_{I,T-1}]$ and $\mathbb{E}_{T-1}[\phi_T^I|c_{I,T-1}]$ as expected values to being a monopolist or duopolist in the next period, given the assumed form of the cost transition. We then use the values of $g(\kappa^*_{T-1})$ and $\frac{\partial\kappa^*_{T-1}(c_{I,T-1})}{\partial c_{I,T-1}}$ that we calculated when solving the potential entrant's problem to solve for the pricing strategy of the incumbent. Starting from the boundary condition, where an incumbent with the highest marginal cost should set the static monopoly price, we use

$$\frac{\partial p^*_{I,T-1}}{\partial c_{I,T-1}}=\frac{\beta g(\kappa^*_{T-1})\frac{\partial\kappa^*_{T-1}(c_{I,T-1})}{\partial c_{I,t}}\{\mathbb{E}_{T-1}[V_T^I|c_{I,T-1}]-\mathbb{E}_{T-1}[\phi_T^I|c_{I,T-1}]\}}{\frac{\partial\pi_I^M(p_{I,T-1},c_{I,T-1})}{\partial p_{I,T-1}}}$$

to find the equilibrium pricing schedule. This is done using `ode45` in MATLAB.[77] As we solve the differ-

[77] We have used a variety of differential equation solvers with essentially identical results. We use `ode45`, so we can use MATLAB Coder to translate a function of which solving the differential equation is a part into C, which greatly speeds computation.

ential equation we interpolate, using cubic splines, the values of $g(\kappa^*_{T-1})$, $\frac{\partial \kappa^*_{T-1}(c_{I,T-1})}{\partial c_{I,t}}$, $\{\mathbb{E}_{T-1}[V^I_T|c_{I,T-1}]-\mathbb{E}_{T-1}[\phi^I_T|c_{I,T-1}]\}$ and $\frac{\partial \pi^M_I(p_{I,T-1},c_{I,T-1})}{\partial p_{I,T-1}}$ from the relevant grid points.

We use the resulting pricing function to calculate the incumbent's profits in period $T-1$ given this strategy, $\pi^M_I(c_I, p^{\text{DLP}}_{T-1}) = (p^{\text{DLP}}_{T-1}(c_I) - c_I)Q(p^{\text{DLP}}_{T-1})$. The incumbent's value functions at the beginning of period $T-1$ are then calculated as

$$\begin{aligned}
\phi^I_{T-1}(c_{I,T-1}) &= \pi^D_I(c_{I,T-1}) + \beta\mathbb{E}_{T-1}[\phi^I_T|c_{I,T-1}] \\
V^I_{T-1}(c_{I,T-1}) &= \pi^M_I(c_I, p^{\text{DLP}}_{T-1}) + \beta G(\kappa^*_{T-1}(c_{I,T-1}))\mathbb{E}_{T-1}[\phi^I_T|c_{I,T-1}] + ... \\
&\quad \beta(1 - G(\kappa^*_{T-1}(c_{I,T-1})))\mathbb{E}_{T-1}[V^I_T|c_{I,T-1}].
\end{aligned}$$

With these value functions in hand, we can then proceed back to the previous period and repeat the calculations, before proceeding backwards through the rest of the game.

B.1.4 Infinite Horizon Game

In the limiting infinite horizon version of the model, this procedure of solving for period-specific pricing strategies is unnecessary. Instead, we first calculate the incumbent's value function as a duopolist (ϕ^I) in an infinitely repeated static game. We then use an iterative procedure where we solve for differential equations and pricing functions repeatedly to find a fixed point in the incumbent's value function as a monopolist (V^I) and its pricing function, taking into account that limit pricing affects the incumbent's value of being a monopolist rather than a duopolist in the future. This procedure usually converges in less than 20 iterations so that it saves significant time compared to solving for a large number of periods of a finite horizon game.

B.1.5 Increasing Mean Entry Costs

When we calibrate the model we allow for the mean of the entry cost distribution to increase with the number of periods since E became a potential entrant. We implement this model by creating an additional discrete state variable, $Z = 1, 2, ..., \overline{Z}$, whose value determines the mean of the entry cost distribution, and by specifying a matrix P^Z that describes the transition of Z from period to period. For our calibration, we assume a deterministic transition where Z always increases by one, until it arrives in the absorbing state $\overline{Z}$, and we set $\overline{Z} = 30$. We match entry probabilities from the first 20 quarters that Southwest is a potential entrant, so that the effect of this upper bound is not too great (the probabilities for the first 20 periods are essentially identical if we use $\overline{Z} = 50$).

We now solve for infinite horizon values for E's value functions and entry thresholds where these functions will now depend on the value of Z as well c_I. The procedure is identical to the one used above, except for the fact that when we take expectations over values in the next period we need to recognize that Z will have transitioned if $Z < \overline{Z}$, and we need to check convergence for a set of value functions, entry strategies and pricing strategies, rather than a single vector.

B.2 Extension with Capacity Investment and Endogenous Marginal Costs

We start by specifying grids for the state variables. For the post-entry game, the grid is three-dimensional $(\theta_I^{NL}, K_I, K_E)$. For the pre-entry game it is two-dimensional. (θ_I^{NL}, K_I). In calculating the results in our base parameterization in Section 6, we use a 30-point grid for $\theta_I^{NL} \in [150,000, 250,000]$, a 40-point grid for $K_I \in [8,000, 58,000]$, and a 38-point grid for $K_E \in [4,000, 52,000]$. In addition, we specify a 237-point grid for the incumbent's local price (p_I^L) which runs from \$250 below the lowest monopoly price for local traffic (i.e., the monopoly price with maximum capacity and least connecting traffic) to just above the highest monopoly price. Finally, we create a $(\theta_I^{NL}, \widehat{\theta_I^{NL}}, K_I, p_I^L)$ grid that we will use in verifying the single-crossing condition.

For each of the duopoly grid points we solve for profits in the duopoly stage game (denote these $\pi_j^D(\theta_I^{NL}, K_I, K_E)$). With logit or nested logit demands and marginal costs that increase monotonically in a carrier's load factor, this pricing game has a unique equilibrium. For each point on the monopoly grid, we calculate the static monopoly prices, for both local and connecting traffic, and variable profits. We also calculate the derivative of the incumbent's profit with respect to its local price at every point on the price grid $\left(\frac{\partial \pi_I^M(p_I^L, p_I^{*NL}(p_I^L), \theta_I^{NL}, K_I)}{\partial p_I^L}\right)$, where we account for the fact that when the monopolist has a local price that is below the monopoly price, it will optimally set a higher connecting price (p_I^{NL}) in order to reduce its marginal cost. These derivatives will be used when solving the differential equations for the incumbent's limit pricing strategy. We can also use it to verify that the first condition in the Malaith and von Thadden theorem (Appendix A), which only relates to the shape of the monopoly profit function, is satisfied.[78] The second condition can be confirmed analytically as, holding prices and capacity fixed, marginal costs increase in θ_I^{NL}.

We then turn to solving the dynamic game, where we need to compute investment strategies under both monopoly and duopoly and the incumbent's pricing strategy before entry has occurred. Because we are not able to verify that the conditions needed for existence and uniqueness of equilibrium strategies will always hold prior to solving the game, we are reliant on a recursive approach where we start from the end of the game and verify that the conditions hold in every period.

B.2.1 Final Period (T)

Given our assumptions on the timing of when costs are incurred, in the final period there will be no changes to capacity; no entry; and, an incumbent monopolist will set static monopoly prices for both types of traffic. We use these to define the following value functions:

1. the value of a monopolist incumbent at the start of period T, $V_T^I(\theta_{I,T}^{NL}, K_{I,T})$, for each monopoly grid point. This is equal to the variable profit from serving both types of traffic at static monopoly prices, less the capacity cost, $\gamma_I^K K_{I,T}$.

2. the value of a potential entrant at the start of period T, $V_T^E(\theta_{I,T}^{NL}, K_{I,T}) = 0$, for each monopoly grid point.

[78] In this model, the relevant Mailath and von Thadden theorem replaces $c_{I,t}$ with the unobserved factor $\theta_{I,t}^{NL}$, and the price with the price set for local traffic.

3. the values of duopolists at the start of period T, $\phi^I_T(\theta^{NL}_{I,T}, K_{I,T}, K_{E,T})$ and $\phi^E_T(\theta^{NL}_{I,T}, K_{I,T}, K_{E,T})$, which are equal to duopoly variable profits less capacity costs.

B.2.2 Earlier Period (t)

We then proceed through all earlier periods recursively. For each period, we work as follows:

Capacity Choice.

Monopoly. We first solve the capacity choice, $K^*_{I,t+1}(\theta^{NL}_{I,t}, K_{I,t})$, of a monopolist incumbent that decides to change its capacity. For each $(\theta^{NL}_{I,t}, K_{I,t})$ grid point we can calculate the expected continuation value from each $K_{I,t+1}$ (on the same grid) taking into account the non-fixed component of the adjustment cost.

$$CV_I(K_{I,t+1}|\theta^{NL}_{I,t}, K_{I,t}) = \beta \int_{\underline{\theta^{NL}_I}}^{\overline{\theta^{NL}_I}} V^I_{t+1}(\theta^{NL}_{I,t+1}, K_{I,t+1})\psi(\theta^{NL}_{I,t+1}|\theta^{NL}_{I,t})d\theta^{NL}_{I,t+1} - \zeta(K_{I,t+1} - K_{I,t})^2$$

where the integration is performed using the trapezium rule. We then find $K^*_{I,t+1}(\theta^{NL}_{I,t}, K_{I,t})$ by maximizing this continuation value, interpolating over the grid points using a cubic spline (so that a capacity choice that is not at one of the grid points can be optimal). With $K^*_{I,t+1}(\theta^{NL}_{I,t}, K_{I,t})$ in hand, we can then compute the probability that the incumbent changes its capacity given the distribution of fixed adjustment costs, the expected fixed adjustment cost given that it chooses to change capacity ($\eta^*_{I,t}(K^*_{I,t+1}, \theta^{NL}_{I,t}, K_{I,t})$) and the incumbent's expected value (which we call the intermediate value function) before the adjustment cost is drawn:

$$\begin{aligned} V^I_{int-t}(\theta^{NL}_{I,t}, K_{I,t}) = {} & \Pr(\text{capacity change}) \times [CV_I(K^*_{I,t+1}|\theta^{NL}_{I,t}, K_{I,t}) - \eta^*_{I,t}(K^*_{I,t+1}, \theta^{NL}_{I,t}, K_{I,t})] + ... \\ & (1 - \Pr(\text{capacity change})) \times CV_I(K_{I,t}|\theta^{NL}_{I,t}, K_{I,t}) \end{aligned}$$

We also calculate the value, before the adjustment cost is drawn, of the potential entrant

$$\begin{aligned} V^E_{int-t}(\theta^{NL}_{I,t}, K_{I,t}) = {} & \Pr(\text{capacity change}) \times \beta \int_{\underline{\theta^{NL}_I}}^{\overline{\theta^{NL}_I}} V^E_{t+1}(\theta^{NL}_{I,t+1}, K^*_{I,t+1})\psi(\theta^{NL}_{I,t+1}|\theta^{NL}_{I,t})d\theta^{NL}_{I,t+1} + ... \\ & (1 - \Pr(\text{capacity change})) \times \beta \int_{\underline{\theta^{NL}_I}}^{\overline{\theta^{NL}_I}} V^E_{t+1}(\theta^{NL}_{I,t+1}, K_{I,t})\psi(\theta^{NL}_{I,t+1}|\theta^{NL}_{I,t})d\theta^{NL}_{I,t+1} \end{aligned}$$

Duopoly. Under duopoly we have to solve for the capacity policies of both firms at each $(\theta^{NL}_{I,t}, K_{I,t}, K_{E,t})$ grid point. To do this, we simultaneously solve the pair of first-order conditions that define optimal choices if capacity is changed. In our presented examples, we assume that E has no adjustment costs, but we also find the probability that I will change its capacity. For E, the continuation value given a capacity choice $K_{E,t+1}$, where I chooses $K^*_{I,t+1}$ if it changes its capacity, is

$$CV_E(K_{I,t+1},K_{E,t+1}|\theta^{NL}_{I,t},K_{I,t},K_{E,t}) = \left[\begin{array}{c} \Pr(I \text{ capacity change}) \times ... \\ \beta \int_{\underline{\theta^{NL}_I}}^{\overline{\theta^{NL}_I}} \phi^E_{t+1}(\theta^{NL}_{I,t+1},K_{I,t+1},K_{E,t+1})\psi(\theta^{NL}_{I,t+1}|\theta^{NL}_{I,t})d\theta^{NL}_{I,t+1} \end{array}\right] + ...$$

$$\left[\begin{array}{c} (1-\Pr(I \text{ capacity change})) \times ... \\ \beta \int_{\underline{\theta^{NL}_I}}^{\overline{\theta^{NL}_I}} \phi^E_{t+1}(\theta^{NL}_{I,t+1},K_{I,t},K_{E,t+1})\psi(\theta^{NL}_{I,t+1}|\theta^{NL}_{I,t})d\theta^{NL}_{I,t+1} \end{array}\right]$$

where we perform integration using the trapezium rule and then calculate numerical derivatives to find the value of the first-order condition $\left(\frac{\partial CV_E(K_{I,t+1},K_{E,t+1}|\theta^{NL}_{I,t},K_{I,t},K_{E,t})}{\partial K_{E,t+1}}\right)$ at each of the grid points. To find the value of the first-order conditions at $(K_{I,t+1},K_{E,t+1})$ values that are not on the grid we use MATLAB's piecewise cubic Hermite interpolation. Of course, we would like there to be a unique equilibrium in the capacity choice game. We have examined the shape of the reaction functions for many parameters and periods and have consistently found that the reaction functions of both firms have been quite linear in the other firm's capacity. Under linearity, there will almost necessarily be a single equilibrium. Having solved for the capacity choices, we then calculate the values $\phi^I_{int-t}(\theta^{NL}_{I,t},K_{I,t},K_{E,t})$ and $\phi^E_{int-t}(\theta^{NL}_{I,t},K_{I,t},K_{E,t})$, which are defined prior to I's fixed adjustment cost being drawn, in a similar fashion to above.

Entry. We calculate E's entry strategy at each point on the monopoly grid when it has not yet entered the market.[79] E will want to enter whenever $\phi^E_{int-t}(q^{NL}_{I,t},K_{I,t},0)-\kappa_t > V^E_{int-t}(\theta^{NL}_{I,t},K_{I,t})$, where κ_t is the draw of entry costs, so that $\kappa^*_t(\theta^{NL}_{I,t},K_{I,t}) = \phi^E_{int-t}(\theta^{NL}_{I,t},K_{I,t},0)-V^E_{int-t}(\theta^{NL}_{I,t},K_{I,t})$. We assume that κ_t is drawn from a distribution $G(\kappa)$ on $[0,\overline{\kappa}]$ where we set $\overline{\kappa}$ =\$100 million. To generate a fully separating equilibrium we need the probability of entry to be on the (0,1) interval and to be strictly monotonically increasing in $\theta^{NL}_{I,t+1}$, properties that we verify.[80] We then calculate the pdf function $g(\kappa^*_t(\theta^{NL}_{I,t},K_{I,t}))$ and $\frac{\partial\kappa^*_t(\theta^{NL}_{I,t},K_{I,t})}{\partial\theta^{NL}_{I,t}}$ (numerically) for every grid point, together with the expected entry cost if the firm enters.

Pricing/Market Competition.

Duopoly. For the duopoly game we have already calculated the equilibrium profits for each $(\theta^{NL}_{I,t},K_{I,t},K_{E,t})$ combination. Therefore, we can simply calculate the beginning of period firm values at each grid point as

$$\phi^j_t(\theta^{NL}_{I,t},K_{I,t},K_{E,t}) = \pi^D_j(\theta^{NL}_{I,t},K_{I,t},K_{E,t}) + \phi^j_{int-t}(\theta^{NL}_{I,t},K_{I,t}K_{E,t})$$

Monopoly. Here we have to solve for the limit pricing schedule having verified that the signaling payoff function satisfies the properties of belief monotonicity, type monotonicity and single-crossing.

[79] Note that here the θ^{NL}_I grid is being interpreted as the entrant's beliefs about the incumbent's connecting traffic. Of course, in a fully separating equilibrium, these beliefs are correct.

[80] Note that in the last periods of the game where the entry cost will typically be much bigger than the PDV value of profits of a new entrant, the probability of entry may be numerically indistinguishable from zero due to rounding error. In this case, the incumbent's pricing strategy is set equal to static monopoly pricing.

The signaling payoff function is

$$\begin{aligned}\Pi^{I,t}(\theta_{I,t}^{NL},\widehat{\theta_{I,t}^{NL}},p_{I,t}^{L},K_{I,t}) = \pi_I^M(p_{I,t}^L,p_I^{*NL}(p_{I,t}^L),\theta_{I,t}^{NL},K_{I,t}) + ...\\ (1-G(\kappa_t^*(\widehat{\theta_{I,t}^{NL}},K_{I,t}))V_{int-t}^I(\theta_{I,t}^{NL},K_{I,t}) + ...\\ G(\kappa_t^*(\widehat{\theta_{I,t}^{NL}},K_{I,t}))\phi_{int-t}^I(\theta_{I,t}^{NL},K_{I,t},0)\end{aligned}$$

Given a value of $K_{I,t}$, we can verify, numerically, the remaining conditions of the Mailath and von Thadden theorem (Appendix A) required for uniqueness of a fully separating equilibrium. These are: (i) $\Pi_2^{I,t}(\theta_{I,t}^{NL},\widehat{\theta_{I,t}^{NL}},p_{I,t}^{L},K_{I,t}) \neq 0$ for all $(\theta_{I,t}^{NL},\widehat{\theta_{I,t}^{NL}},p_{I,t}^{L},K_{I,t})$, which, given the monotonicity of $\kappa_t^*(\widehat{\theta_{I,t}^{NL}},K_{I,t})$ simply involves verifying that $V_{int-t}^I(\theta_{I,t}^{NL},K_{I,t}) > \phi_{int-t}^I(\theta_{I,t}^{NL},K_{I,t},0)$ [belief monotonicity]; and (ii) $\frac{\Pi_3^{I,t}(\theta_{I,t}^{NL},\widehat{\theta_{I,t}^{NL}},p_{I,t}^{L},K_{I,t})}{\Pi_2^{I,t}(\theta_{I,t}^{NL},\widehat{\theta_{I,t}^{NL}},p_{I,t}^{L},K_{I,t})}$ is a monotone function of $\theta_{I,t}^{NL}$ for all, $\widehat{\theta_{I,t}^{NL}}$ and all $p_{I,t}^L$ below the local static monopoly price [single-crossing]. For each $(\theta_{I,t}^{NL},\widehat{\theta_{I,t}^{NL}},K_{I,t})$ grid point we first compute

$$\frac{\Pi_3^{I,t}(\theta_{I,t}^{NL},\widehat{\theta_{I,t}^{NL}},p_{I,t}^{L},K_{I,t})}{\Pi_2^{I,t}(\theta_{I,t}^{NL},\widehat{\theta_{I,t}^{NL}},p_{I,t}^{L},K_{I,t})} = \frac{\frac{\partial \pi_I^M(p_{I,t}^L,p_I^{*NL}(p_{I,t}^L),\theta_{I,t}^{NL},K_{I,t})}{\partial p_{I,t}^L}}{-g(\kappa_t)\left\{V_{int-t}^I(\theta_{I,t}^{NL},K_{I,t}) - \phi_{int-t}^I(\theta_{I,t}^{NL},K_{I,t},0)\right\}}$$

at each of our 300 incumbent local price grid points (recall that we have already calculated the numerator). For each $(\widehat{\theta_{I,t}^{NL}},K_{I,t},p_{I,t}^L)$ grid point (for local prices below the static monopoly price), we then take differences with respect to $\theta_{I,t}^{NL}$ and verify that there are no changes in sign. The same calculations show that the single-crossing condition in the Ramey theorem in Appendix A, will also be satisfied.

If these conditions hold, we can then calculate the equilibrium limit pricing schedule for a given $K_{I,t}$, by solving the Mailath and von Thadden (2013) differential equation with a boundary condition where a firm with connecting traffic equal to $\overline{\theta_I^{NL}}$ charges the static monopoly price. The form of the differential equation is

$$\frac{\partial p_{I,t}^{*L}(\theta_{I,t}^{NL},K_{I,t})}{\partial \theta_{I,t}^{NL}} = \frac{g(\kappa_t^*(\theta_{I,t}^{NL},K_{I,t}))\frac{\partial \kappa_t^*(\theta_{I,t}^{NL},K_{I,t})}{\partial \theta_{I,t}^{NL}}\{V_{int-t}^I(\theta_{I,t}^{NL},K_{I,t}) - \phi_{int-t}^I(\theta_{I,t}^{NL},K_{I,t},0)\}}{\frac{\partial \pi_I^M(p_{I,t}^L,p_I^{*NL}(p_{I,t}^L),\theta_{I,t}^{NL},K_{I,t})}{\partial p_{I,t}^L}}$$

All of the terms in this expression have already been calculated for points on the grids, so when we solve the differential equation we interpolate them. The denominator is interpolated using a cubic spline, while the other terms are interpolated using piecewise cubic Hermite interpolation. The differential equation itself is solved in MATLAB using the `ode45` routine. We then calculate the beginning of period firm values as:

$$
\begin{aligned}
V_t^I(\theta_{I,t}^{NL}, K_{I,t}) = {} & \pi_I^M(p_{I,t}^{*L}, p_I^{NL}(p_{I,t}^{*L}), \theta_{I,t}^{NL}, K_{I,t}) - \gamma_I^K K_{I,t} + ... \\
& (1 - G(\kappa_t^*(\theta_{I,t}^{NL}, K_{I,t}))V_{int-t}^I(q_{I,t}^{NL}, K_{I,t}) + ... \\
& G(\kappa_t^*(\theta_{I,t}^{NL}, K_{I,t}))\phi_{int-t}^I(q_{I,t}^{NL}, K_{I,t}, 0) \\
V_t^E(\theta_{I,t}^{NL}, K_{I,t}) = {} & (1 - G(\kappa_t^*(\theta_{I,t}^{NL}, K_{I,t}))V_{int-t}^E(\theta_{I,t}^{NL}, K_{I,t}) + ... \\
& G(\kappa_t^*(\theta_{I,t}^{NL}, K_{I,t}))\phi_{int-t}^E(\theta_{I,t}^{NL}, K_{I,t}, 0)
\end{aligned}
$$

At this point we can then move on to capacity choices in the previous period.

C List of Dominant Incumbent Markets

In the following list (*) identifies markets in the subset of 65 markets where Southwest is observed for at least some quarters 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, Omaha-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(*)

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

Delta (DL): Albuquerque-Minneapolis(*), 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(*), Fresno-Salt Lake City(*), Fort Lauderdale-Minneapolis(*), Spokane-Minneapolis(*), Spokane-Salt Lake City, Jacksonville-LaGuardia(*), Los Angeles-Salt Lake City, LaGuardia-New Orleans(*), LaGuardia-Southwest Florida(*), LaGuardia-Tampa(*), Kansas City-Salt Lake City(*), Minneapolis-New Orleans(*), Minneapolis-Oklahoma City(*), Minneapolis-Omaha(*), Minneapolis-Providence(*), Minneapolis-Orange County(*), 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, Salt Lake City-Tuscon

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-Pittsburgh(*), Baltimore-Providence, Baltimore-Tampa, Columbus-Philadelphia(*), Jacksonville-Philadelphia(*), Colorado Springs-Phoenix(*), Las Vegas-Omaha, Las Vegas-Pittsburgh, Las Vegas-Tuscon, 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(*), Kansas City-Milwaukee; Airtran (FL): Baltimore-Milwaukee; Midway Airlines (JI): Jacksonville-Raleigh(*); ATA (TZ): Chicago Midway-Philadelphia, Chicago Midway-Southwest Florida.

D 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.[81] 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 (see also Appendices H and I) 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 (Appendix E).

We estimate a generalized gravity equation using our full sample of markets, where the expected number of passengers traveling on a route is allowed to be 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 endogeneity problems arising from passenger flows later in our sample being affected by Southwest's route-level entry decisions and incumbents responses to them.[82]

$$\mathbb{E}\left[\text{Passengers}_{o,d,t}\right] = \exp\left\{\begin{array}{c} \beta_0 + \beta_1 Q_t + \beta_2 \log(\text{Distance}_{o,d}) + \beta_2 \log(\text{Distance}^2_{o,d}) + ... \\ \beta_3 \log(\text{Originating}_{o,1993}) + \beta_4 \log(\text{Originating}_{d,1993}) + ... \\ \beta_5 \log(\text{Destination}_{o,1993}) + \beta_6 \log(\text{Destination}_{d,1993}) + ... \\ \text{interactions between } \log(\text{Distance}) \\ \text{and originating and destination variables} \end{array}\right\}$$

where o is the origin airport, d is the destination airport and Q_t are quarter dummies. $\text{Originating}_{j,1993}$ is the number of DB1 passengers in Q1 1993 with itineraries in originating at $j = \{o, d\}$. $\text{Destination}_{j,1993}$ is the number of DB1 passengers in Q1 1993 with itineraries where $j = \{o, d\}$ is the final destination. 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. The estimates on several coefficients are shown in Table D.1.

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%.

[81] 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 many more visitors than would be expected based on their populations.

[82] However, our measure will vary across quarters because of the quarter dummies included in the specification.

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

	DB1 Passengers
log(Distance)	10.43***
	(0.061)
log(Distance)^2	-0.68***
	(0.004)
log(Destination$_{o,1993}$)	-5.30***
	(0.084)
log(Destination$_{o,1993}$)$\times$ log(Distance)	2.49***
	(0.035)
log(Destination$_{d,1993}$)	4.46***
	(0.024)
log(Destination$_{d,1993}$)$\times$ log(Distance)	-0.34***
	(0.005)
log(Originating$_{o,1993}$)	0.01***
	(0.0002)
log(Originating$_{o,1993}$)$\times$ log(Distance)	-0.05***
	(0.002)
log(Originating$_{d,1993}$)	-3.21***
	(0.085)
log(Originating$_{d,1993}$)$\times$ log(Distance)	2.06***
	(0.035)
Observations	148,158
Pseudo-R^2	0.803

Note: *** denotes statistical significance at the 1% level.

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

As outlined in Section 4, 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 1,542 markets to predict Southwest's entry at the route-level. There is one observation per market, and the dependent variable (Entry4$_{m,t}$) is equal to 1 if Southwest enters market m within four quarters of starting to operate at both endpoint airports (i.e., within four quarters of becoming a potential entrant). As noted in Section 4, around 70% of all of the Southwest entries that we observe happen within four quarters.

$$\Pr(Entry4_{m,t}|X,t) = \Phi(\tau_t + \alpha X_{m,t})$$

where τ_t contains 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: the Phase 1 average our estimated market size[83] (also Market Size^2), excluding the last four quarters of Phase 1. For those markets where there are less than or equal to four quarters observed for Phase 1, we average over all of the Phase 1 quarters in the data for that market;
- Slot: a dummy that is equal to 1 if either endpoint airport is a slot-controlled airport;
- Leisure Destination: 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 Phase 1 average HHI, based on passenger numbers, excluding the last four quarters of Phase 1. For those markets where there are less than or equal to four quarters observed for Phase 1, we average over all of the Phase 1 quarters in the data for that market.

For each of the endpoint airports 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;
- Secondary Airport: a dummy equal to 1 for an airport other than the largest in a multiple airport city;
- Incumbent Presence: the Phase 1 average of the average proportion of all passenger originations accounted for by the incumbents on route m at the airport, excluding the last four quarters of Phase 1 (also Incumbent Presence^2). For those markets where there are less than or equal to four quarters observed for Phase 1, we average over all of the Phase 1 quarters in the data for that market;
- Southwest Presence: the Phase 1 average of the proportion of all passenger originations accounted for by Southwest at the airport, excluding the last four quarters of Phase 1 (also Southwest Presence^2). For those markets where there are less than or equal to four quarters observed for Phase 1, we average over all of the Phase 1 quarters in the data for that market.

The results are reported in Table E.1, where by "origin" we simply mean the airport with the three-letter IATA airport code that is alphabetically first for the airport-pair. Larger market size, shorter distances, leisure destinations and more concentrated markets are all more likely to attract entry.

[83] See Appendix D for details.

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

	Entry by Southwest Within Four Quarters	
Distance	-0.487**	
	(0.241)	
Distance^2	0.019	
	(0.040)	
Long Distance	0.052	
	(0.201)	
Average Pop.	-0.401***	
	(0.131)	
Average Pop.^{2}	0.028***	
	(0.008)	
Market Size	0.334***	
	(0.048)	
Market Size^2	-0.009***	
	(0.002)	
Slot	-1.918***	
	(0.527)	
Leisure Destination	0.650***	
	(0.196)	
Big City	-0.049	
	(0.150)	
Southwest Alternate Airport	-0.243	
	(0.227)	
HHI	1.192***	
	(0.323)	
Airport-Specific Variables	Origin	Destination
Primary Airport	0.567**	0.449*
	(0.283)	(0.236)
Secondary Airport (origin)	0.910***	0.229
	(0.238)	(0.255)
Incumbent Presence	-5.607	-11.547**
	(9.518)	(5.599)
Incumbent Presence^2	26.293	22.073**
	(28.467)	(10.163)
Southwest Presence	1.947**	-0.591
	(0.991)	(1.063)
Southwest Presence^2	-2.564**	-0.029
	(1.204)	(1.286)
Observations	1,524	
Pseudo-R^2	0.399	

Notes: Specification also includes dummies for the quarter in which Southwest becomes a potential entrant. Robust standard errors in parentheses. ***,**,* denote statistical significance at the 1, 5 and 10% levels respectively.

F Balance Table

This Appendix provides a 'balance table' for the dominant firm sample, where we divide markets into three groups based on the probability of Southwest entry implied by the estimated first-stage probit (see Appendix E).

For each market, we first calculate the mean of the variable across Phase 1 observations (i.e., before Southwest is a potential entrant, with two exceptions noted below), and the reported means are averages across these market-level observations. Standard deviations are in parentheses and the right-hand columns present p-values from tests that the means of the variables are the same across the three groups.

In most cases, the mean values for the intermediate probability of entry markets lie between those for the low and high probability markets (e.g., HHI, market size, and average incumbent Phase 1 fare). In other cases, for example, average endpoint population or multi-airport endpoints, we cannot reject the hypothesis that the means for the three different groups are the same. In the case of the load factor, the value for intermediate entry probability markets is slightly lower than for the high entry probability markets, but the size of the difference is quite small, and we cannot reject the hypothesis that the population means for the intermediate and high probability markets are equal.

The final two rows report statistics on Southwest's average market share during Phase 2, as a measure of how much competition Southwest may offer via connecting service (by definition it is not providing significant non-stop service in Phase 2). We would be concerned if Southwest's share was highest in the intermediate tercile where we see the largest decline in prices, as increased competition from connecting service could provide an alternative explanation for why the incumbent lowers prices. This is not the case, and Southwest's share is largest, on average, in the low probability tercile. We noticed that this result partly reflects relatively large shares for Southwest on a set of routes out of Minneapolis (MSP). Southwest entered MSP in 2009 with service to Chicago-Midway, which provides a convenient connection point for a number of Southwest routes. If we exclude MSP routes there is not a significant difference in Southwest's share across the low and intermediate terciles.

Table F.1: Balance Table for Dominant Firm Sample

	Market Probability of WN Entry			p-value for 2-Sided Test of Equality of Means		
Variable Description	Low	Intermediate	High	Low and Int.	Int. and High	All Three
Market entered by	0.194	0.583	0.838	0.000	0.016	0.000
Southwest (dummy)	(0.401)	(0.500)	(0.374)			
Incumbent is a legacy	0.917	0.806	0.784	0.178	0.821	0.268
carrier (dummy)	(0.280)	(0.401)	(0.417)			
Non-stop Distance	1,822.9	1,113.1	848.0	0.000	0.030	0.000
(roundtrip)	(804.1)	(549.1)	(471.0)			
Market Size	3,317.0	5,373.7	10,937.3	0.020	0.002	0.000
	(2,616.1)	(4,461.6)	(9,184.4)			
Average endpoint	2,860,283	2,596,064	3,040,410	0.546	0.338	0.618
city population	(1,855,009)	(1,842,922)	(2,084,905)			
One or both endpoint airport is hub	0.917	0.778	0.676	0.104	0.335	0.040
for dominant incumbent	(0.280)	(0.422)	(0.474)			
One or both endpoint cities is	0.528	0.472	0.703	0.643	0.046	0.117
multi-airport market	(0.506)	(0.506)	(0.463)			
One or both endpoints is a	0.083	0.023	0.216	1.000	0.014	0.030
leisure destination	(0.280)	(0.167)	(0.417)			
Phase 1 route HHI	0.563	0.792	0.882	0.000	0.010	0.000
	(0.180)	(0.159)	(0.129)			
Phase 1 proportion of traffic	0.847	0.837	0.826	0.660	0.716	0.744
making connections	(0.097)	(0.105)	(0.138)			
Phase 1 load factor	0.654	0.588	0.593	0.009	0.835	0.018
	(0.119)	(0.090)	(0.092)			
Incumbent Phase 1	517.43	467.37	438.68	0.134	0.343	0.041
direct fare ($)	(144.33)	(135.52)	(120.62)			
Phase 2 Southwest	0.032	0.008	0.001	0.005	0.075	0.000
share	(0.040)	(0.016)	(0.003)			
Phase 2 Southwest	0.014	0.008	0.001	0.367	0.073	0.003
share, excluding MSP	(0.019)	(0.016)	(0.003)			
Number of markets	36	36	37			

Notes: The left-hand columns report the mean of the variable during Phase 1 (before Southwest is a potential entrant), unless otherwise noted, where we first average across quarters for each market, and then report the average across markets. The standard deviation (in parentheses) is the across-market standard deviation. The right-hand columns report the p-values from t-tests for equality of the means for low/intermediate and intermediate/high groups, and a test for equality of all three means (implemented using `mvtest means` in STATA). We assume that, under the null hypothesis, the variances may be heterogeneous across the three groups for continuous variables such as population and market size, and that they are the same across groups for dummy variables such as whether the market was entered.

G Reduced-Form Results for the Distribution of Prices

Tables G.1-G.3 present the results of the GS regressions using the 25^{th}, 50^{th} or 75^{th} percentiles of the price distribution on the incumbent to form the dependent variable, rather than the average fare.

We can also repeat the EE analysis, which in Section 4 used average prices and yields, using the percentiles. Corresponding to the column (1) of Table 4, which showed results for the average yield, Table G.4 shows the results for the percentiles of the yield distribution.

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

		Phase 1		*Phase 2*		*Phase 3*
Fare						
	t_0-8	-0.047	t_0	-0.049	t_e	-0.455^{***}
		(0.029)		(0.038)		(0.073)
	t_0-7	0.006	t_0+1	-0.092^{**}	t_e+1	-0.518^{***}
		(0.033)		(0.046)		(0.077)
	t_0-6	-0.033	t_0+2	-0.106^{**}	t_e+2	-0.529^{***}
		(0.031)		(0.044)		(0.078)
	t_0-5	-0.040	t_0+3	-0.132^{***}	t_e+3	-0.561^{***}
		(0.034)		(0.040)		(0.082)
	t_0-4	0.030	t_0+4	-0.097^{**}	t_e+4	-0.580^{***}
		(0.036)		(0.041)		(0.086)
	t_0-3	0.010	t_0+5	-0.105^{**}	t_e+5	-0.576^{***}
		(0.034)		(0.048)		(0.085)
	t_0-2	-0.0287	t_0+6-12	-0.165^{***}	t_e+6-12	-0.521^{***}
		(0.029)		(0.055)		(0.084)
	t_0-1	-0.032	t_0+13+	-0.280^{***}	t_e+13+	-0.505^{***}
		(0.025)		(0.058)		(0.086)
Yield						
	t_0-8	-0.027^{**}	t_0	-0.017	t_e	-0.185^{***}
		(0.013)		(0.018)		(0.040)
	t_0-7	0.013	t_0+1	-0.017	t_e+1	-0.202^{***}
		(0.017)		(0.020)		(0.042)
	t_0-6	-0.017	t_0+2	-0.031	t_e+2	-0.200^{***}
		(0.014)		(0.019)		(0.045)
	t_0-5	-0.014	t_0+3	-0.041^{**}	t_e+3	-0.204^{***}
		(0.014)		(0.019)		(0.043)
	t_0-4	0.017	t_0+4	-0.035^{*}	t_e+4	-0.210^{***}
		(0.016)		(0.021)		(0.045)
	t_0-3	0.011	t_0+5	-0.040^{*}	t_e+5	-0.220^{***}
		(0.016)		(0.021)		(0.046)
	t_0-2	-0.008	t_0+6-12	-0.066^{**}	t_e+6-12	-0.215^{***}
		(0.015)		(0.025)		(0.049)
	t_0-1	-0.009	t_0+13+	-0.110^{***}	t_e+13+	-0.231^{***}
		(0.015)		(0.034)		(0.052)

Notes: Estimates of specification (6) when dependent variable is log of the 25^{th} percentile passenger-weighted fare ("Fare") or this fare divided by the non-stop route distance ("Yield"). The adjusted R^2s are 0.71 ("Fare") and 0.74 ("Yield"). Other notes from Table 3 apply here.

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

		Phase 1		*Phase 2*		*Phase 3*
Fare						
	$t_0 - 8$	-0.0384	t_0	-0.089^{**}	t_e	-0.544^{***}
		(0.032)		(0.034)		(0.092)
	$t_0 - 7$	-0.015	$t_0 + 1$	-0.105^{**}	$t_e + 1$	-0.654^{***}
		(0.036)		(0.047)		(0.092)
	$t_0 - 6$	-0.030	$t_0 + 2$	-0.112^{***}	$t_e + 2$	-0.657^{***}
		(0.036)		(0.041)		(0.097)
	$t_0 - 5$	-0.012	$t_0 + 3$	-0.123^{***}	$t_e + 3$	-0.721^{***}
		(0.037)		(0.040)		(0.103)
	$t_0 - 4$	-0.035	$t_0 + 4$	-0.161^{***}	$t_e + 4$	-0.712^{***}
		(0.039)		(0.041)		(0.107)
	$t_0 - 3$	-0.018	$t_0 + 5$	-0.166^{***}	$t_e + 5$	-0.671^{***}
		(0.035)		(0.050)		(0.106)
	$t_0 - 2$	-0.082^{***}	$t_0 +$ 6-12	-0.234^{***}	$t_e +$ 6-12	-0.615^{***}
		(0.032)		(0.054)		(0.105)
	$t_0 - 1$	-0.066^{**}	$t_0 + 13+$	-0.345^{***}	$t_e + 13+$	-0.601^{***}
		(0.032)		(0.062)		(0.108)
Yield						
	$t_0 - 8$	-0.024	t_0	-0.047^{**}	t_e	-0.302^{***}
		(0.017)		(0.022)		(0.065)
	$t_0 - 7$	-0.003	$t_0 + 1$	-0.037	$t_e + 1$	-0.341^{***}
		(0.021)		(0.028)		(0.066)
	$t_0 - 6$	-0.014	$t_0 + 2$	-0.050^{*}	$t_e + 2$	-0.340^{***}
		(0.024)		(0.025)		(0.069)
	$t_0 - 5$	0.007	$t_0 + 3$	-0.060^{**}	$t_e + 3$	-0.361^{***}
		(0.022)		(0.024)		(0.071)
	$t_0 - 4$	-0.023	$t_0 + 4$	-0.081^{***}	$t_e + 4$	-0.371^{***}
		(0.022)		(0.028)		(0.074)
	$t_0 - 3$	-0.006	$t_0 + 5$	-0.078^{**}	$t_e + 5$	-0.370^{***}
		(0.023)		(0.030)		(0.075)
	$t_0 - 2$	-0.053^{**}	$t_0 +$ 6-12	-0.139^{***}	$t_e +$ 6-12	-0.365^{***}
		(0.023)		(0.035)		(0.077)
	$t_0 - 1$	-0.041^{*}	$t_0 + 13+$	-0.210^{***}	$t_e + 13+$	-0.388^{***}
		(0.023)		(0.050)		(0.084)

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 0.70 ("Fare") and 0.81 ("Yield"). Other notes from Table 3 apply here.

Table G.3: Incumbent Pricing In Response to Southwest's Actual and Potential Entry: 75$^{\text{th}}$ Percentile of Prices

		Phase 1		*Phase 2*		*Phase 3*
<u>Fare</u>						
	$t_0 - 8$	-0.051	t_0	-0.125^{***}	t_e	-0.479^{***}
		(0.032)		(0.042)		(0.089)
	$t_0 - 7$	-0.051	$t_0 + 1$	-0.158^{***}	$t_e + 1$	-0.621^{***}
		(0.034)		(0.043)		(0.092)
	$t_0 - 6$	-0.065^{*}	$t_0 + 2$	-0.177^{***}	$t_e + 2$	-0.617^{***}
		(0.038)		(0.045)		(0.098)
	$t_0 - 5$	-0.060	$t_0 + 3$	-0.162^{***}	$t_e + 3$	-0.682^{***}
		(0.039)		(0.044)		(0.105)
	$t_0 - 4$	-0.040	$t_0 + 4$	-0.193^{***}	$t_e + 4$	-0.700^{***}
		(0.041)		(0.044)		(0.103)
	$t_0 - 3$	-0.041	$t_0 + 5$	-0.179^{***}	$t_e + 5$	-0.672^{***}
		(0.036)		(0.050)		(0.103)
	$t_0 - 2$	-0.081^{**}	$t_0 +$ 6-12	-0.228^{***}	$t_e +$ 6-12	-0.652^{***}
		(0.037)		(0.061)		(0.102)
	$t_0 - 1$	-0.074^{**}	$t_0 +$ 13+	-0.372^{***}	$t_e +$ 13+	-0.613^{***}
		(0.034)		(0.069)		(0.111)
<u>Yield</u>						
	$t_0 - 8$	-0.029	t_0	-0.080^{***}	t_e	-0.353^{***}
		(0.022)		(0.028)		(0.079)
	$t_0 - 7$	-0.031	$t_0 + 1$	-0.086^{***}	$t_e + 1$	-0.422^{***}
		(0.021)		(0.032)		(0.079)
	$t_0 - 6$	-0.030	$t_0 + 2$	-0.097^{***}	$t_e + 2$	-0.428^{***}
		(0.023)		(0.031)		(0.083)
	$t_0 - 5$	-0.028	$t_0 + 3$	-0.086^{***}	$t_e + 3$	-0.454^{***}
		(0.024)		(0.031)		(0.086)
	$t_0 - 4$	-0.035	$t_0 + 4$	-0.114^{***}	$t_e + 4$	-0.470^{***}
		(0.025)		(0.033)		(0.088)
	$t_0 - 3$	-0.038^{*}	$t_0 + 5$	-0.111^{***}	$t_e + 5$	-0.470^{***}
		(0.023)		(0.036)		(0.086)
	$t_0 - 2$	-0.062^{**}	$t_0 +$ 6-12	-0.168^{***}	$t_e +$ 6-12	-0.471^{***}
		(0.025)		(0.045)		(0.086)
	$t_0 - 1$	-0.057^{**}	$t_0 +$ 13+	-0.273^{***}	$t_e +$ 13+	-0.493^{***}
		(0.023)		(0.052)		(0.098)

Notes: Estimates of specification (6) when dependent variable is log of the 75$^{\text{th}}$ percentile passenger-weighted fare ("Fare") or this fare divided by the non-stop route distance ("Yield"). The adjusted R^2s are 0.72 ("Fare") and 0.84 ("Yield"). Other notes from Table 3 apply here.

Table G.4: Second-Stage Ellison and Ellison Analysis with Percentiles of the Yield Distribution

	(1) 25$^{\text{th}}$ percentile	(2) 50$^{\text{th}}$ percentile	(3) 75$^{\text{th}}$ percentile
$SWPE_{m,t}$	0.00284	0.0164	-0.0142
	(0.0118)	(0.0154)	(0.0172)
$\widehat{\rho_m} \times SWPE_{m,t}$	-0.628***	-0.748***	-0.824***
	(0.0873)	(0.113)	(0.127)
$\widehat{\rho_m}^2 \times SWPE_{m,t}$	0.894***	0.877***	1.055***
	(0.117)	(0.152)	(0.170)
Observations	3,867	3,867	3,867

Notes: Specification equivalent to specification (1) in Table 4 except that a percentile of the yield distribution replaces the average yield as the dependent variable. Notes from Table 4 apply here.

H Analysis of Demand Dynamics

As explained in Section 4, one interpretation of Phase 2 price cuts is that incumbents are trying to increase customer loyalty. This strategy could help to deter entry, by reducing Southwest's expected demand, or increase the incumbent's expected profits in the duopoly game that follows entry.[84] In this Appendix we provide some evidence that suggests that lower prices do not significantly raise an incumbent's own demand in future quarters.

We estimate a simple nested logit demand model of the incumbent's demand, where the outside good is 'not flying' and different carriers flying the route are gathered in the single nest (see Appendix I.1 where we use the same demand model specification to estimate demand and marginal cost parameters for our parameterization of the dynamic limit pricing model in Section 5). Our market size measure is described in Appendix D. Our estimating equation is the standard one used with aggregate data, following Berry (1994), and given that we are focused here on understanding whether the incumbent can increase its future demand by lowering prices, we estimate the model using only (average) price and share observations for the incumbent. However, as well as the carrier's average price in the current period, we also include prices in previous quarters, and, if there is a significant loyalty effect, then we expect the coefficients on these lagged prices to also be negative. As we describe in Appendix I.1, our instruments for the current average price and the inside share are the one-quarter lagged jet fuel price, the interaction of this price and the non-stop route distance, the carrier's presence at the endpoints and a dummy for whether Southwest has entered the market. When we include price lags, we introduce appropriately lagged values of these variables as additional instruments. Our sample consists of dominant incumbent observations from the dominant firm markets, and we use observations either from Phases 1 or 3, or from all Phases, including Phase 2, when entry is threatened.

[84]Our empirical evidence in Section 4 indicates that price cuts are motivated by deterrence and not accommodation, as we do not observe large price cuts in the dominant incumbent sample markets where entry is most likely. Of course, an incumbent might not want to increase consumer loyalty if it expects entry, if this would cause the entrant to price more aggressively.

The estimated coefficients are shown in Table H.1. Columns (1)-(4) use observations from Phases 1 and 3 only, with the specifications including different lagged price variables. The F-statistics in the first-stage regressions (not reported) are all greater than 45. We observe that none of the coefficients on the lagged prices are statistically significant at the 5% level[85] and that they vary in sign, while the coefficient on the current price remains significant. Columns (5)-(8) repeat this analysis using observations from all phases to illustrate the robustness of our findings that lower current incumbent prices do not increase its future demand.

Table H.1: Nested Logit Demand Estimates for the Incumbent with Lagged Prices

	(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)
Fare ($100s)	-0.452***	-0.237*	-0.445***	-0.461***	-0.442***	-0.266**	-0.468***	-0.450***
	(0.0416)	(0.137)	(0.130)	(0.0661)	(0.0386)	(0.129)	(0.130)	(0.0634)
Inside Share	0.808***	0.853***	0.707***	0.754***	0.802***	0.852***	0.775***	0.797***
	(0.105)	(0.110)	(0.121)	(0.115)	(0.0969)	(0.102)	(0.116)	(0.110)
Fare_{t-1}		-0.189	-0.0340			-0.159	0.0259	
		(0.135)	(0.218)			(0.126)	(0.221)	
Fare_{t-2}			0.0621				0.0300	
			(0.224)				(0.221)	
Fare_{t-3}			0.0988				0.0800	
			(0.219)				(0.210)	
Fare_{t-4}			0.0121	0.0901*			0.00352	0.0652
			(0.139)	(0.0546)			(0.130)	(0.0504)
Phases	1 & 3	1 & 3	1 & 3	1 & 3	All	All	All	All
Observatons	4,251	4,015	3,466	3,627	5,352	5,053	4,385	4,632

Notes: Specifications also include a linear time trend, carrier dummies, a dummy for whether the incumbent is a hub carrier on the route, 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 are described in the text. The first four specifications use only observations from Phases 1 and 3, while the last four use observations from all phases. Robust standard errors in parentheses. ***,** ,* denote statistical significance at the 1, 5 and 10% levels respectively.

Taken on its own this evidence provides some evidence against demand dynamics being important, although it comes with at least three caveats. First, the standard errors on the lagged variables are large enough that we cannot formally reject quite substantial demand dynamics. Second, a more explicitly dynamic demand model estimated using individual-level data, which might include information on frequent-flyer program participation, might be better able to recover dynamics[86]; and, third, we are not directly testing whether the incumbent's lagged price affects Southwest's post-entry demand (apart from

[85] The p-value for the coefficient on the one-year lagged price in column (4) is 0.10, but the coefficient is positive, i.e. it has the 'wrong' sign.

[86] For example, it is possible that the future demand of some especially valuable travelers responds to price discounts in a way that we cannot detect with our data.

through the assumed nested logit structure) which is how a deterrence-based explanation would work. But, if we cannot identify significant effects on the incumbent's own demand, any effects on Southwest's demand are likely to be small. While these caveats mean that we would not claim that the results presented here are decisive, we discuss, in Section 4, several additional reasons why we believe that, even if they exist, incentives to build customer loyalty are unlikely to explain the large price reductions observed in the data for intermediate probability of entry markets.

I Calibration

In this Appendix, we detail how we calibrate our model. Our goal is to see whether our model predicts significant price shading, which varies with the probability of entry in the same way as in our data (Section 4) when we use parameters appropriate for the markets in our sample. We calibrate the key parameters without using any information on the incumbent's pricing when it is threatened with entry in Phase 2, introducing asymmetric information once we have calibrated the parameters in order to see the pricing patterns that are predicted.[87] We abstract away from some of the heterogeneity in both price reductions and entry patterns that exist in our data and, for this reason, we view what we do as calibration, rather than estimation.

I.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.[88] Markets are non-directional (so that we are adding the number of passengers across directions), and we use our gravity model-based definition of market size (Appendix D), added up across directions, to calculate market shares.[89] Travel on carriers other than the dominant incumbent and Southwest is included in the outside good. We do, however, include the number of other carriers that fly any passengers non-stop as a control in our specification of mean utility so that increased competition can raise the effective quality of the outside good. Viewing each carrier in the market as offering a single product, we assume the standard nested logit indirect utility specification with a single 'fly/do not fly' level of nesting (e.g., Berry (1994)):

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

where μ_j is a carrier j fixed 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 one of the endpoints 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 that are recorded in DB1 as serving passengers direct (i.e., non-stop or without a change of planes).

[87] The one set of parameters that we cannot calibrate/estimate is the support of the incumbent's marginal cost, because supports are intrinsically difficult to estimate, and here we are really interested in the support of the component of the incumbent's marginal cost that a potential entrant cannot observe. We choose a relatively narrow support (equal to just over one standard deviation of the observed innovations in marginal cost) so that incentives to limit price are not too great.

[88] 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 the size of our sample or the demand estimates.

[89] 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.

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

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

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 I.1 presents OLS and 2SLS estimates of the demand model.[90] In the latter case 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[91], 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 elasticity implied by the column (2) estimates is -2.4) 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 parameterize our model using $\widehat{\alpha} = -0.438$ and $\widehat{\lambda} = 0.814$. We homogenize across markets by using the mean θ for incumbents of 0.73, and a θ for Southwest of 0.63 for all markets.[92] When we solve the model we assume that carrier qualities are also fixed over time (i.e., we set the $\xi_{j,t}$s to zero). While this assumption could be relaxed if we assume that qualities are always observed, doing so would increase the computational burden significantly.

I.2 Marginal Costs

We use the demand estimates to infer carrier marginal costs in each market-quarter using static, complete information monopoly/Bertrand Nash first-order conditions using data from Phases 1 and 3 (i.e., excluding the period when we believe limit pricing may be happening). This is consistent with our assumption that there is complete information once E enters, but it does make a strong assumption about the fact that the incumbent prices statically except in Phase 2. The average implied marginal cost for the incumbent is \$262, or 16 cents per mile. On average, Southwest's marginal costs are 30% lower, or 5.3 cents per mile, than the incumbent's.[93] When we calibrate our model we assume that Southwest's

[90] The 2SLS estimates are qualitatively similar to those reported in Appendix H where we only use observations on the incumbent, but also include observations from Phase 2.

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

[92] We can back out implied values for $\theta_{j,m,t}$ from observed prices and market shares for each carrier-quarter. When these $\theta_{j,m,t}$s are regressed on route-quarter fixed effects and a Southwest dummy, we find that, on average, Southwest's θs is 0.096 lower than the incumbent's, which is consistent with Southwest having a similar market share but a lower price in Phase 3 (Table 2).

[93] The estimates of the differences come from regressing implied costs, or implied costs per mile, on a dummy for Southwest and route-quarter dummies. While publicly available accounting data does not conform to an economist's definition of marginal costs, these differences are consistent with informed estimates. For example, based on Department of Transportation Form 41 data, the MIT Airline Data project (http://web.mit.edu/airlinedata/www/default.html) reports that the average difference between legacy carriers' "operating costs per available seat mile (CASM)" and "operating costs per equivalent seat mile (CESM)" (this second measure adjust for distance) and those of Southwest over the period 1995 to 2010 were 3.7 and 6.1 cents respectively.

Table I.1: Nested Logit Demand: Selected Coefficient Estimates

	OLS	2SLS
Fare (\$00s, $\widehat{\alpha}$)	-0.314***	-0.438***
	(0.011)	(0.034)
Inside Share ($\widehat{\lambda}$)	0.741***	0.814***
	(0.033)	(0.073)
Hub Carrier	0.205***	0.240***
	(0.026)	(0.028)
Selected Carrier Dummies		
American	-0.034	-0.022
	(0.056)	(0.061)
Continental	0.157*	0.328***
	(0.085)	(0.099)
Delta	-0.147***	-0.168***
	(0.042)	(0.043)
Northwest	0.349***	0.609***
	(0.045)	(0.077)
United	-0.266***	-0.202***
	(0.075)	(0.077)
US Airways	0.103**	0.246***
	(0.044)	(0.055)
Southwest	0.146***	0.069
	(0.041)	(0.047)
Observations	6,096	6,096
R^2	0.299	-

Notes: Specification also includes a linear time trend, quarter of year dummies, dummies for some additional, smaller carriers, 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.

marginal costs are equal to \$167 and we allow the incumbent's marginal costs to lie between $\underline{c_I} = \$242$ and $\overline{c_I} = \$282$.

We also use the implied marginal costs to estimate an AR(1) process for how marginal cost evolve. To do so, we regress carrier-route-quarter marginal costs per mile on its value for the previous quarter, and controls that include quarter dummies, carrier dummies, interactions between the one-quarter lagged jet fuel price and route distance, market size, market population, distance and a dummy for whether one or both of the endpoint airports are slot-constrained.

Column (1) of Table I.2 shows the estimates when we pool observations for both incumbents and Southwest. 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 this is the value that we use in our calibration. We set the standard deviation of marginal cost innovations equal to \$36, which allows us to match the interquartile range for the changes in per-mile marginal costs based on the estimates in column (2) when we consider a representative market of 1,200 miles.[94] Given that the assumed range of marginal costs equals \$40, this means that marginal costs can move quickly from being 'low' to 'high', or vice-versa, within our range. All else equal this should mean that signaling incentives should not be too strong, which makes the fact that our calibrated model predicts significant shading a strong finding in support of our model.

Table I.2: Marginal Cost Evolution: Selected Coefficient Estimates

	(1) OLS All Carriers	(2) 2SLS All Carriers	(3) 2SLS Southwest	(4) 2SLS Incumbents
$\widehat{\text{MC per mile}}_{j,m,t-1}$	0.915*** (0.039)	0.975*** (0.024)	0.981*** (0.035)	0.961*** (0.012)
Observations	5,725	4,788	1,561	3,227
R^2	0.817	-	-	-

Notes: The dependent variable is $\widehat{\text{MC per mile}}_{j,m,t}$, 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.

I.3 Entry Probablities and Rescaled Market Size

The next step involves calculating some moments that describe Southwest's entry that we will seek to match when we choose the parameters of the entry cost distribution. We want to match variation in entry probabilities across markets and over time. The challenge is that we know from Section 4 and

[94]The distribution of estimated innovations has fatter tails than a normal, and we expect that there will be outliers that may reflect the limitations of our demand model rather than true marginal cost innovations.

Appendix E that there are many variables that appear to determine how attractive a market is for Southwest to enter, and we want to be able to calibrate our model without estimating a large number of parameters to take all of these factors into account. Therefore we estimate a Weibull hazard model using our full sample of markets, where we allow the same observed variables, including market size, that we included in the EE first-stage probit model to affect the probability of entry[95], and, as we describe below, we then use the estimated coefficients on these variables to rescale market size so that we create a new variable that takes all of these effects into account.[96] Duration is measured as the time since Southwest became a potential entrant, so that we can capture the pattern in the data that most entry happens quite quickly.[97]

We calculate the implied hazard that Southwest will enter in a particular quarter for each of the dominant incumbent markets in our sample.[98] The hazard rates vary significantly across markets and they fall over time. This provides significant variation to match when calibrating the entry cost parameters.

The next step is to rescale our market size variable so that it captures the effects of the other market-level variables included in the baseline hazard equation (i.e., we get the same predicted entry probabilities when only our rescaled market size variable enters the hazard as in our full hazard model). We then translate the resulting market sizes so that the smallest rescaled market size is equal to the smallest original market size measure for our dominant incumbent markets. Table I.3 shows how hazards vary and how rescaling plays out for three markets with Omaha as an endpoint. The entry probabilities after 10 periods are more than 50% lower than the entry probability in the second period. Las Vegas - Omaha is estimated to be an attractive market for Southwest (because Las Vegas is a tourist destination and it is a high presence focus city for Southwest), so that its rescaled market size is significantly larger than Minneapolis - Omaha even though our gravity-based market size measure is larger for the Minneapolis route.

I.4 Calibration of the Entry Cost Parameters

The remaining parameters are the distribution of entry costs. To be able to fit the panel variation in entry rates, we need to augment the model in Section 2. We assume that entry costs are normally distributed, but we allow the mean of the entry cost distribution to vary with rescaled market size and to increase over time. We view the variation with market size as reflecting the fact that our estimates of marginal costs are unlikely to capture all of the costs that carriers have when providing service on a

[95] There are two minor differences to the specification. First, we do not include the square of market size as an explanatory variable in the hazard model as this would complicate the rescaling of market size. Second, we include a dummy for a market being in the dominant firm sample, so that we exactly match the average level of entry observed in these markets during our sample period. As for the probit model, we use time-invariant variables that are measured before Southwest becomes a potential entrant.

[96] As with the probit model described in Appendix E, we define the values of the explanatory variables based on observations prior to Southwest becoming a potential entrant in order to reduce concerns about endogeneity.

[97] The exact definition is that we use the quarter of entry onto the route minus the quarter that Southwest became a potential entrant plus 0.25, where the addition is needed because the hazard model cannot be estimated when the exit occurs at the same moment the unit is placed at risk.

[98] This is done by calculating the survival probability, $S_{m,t}$, for each period, and then calculating the hazard rate as $\frac{(S_{m,t-1}-S_{m,t})}{S_{m,t-1}}$.

Table I.3: Weibull Hazard Model: Predicted Hazard Rates and Rescaled Market Size for 3 Markets

Route	Original Market Size	$\widehat{h_{m,2}}$	$\widehat{h_{m,10}}$	Rescaled Market Size
Las Vegas - Omaha	19,859	0.217	0.103	45,139
Omaha - St Louis	36,659	0.088	0.040	35,528
Minneapolis - Omaha	38,770	0.037	0.017	26,689

Notes: The table shows, for three example markets, the original market size (constructed as described in Appendix D), estimated probabilities of entry after two and ten quarters ("hazard rates"), conditional on not having entered in an earlier period, and our rescaled market size which captures all of the observed variables entering the linear index of the hazard model.

route and that some fixed costs, such as those associated with capacity, are likely to be bigger in larger markets. The increase in entry costs over time is more ad-hoc, but it allows us to capture the clear decrease in entry probabilities during Phase 2 in our data. One explanation would be that it is more attractive for Southwest to enter a route when it initially enters the endpoint airports, as airport entry by Southwest is usually associated with a lot of free advertising in the form of favorable press coverage, and is sometimes associated with explicit subsidies that may no longer be available if entry is delayed. For example, one of the subsidy schemes offered by Columbus International Airport grants carriers that have entered the airport in the last twelve months, waivers to all landing fees and $75,000 in marketing support or cost subsidies when they enter additional routes.[99] Another explanation is that Southwest's management may have limited attention and will focus more on identifying profitable opportunities during the initial build out of routes. Either story is plausible given that the increase in entry costs required to match the data is estimated to be small. In Section 6 we discuss an alternative theory that can lead to falling entry probabilities over time where there is permanent unobserved heterogeneity in attractiveness across routes.

Specifically, we assume that Southwest's entry costs in market m, t quarters after it became a potential entrant are normally distributed $N(\mu_{m,t}, \sigma^2)$. We use a single parameter for the standard deviation of entry costs because this is an important parameter for determining the amount of shading because it directly affects $g(\kappa)$ and therefore the value of the numerator in differential equation (4). We allow the log of the mean of the entry cost distribution to vary with the log of market size[100] and, in each period, the previous period's mean is multiplied by $(1 + \gamma_{m,1}t^{\gamma_{m,2}})$, where t is the number of quarters since Southwest became a potential entrant, for each of the first thirty periods since Southwest became a potential entrant. We assume that Southwest anticipates this increase, which can lead to quite a strong incentive to enter at once even if $\gamma_{m,1}$ is quite small. We allow the log of $\gamma_{m,1}$ (we restrict $\gamma_{m,1}$ to be positive so that entry costs do increase over time) and $\gamma_{m,2}$ to vary with a quadratic in rescaled market size.[101]

[99] "What's Behind Your Airport's New Nonstop Route?" by Jen Kinney, February 9, 2017, published at https://nextcity.org/daily/entry/airports-new-routes-announced-economics (accessed June 1, 2017).

[100] We initially calibrated the parameters for five sub-groups of markets with a single mean entry cost parameter and found that this particular formulation allowed us to match the variation across the sub-groups almost perfectly. In practice, the estimates imply that the relationship between mean entry costs and market size is almost linear.

[101] If we do not allow them to vary with market size we cannot match entry probabilities for the smallest and largest markets simultaneously. The types of incentives that airports offer carriers to fly on particular routes, and the attention

Table I.4: Calibration of Entry Costs: Parameter Estimates

	Constant	$\text{Log}(\frac{\text{Rescaled Market Size}}{100{,}000})$	
$\text{Log}\left(\frac{\text{Mean Entry Costs}}{10\text{ million}}\right)$	2.514 (0.009)	0.968 (0.009)	
$\text{Log}\left(\frac{\text{Std. Dev. of Entry Costs}}{1\text{ million}}\right)$	−1.6124 (0.272)	-	
	Constant	$\frac{\text{Rescaled Market Size}}{100{,}000}$	$\left(\frac{\text{Rescaled Market Size}}{100{,}000}\right)^2$
$\text{Log}(\gamma_1)$	−6.482 (1.406)	8.419 (5.232)	−13.140 (4.577)
γ_2	−2.054 (1.158)	−4.080 (4.145)	11.176 (3.717)

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

We perform the calibration by minimizing $\sum_{m=5,10,..,105}\sum_{t=2,..,20}\left(h_{m,t}-h_{m,t}(\theta,M'_m)\right)^2$ where $h_{m,t}$ is the hazard rate for market m in quarter t (since Southwest became a potential entrant) predicted by the Weibull model, and $h_{m,t}(\theta,M'_m)$ is the prediction of the structural model given rescaled market size M'_m, when we assume that the game has an infinite horizon. We reduce the computational burden by only using every fifth market for the calibration, when markets are ordered in terms of rescaled market size, and when we solve for the entry probabilities we do not, of course, need to solve for equilibrium limit pricing strategies because entry strategies are the same under complete information.

Table I.4 presents the parameter estimates and Figure I.1 shows how initial entry costs and the γ parameters vary with the size of the market. We report standard errors in parentheses beneath the parameters, although they only reflect the minimizing of square residuals part of the procedure, not the various adjustments and choices made prior to this stage. The mean entry cost parameters are identified precisely. For the median market in our data, the average initial entry cost is \$41.6 million, although it should be remembered that this includes the present discounted value of fixed costs which, in our model, Southwest commits to paying when it enters. We estimate that an increase in rescaled market size of 1,000 people increases mean entry costs by around \$1.2 million or around \$90 per Southwest passenger per quarter given an assumed discount factor of 0.98 and Southwest average post-entry market shares. This compares with average variable Southwest profits per passenger of around \$120. If we assumed that all of the variation in mean entry costs with market size reflects the fixed costs associated with capacities, we would infer that the remaining true sunk entry cost would be close to \$1.3 million, which seems plausible.[102] The standard deviation of entry costs is close to \$200,000, which does not seem unreasonable for the types of routes in our sample. Figure I.2 shows the implied path of the mean entry cost (including discounted fixed costs) and the probability of entry for the median market. The

that routes get from managers, may also vary with some factors that determine market size so the flexibility that we allow is not unreasonable.

[102] This calculation is done assuming that the relationship all of the way down to the intercept is linear, which would not be consistent with the assumed functional form, even though the relationship is clearly close to linear in the data.

Figure I.1: Variation of Initial Mean Entry Costs and Parameters Affecting Increase in Entry Costs over Time With Rescaled Market Size

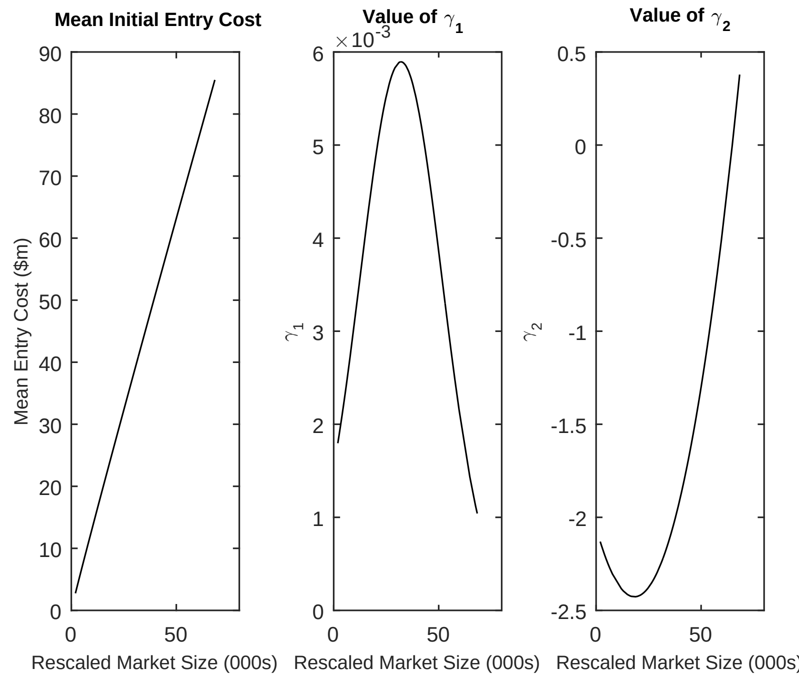
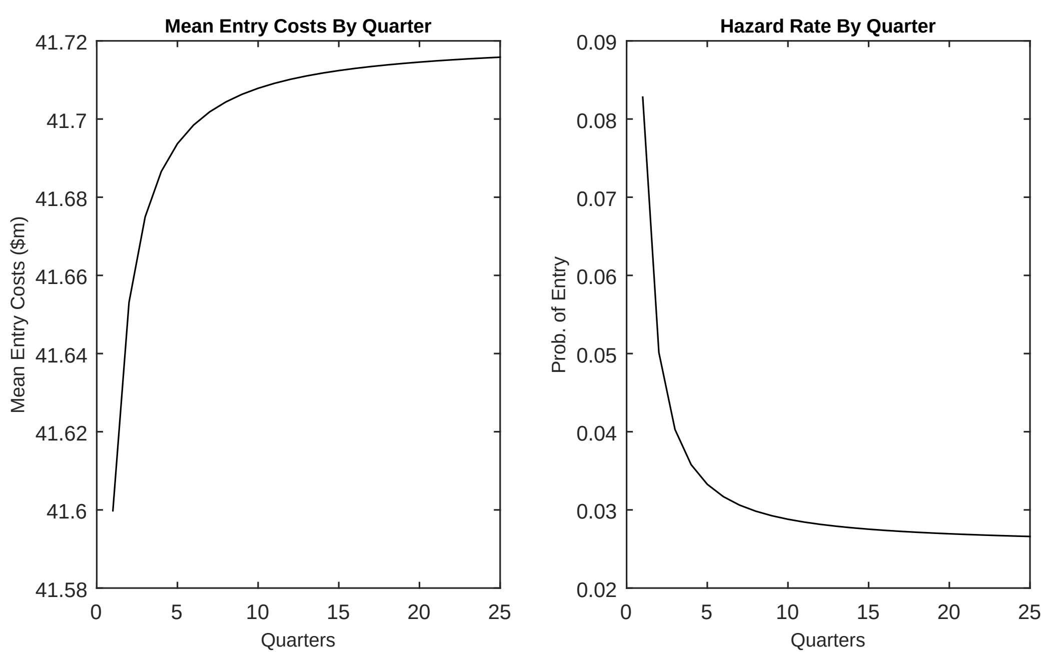


Figure I.2: Variation of Mean Entry Costs and Entry Probabilities Over Time for the Median Market



entry probability declines quite quickly even though the increase in entry costs is very small because the expectation of a future increase in entry costs is enough to cause Southwest to want to bring its entry decision forward.

Figure 6 in the text shows the relationship between market size, the predicted probability of entry and the predicted change in the incumbent's price when Southwest becomes a potential entrant, given these parameters.[103] The main text also explains how we calculate the welfare effects of limit pricing.

[103] The reported shading is the expected difference between the observed price and the monopoly price in the first period when Southwest becomes a potential entrant, assuming that the incumbent's marginal cost in that period is drawn from its steady state distribution.