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. We show that model provides a plausible explanation for why incumbent airlines cut prices dramatically on routes threatened with entry by Southwest Airlines by providing new evidence that incumbents sought to deter entry, showing that other suggested explanations are inconsistent with the data, and demonstrating that our model can predict the size of cuts observed in the data when we parameterize it to capture the main features of these routes.

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Keywords: signaling, strategic investment, entry deterrence, limit pricing, asymmetric information, dynamic pricing, airlines, potential competition.

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1 Introduction

Economists have long been aware that incumbent firms with market power may have incentives to take actions to try to 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, which 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, once the model is extended so that an incumbent can set prices in multiple periods and the potential entrant has multiple opportunities to enter, it is unclear *a priori* whether the model would give a unique prediction about how the incumbent would price (for example, does the incumbent need to set low prices in every period or only in some initial set

[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 be able to 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 Southwest Effect was taken from the title of 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.

of periods?), and indeed, in the applied literature, dynamic games with persistent asymmetric information have often been viewed as being too intractable to work with, at least using standard notions of equilibrium (Doraszelski and Pakes (2007), Fershtman and Pakes (2012)). We show that, when we allow the incumbent's private information to be positively serially correlated, but not perfectly persistent, over time, Markov Perfect Bayesian Equilibrium strategies and beliefs on the equilibrium path are unique under an application of the D1 refinement when a set of conditions on the payoffs of the incumbent hold in every period. When the unobserved variable is the incumbent's marginal cost, and this is assumed to evolve exogenously, we show that these conditions will be satisfied under some simple, and quite weak, restrictions on the static primitives of the model. In this equilibrium, the incumbent engages in limit pricing to perfectly reveal its current marginal cost in every period, so that our model predicts that the incumbent will keep prices low until entry actually occurs, at which point we assume, for simplicity, like MR, that the game changes to be one of complete information.

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 it provides the largest documented case of potential competition lowering prices in any industry (Bergman (2002)), to the best of our knowledge, no one has examined whether a limit pricing story can explain what is observed in the data.

We present two forms of evidence. First, we present new reduced-form evidence, based on a set of markets that fit the assumptions of our model, that these price cuts are motivated by entry deterrence, and that they are not easily rationalized by the leading alternative explanations, including other deterrence mechanisms that might also cause prices to fall, such as a desire to build customer loyalty to increase future demand, or by incumbents increasing their capacities in a way that reduces their marginal costs by lowering their load factors. To do so, we draw on the empirical strategy proposed by Ellison and Ellison (2011) (EE), by showing that price-cutting behavior is more pronounced in markets where, based on exogenous factors, we predict an intermediate probability of entry by Southwest, which is where incumbents' incentives to make costly investments to deter entry should be greatest. 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 readying themselves to accommodate entry.

Second, we show that our model can generate the large price cuts that are observed in the data. This is true both when we consider our simple extension of MR where the incumbent's marginal cost is private information and is assumed to evolve exogenously, and when we use a more sophisticated model where the incumbent's marginal cost is an endogenous function of its pricing and capacity choices, and we assume that the incumbent has private information about the level of demand for connecting service. This may affect an entrant's expected profits by changing the incumbent's marginal cost and also by correlation with how much connecting traffic the entrant will be able to attract. While this is not the only way that one can extend the basic model, we view it as capturing some of the most important economic features of the markets in our sample, which are typically spoke routes from one of the incumbent's hubs (like the markets where Bennett and Craun (1993) originally identified the Southwest Effect), where most passengers are making connections to other destinations. In particular, the theoretical literature on hubs emphasizes how network flows will affect an incumbent's marginal costs of serving local passengers (for example, Hendricks, Piccione, and Tan (1997)), while antitrust analysis of alleged predation on hub routes (Edlin and Farrell (2004) and Elzinga and Mills (2005)) has been dependent on the incumbent's internal accounting data, indicating that there is very likely to be asymmetric information between an incumbent and a potential entrant taking a contemporaneous entry decision. We show that this model, which has a richer structure than the limit pricing models that have been explored previously, and in which it is possible for an incumbent to try to deter entry by investing in capacity (in the spirit of Dixit (1980)), as well as by using limit pricing, remains tractable. Furthermore, we show that the model predicts large price declines with only small changes in capacity, which is what we observe in the data.[3]

[3]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. However, we are not aware of models with information-based limit pricing and capacity investment occurring simultaneously within the same model.

Our work draws on, and is related to, two broad literatures aside from the one that has studied the Southwest Effect. 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. We differ from Roddie not only in considering an entry-deterrence game, but also in the high-level theoretical conditions that we use and that, in the exogenous marginal cost version of our model, we show that these conditions will be satisfied throughout a dynamic game under some sufficient and easy-to-check conditions on static features 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.[4]

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.[5] Much 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.[6]

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

[5]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.

[6]One difference in our reduced-form approach from the one used by Seamans is that we look directly at

In the context of airlines, 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 finite horizon 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.[7] Fershtman and Pakes (2012) consider an alternative way of incorporating persistent asymmetric information in a dynamic game, focusing on infinite horizon games with finite states and actions. They propose an alternative solution concept, Experience Based Equilibrium, under which players have beliefs about expected payoffs from their own alternative actions, rather than their rivals' types. This approach may greatly reduce the memory required to store agents' beliefs in a game where agents of different types choose the same actions in equilibrium (i.e., pooling or semi-pooling). In contrast, we consider a finite horizon game with continuous actions where we can show that the equilibrium involves full separation, so that equilibrium beliefs can be handled easily.[8] In doing so, we can extend one of the classic two-period models of theoretical Industrial Organization by incorporating both dynamics and a much richer, endogenous cost structure.

The rest of the paper is organized as follows. Section 2 lays out our model of dynamic limit pricing when marginal costs are exogenous and characterizes the equilibrium. 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 limit pricing model. Sections 5 shows that parameterized versions of our model can generate significant limit pricing under both exogenous and endogenous marginal costs. Section 6 concludes. Appendices contain theoretical proofs and additional details of our empirical work.

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whether there is a non-monotonicity of *price changes* with respect to a predicted probability of entry once Southwest becomes a potential entrant.

[7]We do not directly estimate our model here, and leave the development of an estimation methodology to future work.

[8]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.

2 Model

In this section we develop a model of a dynamic entry deterrence game with serially correlated asymmetric information. To make the exposition straightforward, we focus on a game where the incumbent has a time-varying (constant) marginal cost of carrying passengers that evolves exogenously. This model is, in essence, a direct extension of MR. 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 and the way that we solve the model is explained in Appendix B. In Section 5 we consider an extended model where marginal costs are endogenous functions of dynamic capacity investments, and the incumbent carrier is signaling information both about its costs and the entrant's likely demand, that can also have a unique equilibrium with substantial limit pricing.

2.1 A Dynamic Limit Pricing Model with Exogenous Marginal Costs

There is a finite sequence of discrete time periods, $t = 1, ..., T$, two long-lived firms and a common discount factor of $0 < \beta < 1$. We assume finite T so that we can apply backwards induction to prove existence and uniqueness, but, when we give numerical illustrations, T will be large and we will focus on the strategies that are (almost) stationary in the early part of the game.[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 $c_{E,t}$ and $c_{I,t}$. In order to economize on notation, we will assume that $c_{E,t} = c_E$ when presenting the theory but all the results hold, with all strategies conditioned on $c_{E,t}$, when $c_{E,t}$ is also serially correlated but publicly observed (see Gedge, Roberts, and Sweeting (2014) for the full presentation of the theory for this case), which is the model we actually compute in our numerical illustrations. $c_{I,t}$ lies on a compact interval

[9] One approach in the theoretical literature (e.g., Toxvaerd (2008)) is to show properties of an infinite game by taking the $T \to \infty$ limit of finite horizon games. We could apply this type of argument in our setting.

[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 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.

$[\underline{c_I}, \overline{c_I}]$ 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 previously observed. 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).*

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.

[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. In our setting, it is important that what is privately known by the potential entrant is not serially correlated, as otherwise, I would need to make inferences about its value, which would greatly complicate the solution of the model. 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. In Section 5 we parameterize a model where c_E is serially correlated, to match the data, but observed.

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***

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]

[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.

[13] For some parameters, although not for our chosen parameters, 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.

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. 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.[14] 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).[15] This makes sense in our empirical setting as Southwest is viewed as having had significantly lower costs than legacy carriers during our sample period.

2.1.3 Equilibrium

We assume that there is a unique Nash equilibrium in the post-entry complete information duopoly game.[16] Our interest is in characterizing pre-entry play. Our basic equilibrium concept

[14] 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 the proof.

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

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

is MPBE (Roddie (2012a), Toxvaerd (2008)), which requires, for each period:

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

In equilibrium, E's entry rule should be optimal given its beliefs, those beliefs should be consistent with the evolution of I's marginal costs and I's strategy 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 react based on these inferences.

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 $t < T$:

(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 $t+1$).[17] *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 linear marginal costs.

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

and an upper boundary condition $p^*_{I,t}(\overline{c_I}) = p^{\text{static monopoly}}(\overline{c_I})$. $\mathbb{E}_t[V^I_{t+1}|c_{I,t}]$ 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 $t+1$. $\mathbb{E}_t[\phi^I_{t+1}|c_{I,t}]$ 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 $\varsigma^{-1}_{I,t}(p_{I,t})$.

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. ■

Note that these strategies constitute the Riley Equilibrium (Riley (1979)) where the incentive compatibility constraints consistent with full separation are satisfied at minimum cost to I.

Our proof applies well-known results from the literature on one-shot signaling models. Mailath and von Thadden (2013)[18] provide conditions on a signaler's payoffs[19] 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 D1 refinement (Cho and Sobel (1990), Ramey (1996)), which restricts the inferences that the receiver can make when observing off-the-equilibrium-path actions[20], can be used to eliminate pooling equilibria given a single-crossing condition as long as any pool does not involve firms choosing the lowest possible price ($\underline{p}$).[21] We apply these results

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

[19] 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.

[20] 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.

[21] Applying D1 in a setting with repeated signaling is potentially complicated by the possibility that an off-the-equilibrium-path signal in one period could change how the receiver interprets signals in future periods. We follow Roddie (2012a) in using a recursive interpretation of D1, where we work backwards through the game, applying the refinement in each period, under the assumption that if an out-of-equilibrium action was observed,

recursively, by which we mean that, starting at the end of the game, we work backwards solving for equilibrium pricing and entry strategies in period $t+1$, and then using these strategies to show the continuation payoffs in period t satisfy the requirements for existence and uniqueness, meaning that we can apply these results to derive period t strategies.

The more novel part of our results is that we can show that our assumptions on static monopoly and duopoly quantities and payoffs are sufficient for the Mailath and von Thadden and Ramey requirements to be met in *every period* of the game, which makes this model particularly tractable as uniqueness can be demonstrated before the model is solved.[22] When we consider a model with endogenous marginal costs that depend on capacity investments, we can no longer rely on simple static conditions, but we are able to verify uniqueness by checking the conditions of Mailath and von Thadden (2013) and Ramey (1996) in every period for all possible capacity levels when we solve the model recursively.

3 Data and Sample Selection

We now turn to examining whether our model can provide a plausible explanation for why incumbent airline carriers cut prices on airline routes when faced by Southwest as a potential entrant. In this section we discuss the empirical setting and existing literature, the data and our selection of a subset of markets that we believe 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

the players would expect refined equilibrium strategies to be used in subsequent periods.

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

one or both endpoints, but not yet serving the route)[23], but the literature has found that "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.[24] While these estimates are far larger than any estimates, of which we are aware, of potential competition effects in any other industry (Bergman (2002)), no clear rationale for why incumbents lower prices when Southwest is a potential competitor 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. We do so by providing new evidence showing that the price declines are motivated by deterrence, and by providing new evidence against other explanations for why prices fall, such as a desire to build customer loyalty or because marginal costs, that are a function of load factors, are falling. We also show that parameterized versions of both our simple model with endogenous marginal costs and an extended version that aims to capture both the endogeneity of marginal costs and the important role that connecting traffic plays on the routes in our sample, can generate price declines of the size observed in the data.

To be as consistent with our model as possible, we focus on a set of airport-pair markets where

[23]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.

[24]The fact that incumbent prices fell on at least some routes that Southwest had not yet entered was also frequently noted in the press. For example, "Consider what happened in the two years since Southwest began flying to TF 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.

there is a dominant incumbent (the exact definition will be given below).[25] 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, it is it well-understood that the incumbent's marginal (opportunity) cost of selling a seat to a local passenger will depend critically on the number and the profitability of connecting passengers that could also travel on the segment. As can be seen in litigation involving alleged predation by carriers at their hubs (Edlin and Farrell (2004), Elzinga and Mills (2005)), which relied on the incumbent's internal accounting measures, appropriately measuring marginal costs on these routes is very complicated even ex-post, partly because of the vast number of different destinations connecting passengers might be flying to. The incumbent's marginal cost is therefore likely to be opaque to potential entrants, including Southwest, that have to make contemporaneous decisions about whether to enter, as well as being likely to evolve over time as network flows and the options available to connecting travelers change.[26] In addition, the traditional importance of hub routes for legacy airline profitability makes it plausible that incumbents would be willing to sacrifice current profits to try to deter the entry of a carrier known to set very low prices once it enters, on as many of these routes as possible.[27]

The other critical part of our model is that the potential entrant's decision to enter should be sensitive to what it believes about the incumbent's marginal cost or some other feature of the market that will affect its post-entry profits. Consistent with GS's logic about pre-announced entry, there are clearly going to be some routes, including to Southwest's focus airports such as Las Vegas or Chicago Midway, where Southwest is almost certain to enter immediately, or very soon after, it enters an airport, independent of an incumbent's actions. At the other extreme, there are likely to be some routes (whether due to distance, or market size) that are very unlikely to be entered even if the incumbent's marginal costs are high. This is recognized

[25]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 small. Morrison (2001) estimates that Southwest has substantially smaller effects on fares when it only serves nearby airports as either an actual or a potential competitor.

[26]One might object that other carriers can use publicly available data to understand these network flows. However, the Department of Transportation only releases these data with a lag of at least three months, and our theoretical 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.

[27]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").

by our identification strategy, as our evidence will come from the fact that we observe the largest price declines in a set of markets that a simple entry model predicts are most likely to be marginal for Southwest to enter, which are the markets where its beliefs about the incumbent are most likely to matter.[28] While our contrasting assumption that other features of the market, such as Southwest's marginal costs, are observed is strong, and is made largely for simplicity and to avoid, like MR do, a model with two-way learning, it can be rationalized by the fact that Southwest operates a simpler point-to-point network with a homogeneous fleet of Boeing 737s, suggesting that some factors that make a legacy carrier's marginal costs at its hub opaque are likely to be less important for the potential entrant.

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, a carrier sells tickets on the same route at many different prices, whereas we assume that the incumbent sets a single price each period. We do show empirically, however, that the incumbent lowers prices in a similar way across the fare distribution. Our model also misses 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, as several of these exist for most of the routes that we consider. While several heterogeneous potential entrants could certainly complicate the pricing game, it is plausible that, because of its low prices once it enters, an incumbent would be particularly willing to make short-run sacrifices to deter or delay the entry of Southwest, which was the largest low-cost carrier during our sample.

[28] While Southwest, like other carriers, has never fully described its entry strategy, comments from the company indicate that it is sensitive to current market conditions. 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). 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). The claim that at least some of Southwest's entry decisions in the mid/late-1990s and 2000s were marginal is supported by existing research, such as Boguslaski, Ito, and Lee (2004), which showed that the ability of a simple probit (based on exogenous market characteristics) to predict Southwest's entry decisions declined significantly in the 1990s (explaining only 41% of entry decisions from 1995-2000 compared with almost 60% for the 1990-2000 decade as whole).

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).[29]

Following GS, we define a market to be a non-directional airport-pair with quarters as periods. We only consider pairs where, on average, at least 50 DB1 passengers are recorded as making return trips each period, possibly using connecting service, and in everything that follows a one-way trip is counted as half of a round-trip. We exclude pairs where the round-trip distance is less than 300 miles. We define Southwest as having entered a route once it has at least 65 flights per quarter recorded in T100 and carries 150 non-stop passengers on the route in DB1, and we consider it to be a potential entrant once it serves at least one route out of each of the endpoint airports.[30]

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

1. to be considered active in a quarter it must carry at least 150 DB1 non-stop passengers;

2. once it becomes active in a market the carrier must be active in at least 70% of quarters

[29] 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 37 for some related comments.

[30] While this definition means that we may consider Southwest to have entered a market when its schedule is quite limited, we note that this is actually a more stringent criterion than the one used by GS.

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.)	2.373	1.974	2.850	1.894	3.155	2.081
Round-trip distance (miles)	2,548.48	1,327.04	1,251.44	749.58	1,315.1	803.07
Constructed market size measure	27,837	44,541	62,751	66,633	47,975	61,397
Origin or destination is a:						
primary airport	0.161	0.368	0.330	0.473	0.277	0.451
secondary airport	0.301	0.459	0.321	0.469	0.354	0.482
big city	0.587	0.492	0.858	0.350	0.877	0.331
leisure destination	0.093	0.291	0.113	0.318	0.108	0.312
slot controlled airport	0.033	0.179	0.057	0.230	0.092	0.292
Number of markets	1,872		106		65	

before Southwest enters, and in 80% of those quarters it must account for 80% of direct traffic on the market and at least 50% of total traffic.[31]

We identify 106 markets with a dominant incumbent before Southwest enters, but in some of these markets Southwest enters at the same time as it becomes a potential entrant (i.e., the market is one of the first ones that Southwest enters when it begins serving one of the endpoint airports) and in a few of them the dominant incumbent becomes active only after Southwest is a potential entrant on the route. In 65 markets we observe quarters where the incumbent carrier is dominant both before Southwest becomes a potential entrant and after it is a potential entrant but before it actually entered. It is data from these routes that will identify the effects of the potential entry threat on the price set by a dominant incumbent, although we include the remaining 41 routes in our regressions as they help to pin down the coefficients on the time effects and other controls included in the specification.[32] The 106 and 65 markets are listed in Appendix C.

Table 1 provides some statistics for the full sample, and the sub-samples of 106 and 65

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

[32] 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.

markets. Relative to the full sample, the dominant incumbent markets tend to be shorter with larger endpoint cities, as measured by either average population or an indicator for whether one of the endpoints meets the "big city"definition of Gerardi and Shapiro (2009).[33] All of the markets in our dominant firm sample are shorter than the longest routes that Southwest flies non-stop (these include long, cross-country routes such as Las Vegas-Providence), so, by this metric, it is plausible that any of our routes could be entered.[34] As only the largest cities have multiple major airports, the dominant incumbent markets are also more likely to involve an airport identified as a primary or secondary airport. On the other hand, the standard deviations show that both 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 in Section 5 and as an additional variable for predicting the probability that Southwest enters a market. As explained in Appendix D, this variable is constructed by estimating a generalized gravity equation using the Poisson Pseudo-Maximum Likelihood approach recommended by Silva and Tenreyro (2006), which allows us to capture the fact that the amount of travel on a route varies systematically with distance and the popularity of the particular airports.

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

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

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

to make investments to deter entry if it is likely that they would be effective. They are also consistent with incumbents responding to the threat of entry by lowering prices, suggesting that limit pricing may be one of these investments.[35]

The summary statistics also provide some evidence against an alternative story for why prices fall in Phase 2. Recall that in Phase 2, Southwest serves both endpoint airports so that passengers may be able to travel the route by connecting on Southwest[36], in which case one might argue that Southwest should be viewed as a competitor with an inferior product rather than just a potential entrant. This could provide an alternative explanation for why prices fall. However, from the table we see that Southwest's average market share in Phase 2 is less than 1.5%, compared with the dominant carrier's share of over 80%, while Southwest's fares for these connections are also high compared to its fares when it enters the market with direct service. Therefore, the degree of direct competitive pressure that Southwest exerts on the incumbent's pricing in Phase 2 should be small. In Section 4 we will provide additional evidence against this 'actual competition' explanation for why prices fall when entry is threatened.

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. We also report an estimate of the proportion of passengers traveling the route to make connections.[37] For both incumbents and Southwest, the majority of passengers carried on these routes are making connections, a point we will return to in Section 5.2. The entry of Southwest as a potential entrant or an actual route entrant is associated with an increase in the incumbent's load factor and a decline in the proportion of connecting passengers, consistent with the fall in local fares raising local demand. We also report a measure of code-sharing by the incumbent,

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

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

[37] The number of connecting passengers is calculated by taking 10 times the number of passengers traveling the route in DB1 from the total number of passengers reported in T100. When one combines data from DB1 and T100, some inconsistencies are introduced, because the DB1 sampling weights are not necessarily the same across routes and some passengers reported as direct in DB1 may be traveling via other airports without a change of plane or on regional affiliates that have not reported T100 data in some of our quarters. Therefore we restrict ourselves to some fairly broad-brush comments about connecting traffic patterns even though, as our extended model in Section 5.2 suggests, the fact that there is a lot of connecting traffic on the routes in our sample may play an important role in explaining why there may be significant limit pricing.

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 / distance)	0.510	0.317	0.525	0.313	0.439	0.297	0.292	0.143
Average fare	472.19	137.68	509.28	147.97	418.13	123.29	254.76	60.50
Southwest Pricing								
Yield (average fare / distance)	-		-		0.254	0.095	0.234	0.726
Average fare	-		-		363.41	84.38	215.98	59.42
Passenger Shares								
Incumbent	0.815	0.193	0.771	0.208	0.851	0.129	0.460	0.195
Southwest	-		-		0.016	0.030	0.486	0.210
Incumbent Capacity and Traffic								
Capacity (seats performed)	75,592	53,430	68,752	49,729	69,324	48,844	100,038	52,900
Segment passengers	45,995	32,828	41,862	30,423	48,413	33,389	71,261	38,987
(incl. connecting passengers)								
Load factor	0.612	0.104	0.618	0.107	0.712	0.117	0.714	0.079
Proportion passengers connecting	0.837	0.118	0.849	0.113	0.832	0.125	0.775	0.098
Code-share measure	0.086	0.211	0.124	0.257	0.257	0.352	0.188	0.245
Southwest Capacity and Traffic								
Capacity (seats performed)	-		-		-		87,629	59,887
Segment passengers	-		-		-		56,403	38,478
(incl. connecting passengers)								
Load factor	-		-		-		0.658	0.080
Proportion passengers connecting	-		-		-		0.702	0.102
Code-share measure	-		-		-		0.018	0.093
Number of markets	106		65		65		54	

based on observations after 1998, where DB1 reports both the ticketing and operating carrier. Our measure is the proportion of the carrier's passengers on a route that were ticketed by a different carrier.[38] Goetz and Shapiro (2012) find that 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

In this section we present reduced-form evidence that a limit pricing model could explain why incumbents cut prices when Southwest becomes a potential entrant on an airline route. In doing so, we extend the analysis in GS by trying to discriminate between several alternative explanations for why prices fall and by focusing on dominant incumbent markets that fit the market structure assumed by most models of strategic investment, including ours.

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

$$\begin{gathered}\text{Price Measure}_{j,m,t} = \gamma_{j,m} + \tau_t + \alpha X_{j,m,t} + \ldots \\ \sum_{\tau=-8}^{8+} \beta_\tau SWPE_{m,t_0+\tau} + \sum_{\tau=0}^{3+} \beta_\tau SWE_{m,t_e+\tau} + \varepsilon_{j,m,t}\end{gathered} \tag{5}$$

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)

[38] A code-sharing arrangement allows specific non-operating (marketing) carriers to sell tickets on a flight operated by 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 we measure a proportion as not being equal to zero is not indicative that a full code-sharing agreement was in place. However, we see much higher proportions for carrier combinations with known code-sharing agreements.

as well as interactions between the jet fuel price[39] and route distance. t_0 is the quarter in which Southwest becomes a potential entrant, so $SWPE_{m,t_0+\tau}$ is an indicator for Southwest being a potential entrant, but not an actual entrant, into market m 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 price and the 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 fall even more during Phase 2 if entry does not occur. For example, the t_0+ 6-12 and t_0+ 13+ coefficients are significantly larger in absolute value than the other t_0 coefficients. This can be explained in our limit pricing model, as not only is there a continued incentive to signal, but also because entry is less likely to occur in markets where marginal costs are falling. We should note, however, that it is possible that some of this additional price fall could be due to incumbents slowly making operational changes, which may not involve changing capacity, that reduce their marginal costs, partly as an additional strategy for deterring entry. An example might be US Airways's 1998 introduction of its 'MetroJet'-branded service on many routes from Baltimore-Washington International (BWI). MetroJet

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

was a response to Southwest's growing presence at that airport, and even though it operated the least efficient Boeing 737-200s in US Airways's fleet, airline executives argued that it had lower costs than mainline US Airways. However, two features of this example suggest that operational changes cannot explain all of the price declines observed in Phase 2. First, despite possibly having lower costs, MetroJet was never profitable and it was closed in 2001, suggesting that on MetroJet routes where Southwest had not yet entered US Airways may have continued to set low prices in order to try to deter additional entry.[40] Second, US Airways only introduced MetroJet five years after Southwest began operations at BWI, indicating that operational changes, which may require significant network re-configuration, can only be introduced slowly. On the other hand, a limit pricing model can explain why we observe incumbents lowering prices significantly as soon as entry is threatened. In fact, as we discuss in Section 5, incumbent prices, in a limit pricing equilibrium, will tend to be lower when the incumbent believes that there will be a lower threat of entry in the future if it is able to deter entry now.

We now address the question of why prices fall in Phase 2. Several explanations are possible. One explanation, 'actual competition', is that once Southwest serves the endpoint airports, its ability to provide connecting service provides enough competition to the dominant incumbent that the static equilibrium response is for prices to fall. The other explanations involve either some type of change in the incumbent's demand (for example, from connecting passengers) that lowers the incumbent's load factor and its marginal costs, and so causes the optimal monopoly price to fall, or some type of strategic response by the incumbent. Strategic responses could be of two types: one type would be that the incumbent is sacrificing current profits to try to increase its profits in the game that will be played once Southwest enters (i.e., 'entry accommodation') and the other is that the incumbent takes actions that will make Southwest perceive that entry will be less profitable ('entry deterrence'). Limit pricing is clearly a deterrence story, given the standard assumption that the game that follows entry is complete information. On the other hand, several strategies might be used for either accommodation or deterrence. For example, the dominant incumbent might change capacity to affect its marginal cost; lower prices to increase future demand by raising customer loyalty; or, sign code-sharing agreements with other carriers.

Another feature of the results in Table 3, also found in GS, is that prices start declining two

[40]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."

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

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

Notes: Estimates of specification (5) 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 3,904 and the adjusted R^2s are 0.81 ("Fare") and 0.86 ("Yield"). Phases are defined in the text.

quarters *before* Southwest becomes a potential entrant. While in some settings one would be concerned that a pre-treatment change must reflect some other development that might cause both prices to fall and Southwest to become a potential entrant, in our setting, this pattern reflects the fact that Southwest announces its entry into an airport some months before it begins flights, while our entry variables are defined by the start of actual operations.[41] As Southwest will make decisions about which routes it will serve in future quarters once its arrival into the airport is announced, this pattern is consistent with strategic explanations for why prices fall, including our limit pricing model. At the same time, however, this decline is not consistent with an actual competition story, or at least one where consumers do not substitute journeys intertemporally, because connecting service on Southwest could only provide a substitute for passengers once Southwest begins operating flights.[42]

A second piece of evidence against the actual competition explanation comes from examining what happens to different percentiles of the price distribution. In Appendix E we report estimates from specification (5) where we use the 25^{th}, 50^{th} and 75^{th} percentiles of the fare and yield distribution as dependent variables. The results reveal that when Southwest threatens entry, prices decline significantly across the fare distribution. One might expect that actual competition from connecting service on Southwest would primarily attract price-elastic leisure travelers who would otherwise buy cheaper tickets on the incumbent. In this case, one might expect to see larger price reductions for cheaper seats, whereas what is observed is that all prices fall, with larger declines at higher percentiles.[43]

Larger declines for more expensive fares might be consistent with explanations where the incumbent lowers fares for frequent business travelers, who are more likely to buy expensive last-minute tickets, in order to try to increase their future demand (for example, by building up their accumulated miles in frequent-flyer loyalty programs). This kind of strategy could be

[41] 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 (dates from http://swamedia.com/channels/By-Category/pages/openings-closings, accessed November 10, 2015).

[42] See Appendix F for some evidence against lagged prices having significant positive or negative effects on the incumbent's demand.

[43] Borenstein and Rose (1995) argue that actual competition tends to increase within-carrier fare dispersion in the airline industry for this reason, whereas here we are observing fare compression. Of course, one might argue that when the price of cheaper tickets fall, a carrier is constrained to lower more expensive business class or more flexible ticket prices in order to maintain incentive compatibility constraints as part of a second degree price discrimination scheme. However, this would not explain why higher prices fall more (both proportionately and in absolute terms) and why prices fall before Southwest actually begins offering connecting service.

used either to try to deter Southwest's entry, by lowering its expected demand, or to strengthen the incumbent's position should Southwest enter. However, it is not clear why the incumbent would also cut the prices of low-priced tickets, that are usually sold further ahead of the date of departure, and are targeted at infrequent, leisure travelers. In contrast, declines across the fare distribution are consistent with a model where the incumbent is signaling the marginal opportunity cost of selling a seat to someone who only wants to fly the segment, as this should affect pricing whatever type of consumer the ticket is sold to, consistent with Pires and Jorge (2012) who show how a multi-market incumbent will cut prices in all markets to signal that its marginal cost is low even when it is only threatened by entry in a single market. In Appendix F we provide more direct evidence against the building demand story by directly examining whether, for our sample of markets, a carrier's demand increases when its prices in recent quarters are lower. Across several specifications, we find no evidence that this is the case, even though one would need quite strong effects to make the large average price cuts observed in the data profitable.[44]

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

[44] Evidence for the hypothesis that frequent-flyer programs increase loyalty is, at best, limited. In their summary of existing research, Uncles, Dowling, and Hammond (2003) argue that "it is mainly the infrequent flyers that are loyal to a single frequent-flyer program, but invariably, these are the less profitable customers," while frequent travelers are usually members of several programs and substitute between carriers.

probability is estimated to construct a single index of the attractiveness of the market to the potential entrant and then, in the second stage, the monotonicity of the relationship between this index and the incumbent's (possibly strategic) investment is examined.

For our first stage, we estimate a probit model of Southwest's entry using the full sample of 1,872 markets where an observation is a route and the dependent variable is equal to one if Southwest entered within four quarters of becoming a potential entrant, where we are implicitly assuming that Southwest will typically choose to enter the most attractive markets from an airport first.[45] The explanatory variables include several measures (and their squares) of market size, including measures of endpoint population and our gravity model-based market size measure; route distance; measures of carrier presence at the endpoint airports; and, an indicator for whether one of the airports is slot constrained. Further details of the variables included and the estimated coefficients are given in Appendix G. Consistent with previous research, e.g. Boguslaski, Ito, and Lee (2004), we are able to explain a reasonable degree of variation (pseudo-R^2 0.37) in Southwest's entry decisions in the full sample, with Southwest more likely to enter shorter routes between bigger cities, especially when it already serves a significant number of routes out of the endpoints. For the subset of 65 markets the predicted within-four-quarter entry probabilities vary from 0.01 to 0.9, with the 20$^{\text{th}}$, 40$^{\text{th}}$ and 60$^{\text{th}}$ and 80$^{\text{th}}$ percentiles at 0.02, 0.085, 0.204 and 0.512.

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

$$\text{Price Measure}_{j,m,t} = \gamma_{j,m} + \tau_t + \alpha X_{j,m,t} + \dots$$
$$\beta_0 SWPE_{m,t} + \beta_1 \widehat{\rho_m} \times SWPE_{m,t} + \beta_2 \widehat{\rho_m}^2 \times SWPE_{m,t} + \epsilon_{j,m,t} \tag{6}$$

where $\widehat{\rho_m}$ is the predicted probability of entry (within one year) for market m, j is the dominant carrier, $\gamma_{j,m}$ and τ_t are market-carrier and quarter fixed effects, and $X_{j,m,t}$ includes the same

[45] It would be inappropriate to use a dummy for Southwest ever entering because, in our relatively long sample, different markets are exposed to the possibility of entry for different periods of time. Using a four quarter rule also means that we minimize the truncation problem associated with the end of the sample while still having a significant number of observations. In the data, Southwest enters around 60% of the routes that it will ever enter from an airport in the first quarter that it begins operations, and of the remaining markets that it eventually enters, it enters around 33% in the following three quarters, 18% in its second year, 13% in its third year and the remainder in later years.

controls that were used in the GS specification. $SWPE_{m,t}$ is an indicator for a market-quarter in which Southwest is a potential entrant (i.e., a Phase 2 observation). Standard errors are adjusted to allow for uncertainty in the first-stage estimate $\widehat{\rho_m}$, as well as heteroskedasticity and first-order serial correlation in the residuals.[46] 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. Obviously given our identification strategy, one might be concerned that there is something unobserved about intermediate probability of entry markets, that will also affect prices. While we cannot assess this directly, we can, of course, assess how observable variables (including some not included in the entry probit) vary with the implied entry probability. To this end, Appendix H presents a 'balance table' where we divide the dominant incumbent markets into three groups based on the implied probability of entry. On most dimensions, the intermediate probability markets lie between the low and high probability markets, and on the remaining dimensions the differences between the groups are not statistically significant.

Figure 1 shows the estimated quadratic relationship between the price change in Phase 2 and the entry probability using the log of the average fare (left panel) and average yield (right panel) 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, the price declines are largest and most statistically significant for intermediate probabilities of Southwest entry, but are smaller, and not necessarily significantly different from zero, for markets where entry probabilities are either high or low. In the regression both the linear and the quadratic terms are statistically significant at the 1% level (this is also true in the log(average price) regression). Appendix Table E.4 shows that the same pattern holds for the 25^{th}, 50^{th} and 75^{th} percentiles of the price distribution, which, as well as indicating the robustness of the result for mean prices, also suggests that incumbents are not targeting particular types of consumers, either to prevent them from making connections on other routes via Southwest (which might lead to targeting of

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

price-sensitive travelers buying the cheapest direct tickets) or to build their future loyalty (which might lead to targeting of business travelers who tend to buy more expensive tickets close to the date of departure), when cutting prices.

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

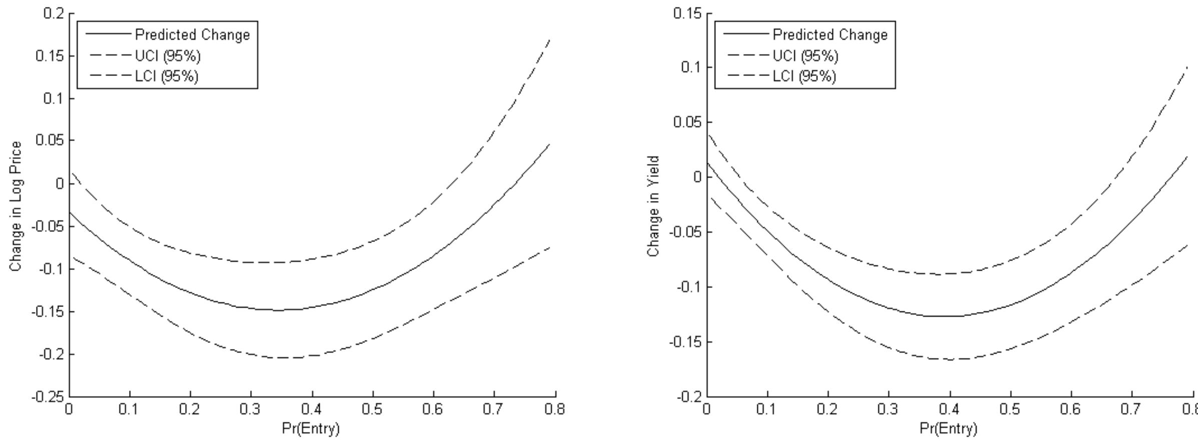


Figure 2 plots the estimated change in yield for each of the dominant incumbent markets separately against the estimated entry probability (the figure using log of the average fare looks very similar). These market-specific effects are estimated by replacing the three $SWPE_{m,t}$ terms in specification (6) with $SWPE_{m,t}\times$market m dummy interactions, with the plotted points being the point estimates of the coefficients on these interactions. While the effects for individual markets are heterogeneous, which is consistent with a limit pricing model where either incumbents have different levels of marginal cost or perceive different degrees of entry threat that are not measured perfectly by our estimated $\widehat{\rho}$s, it is clear that prices do not tend to decrease in markets with high or very low entry probabilities, while a significant proportion of the markets in between experience quite large Phase 2 price declines.

To provide further evidence against the claim that our results are driven by actual competition from connecting service on Southwest during Phase 2, we repeat the second-stage regressions controlling for the convenience of Southwest connections. We do so by including three additional dummies interacted with $SWPE_{m,t}$ that divide the markets into groups based on the convenience of a connection via one of Soutwest's focus airports (Baltimore, Chicago Midway, Phoenix and Las Vegas).[47] We see that the quadratic and linear coefficients in the yield regression, reported

[47]For each market, we calculate the total distance that would be involved in traveling via the most convenient

in column (2) of Table 4, remain statistically significant, and, in fact, contrary to what would be expected if actual competition was causing prices to fall, the coefficients on the dummy variables (not reported) indicate that prices fall most on the routes where Southwest connections are least convenient.

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

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

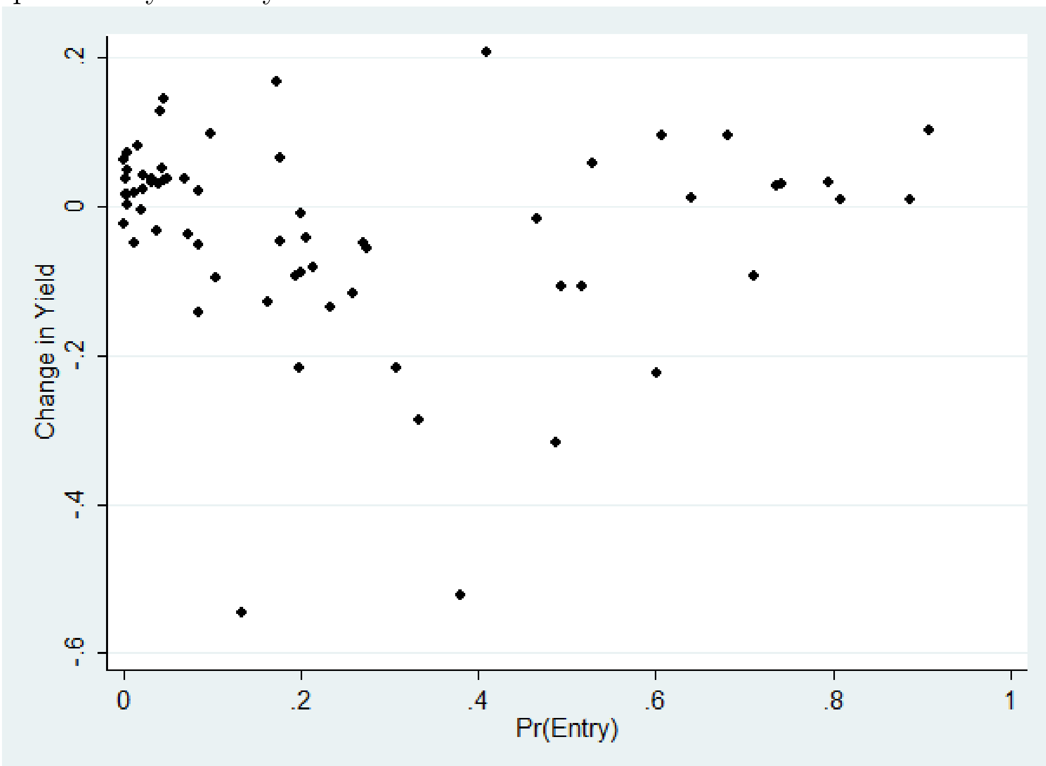
Notes: Heteroskedasticity robust Newey-West standard errors allowing for one period serial correlation and corrected for first-stage approximation error in the entry probabilities in parentheses. Column (2) includes controls for the convenience of connecting on Southwest. The different number of observations 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.

Of course, these results are also consistent with dominant incumbents using other strategies, such as adding capacity (as suggested by Snider (2009) and Williams (2012) in the context of possible predation by hub carriers), to try to deter entry, either instead of or in addition to, limit pricing. Capacity investments might cause monopoly prices to decline, by lowering load factors and therefore lowering the marginal cost of carrying additional passengers. 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 (6). In fact, as seen in Table 4, column (3) and Figure 3 (top-left panel), capacity does not tend to change significantly when Southwest becomes a potential entrant in any type of market, irrespective of the entry probability.

We also use the log of the incumbent's load factor and the log of the number of passengers flown on the route (measured in T100, where both local and connecting passengers are counted)

of these focus airports and divide this distance by the non-stop round-trip distance. Markets are divided into three equally-sized groups based on this ratio.

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



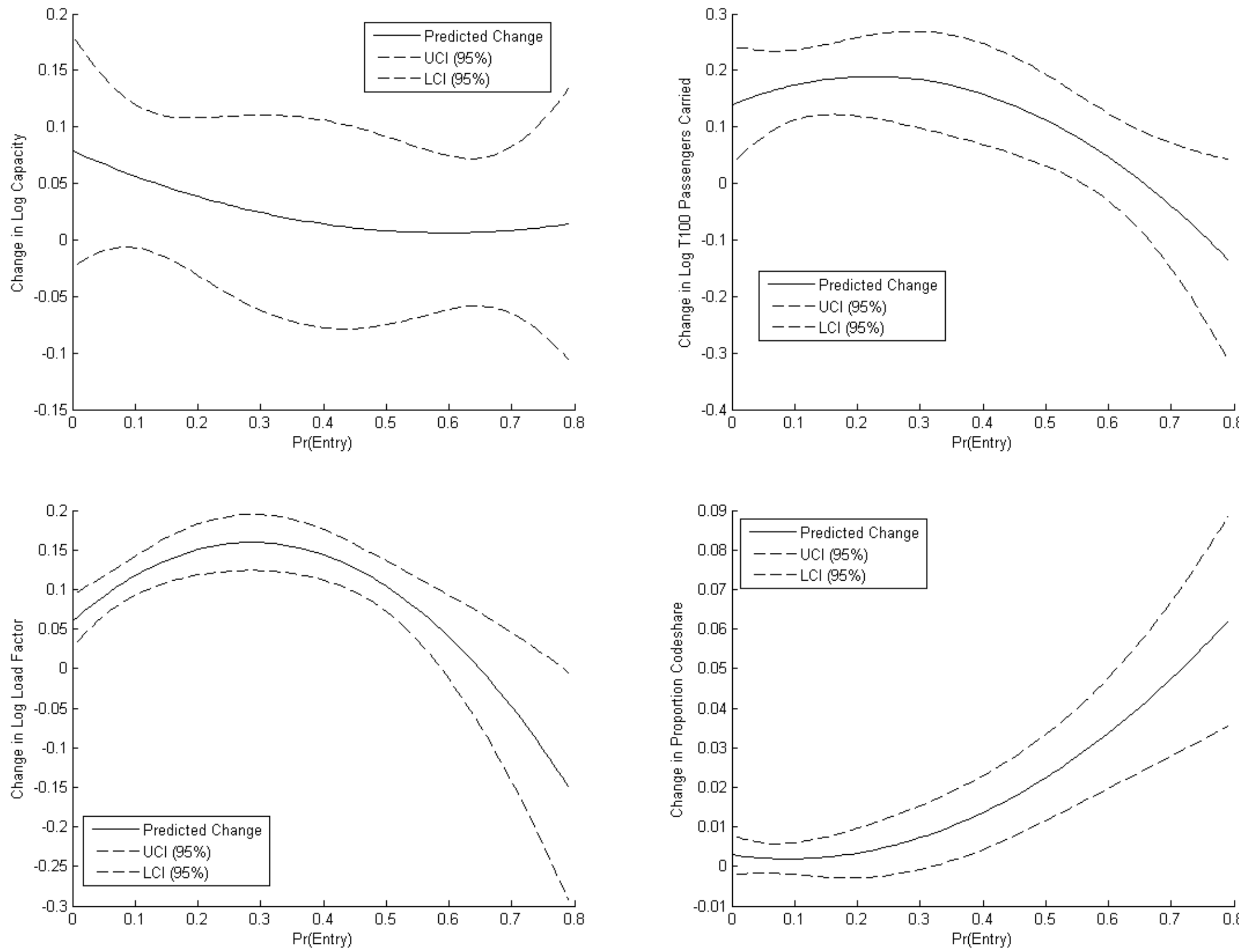
as dependent variables, as reductions in connecting traffic could also cause costs to fall, independent of capacity changes, on some routes.[48] The results are in columns (4) and (5) of Table 4 and the top-right and bottom-left panels of Figure 3. We observe that when Southwest becomes a potential entrant, the dominant carrier tends to carry more passengers and have higher load factors in markets with intermediate probabilities of entry, suggesting that, if anything, its marginal costs increase rather than fall. As we shall see in Section 5, when we allow for capacity investment in our dynamic limit pricing model, we actually predict that capacity should remain close to unchanged on average (typically falling by 0.4-0.6%, a change that lies within the confidence intervals shown in Figure 3 (top-left))) with an increasing load factor when the entry threat is introduced.[49]

Capacity investment is not the only non-limit pricing strategy that carriers might use to try to deter entry. As noted above, code-sharing also increases when entry is threatened. When we use

[48]For example, once Southwest is operating at an airport it may provide more attractive options to customers who would otherwise have connected using the incumbent's route of interest as a segment.

[49]In our model, as in Snider and Williams, we allow for the incumbent to face costs of changing its capacity, so that an investment in capacity before entry can imply some commitment to having higher capacity for at least a few periods after entry occurs.

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



our code-sharing variable as the dependent variable in (6), we see that, in contrast to price cuts, dominant carriers increase code-sharing on routes where Southwest's entry is most likely (column (6) of Table 4 and the bottom-right panel of Figure 3).[50] This suggests that code-sharing, unlike lower prices, is used primarily as a strategy for preemptively accommodating Southwest's entry.

5 Can A Dynamic Limit Pricing Model Generate Large Price Declines?

While the reduced-form evidence is consistent with dominant incumbents using limit pricing to try to deter entry, this raises the question of whether our model can generate the magnitude of declines that are observed. We address this question by, first, parameterizing the model presented in Section 2 where marginal costs are exogenous. We estimate many of the demand and cost parameters using data from the dominant incumbent markets. Second, we parameterize a richer model where we endogenize marginal costs by allowing for capacity investment and provide an explicit role for connecting traffic. We also find significant limit pricing in this model, which provides a much better approximation to the cost structure of the airline industry.

5.1 Model with Exogenous Marginal Costs

We parameterize a model with the structure outlined in Section 2. Details of how we estimate and choose the parameters are provided in Appendix I. The demand of passengers who only want to fly the route has a one-level nested logit, differentiated products structure where the nests are simply 'fly' and 'do not fly'. We set the size of the market (58,777 people) to be equal to the Phase 2-average for the 65 markets with Phase 2 observations. When we solve the model we keep the quality of both carriers fixed over time, and, based on our estimates, the qualities themselves are roughly equal. We assume that carrier marginal costs follow an AR(1) process

$$mc_{j,t} = \rho^{AR} mc_{j,t-1} + (1-\rho^{AR})\frac{\underline{c_j} + \overline{c_j}}{2} + \varepsilon_{j,t} \tag{7}$$

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

We estimate $\rho^{AR} \simeq 0.97$ and set the standard deviation of the innovations ε to match the interquartile range of the innovations in the data. The fact that marginal costs are highly serially correlated is important in generating quantitatively significant limit pricing in this model. We choose supports of $[\underline{c_I}, \overline{c_I}] = [\$160, \$280]$ and $[\underline{c_E}, \overline{c_E}] = [\$90, \$210]$. This choice implies that, consistent with our data for a market of average length, the potential entrant has an average marginal cost advantage of \$70, while the width of the supports ensure that the single-crossing condition on the incumbent's payoffs is satisfied in all cost states. The discount factor is set equal to 0.98, so that periods can be interpreted as quarters.[51]

5.1.1 Equilibrium Strategies

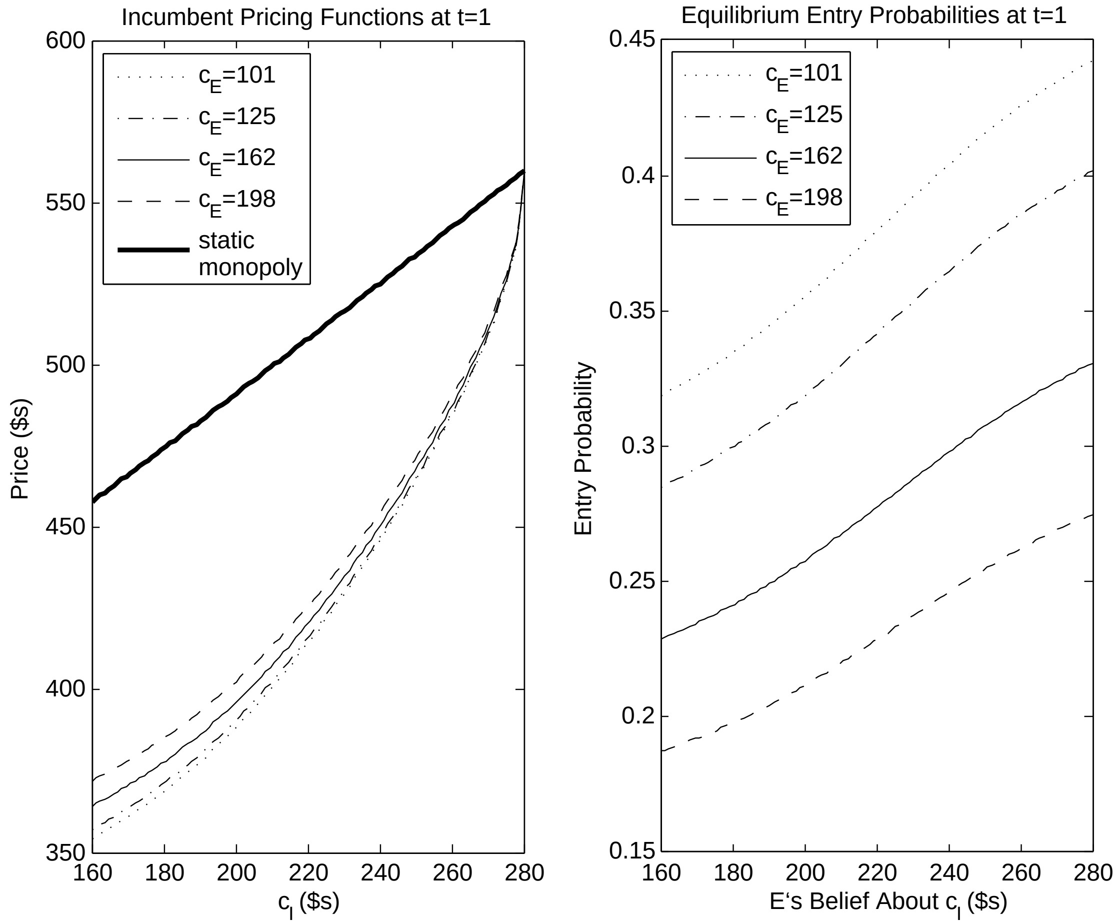
Given an assumed distribution for entry costs, we solve the model using the method described in Appendix B, assuming that $T = 200$. For this T, entry probabilities and pricing strategies are stationary (to four decimal places) at the start of the game. We specify that E's entry costs are drawn from a truncated normal (support of $[\$0, \$100 \text{ million}]$), and find the location and scale parameters, using a coarse grid search, that allow us to match the average price reductions observed in markets with an intermediate probability of entry during Phase 2 using $t = 1$ strategies.[52]

Figure 4 shows the incumbent's pricing functions at $t = 1$, for several values of c_E, together with Southwest's entry probabilities, when the (untruncated) entry cost distribution has a mean of \$55.4 million and a standard deviation of \$2 million. In equilibrium, there is substantial shading below the monopoly price for all $c_I < \overline{c_I}$ and, given the distribution of marginal costs for each firm, on average, prices are \$80.54 or 16.1% below the monopoly price, illustrating that our model can generate significant limit pricing in equilibrium. While these statistics measure limit pricing at the start of the game, it is worth noting that limit pricing can be more pronounced in later periods. For example, in the periods leading up to the time that entry effectively becomes blockaded because of the entry cost, at around $t = 150$ for our parameters, prices may be lowered by as much as 43.5% ($t = 136$), as keeping the entrant out for an additional period may

[51] With these supports, $q_I^D(c_{I,t}, c_{E,t}) - q^M(p_I^{\text{static monopoly}}(c_{I,t})) - \frac{\partial \pi_I^D(c_{I,t}, c_{E,t})}{\partial a_{E,t}} \frac{\partial a^*_{E,t}}{\partial c_{I,t}} < 0$ for all marginal costs. Of course, this condition is sufficient, not necessary, and in practice slightly wider bounds can still work.

[52] We calculate the average amount of price shading implied by the model by averaging the difference between the static monopoly price and the equilibrium limit price using probability weights implied by the steady-state distribution of marginal costs.

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



substantially increase the probability that the incumbent will remain a monopolist in the future. This feature may have some relevance for the initial reaction of incumbent airlines faced with the threat of entry by Southwest if, as we noted in Section 4 when discussing the example of MetroJet, incumbents are aware that they may be able to slowly make operational changes that lower their marginal costs and will reduce the threat of entry in the future if they are able to deter it for the first few years when entry is threatened.

The mean entry costs used in these simulations may seem large, but they should be interpreted as including the present discounted value of recurring fixed costs (for example, gate leases), that will be incurred after entry, as these have not been included elsewhere in the model, as well as the opportunity cost implied by the possibility that Southwest might have used the planes or gates for other routes.[53] We also note that one can still get significant limit pricing with lower

[53]In the case of Southwest, there is documentary evidence that these opportunity costs considerations were significant. For example, in 2011, after the end of our sample, when it reduced its service out of Philadelphia, a

mean entry costs: for example, if we assume mean entry costs that are only \$11.1 million (i.e., 80% smaller) we still generate average shading that is 8.9% of the monopoly price, compared with 16.1% under our baseline assumption.

As in the two-period MR model with a fully separating equilibrium, limit pricing is unambiguously welfare increasing (as long as limit prices are above marginal costs) in our model relative to a model where the potential entrant can observe the incumbent's marginal cost (full information), as entry decisions are the same on the equilibrium path but prices are lower before entry occurs because of limit pricing. For our baseline parameters, the gains in welfare that occur before entry occurs are quite large in percentage terms. Based on the steady-state distribution of marginal costs for this single representative market, the 16.1% shading increases expected consumer surplus by \$843,000 per quarter (26.5% of the full information consumer surplus), while reducing the incumbent's profits by \$154,000 (6.4%).[54]

Shading is substantial in this example because E's entry decision is relatively sensitive to its beliefs about the incumbent's marginal cost, and, consistent with the insights in EE, the average level of the entry probability is neither very high nor very low. Based on solving many games with different parameters, the degree of shading increases when there is greater serial correlation in the incumbent's marginal cost or the variance of the entry cost distribution falls.[55] Greater serial correlation leads to more shading in equilibrium for two reasons. First, from the perspective of the entrant, the incumbent's marginal cost becomes a better predictor of the entrant's profits if it enters, so the entry decision becomes more sensitive to its beliefs. Second, from the perspective of a low-cost incumbent, it also implies that if entry is deterred in the current period it is also likely to be deterred, in equilibrium, in subsequent periods. Both of these effects increase a low-cost incumbent's incentive to invest in entry deterrence by reducing the current price. A lower variance of the entry cost distribution makes the entry decision more sensitive to beliefs about the incumbent, which also increases the incumbent's incentive to limit price. On the other hand, if

Southwest spokesman argued that "This is a matter of rightsizing the market for us. We felt we could reallocate those aircraft to be more productive." (Linda Loyd, "Southwest Airlines to drop Philadelphia-Pittsburgh service", McClatchy-Tribune Business News, July 27 2011). Southwest network expansions were also often timed to coincide with the final delivery of new aircraft that expanded its capacity.

[54]One can do additional welfare comparisons using the model. For example, Gedge, Roberts, and Sweeting (2014) compare welfare under limit pricing and in an alternative model where the incumbent is unable to either observe or infer $c_{I,t}$ because pricing is too opaque, so that there is monopoly pricing prior to entry, but the probability of entry may increase.

[55]For example, if $\rho = 0.99$ and the standard deviation of marginal cost innovations and entry costs are \$5 and \$1.5 million respectively, the average degree of shading at the beginning of the game is 29%.

we either increase or decrease market size substantially then, because the average attractiveness of entry changes in the same direction, and away from the intermediate values that maximize deterrence incentives, the degree of shading falls.[56]

5.2 Dynamic Limit Pricing with Opaque Network Demand and Endogenous Marginal Costs

We now show that significant limit pricing can also happen in a much richer model that captures some additional features of the airline industry, in particular the fact that flows of connecting passengers through the incumbent's network are likely to be particularly opaque to potential entrants and that marginal costs will depend, endogenously, on a carrier's demand, pricing and capacity investment.[57]

5.2.1 Specification and Baseline Parameterization

On a given route, carriers use their available capacity (seats) to serve two mutually exclusive types of traveler: 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.[58] The incumbent's connecting demand is not observed by the potential entrant, but the profitability of entry can be affected by it in two ways: first, high connecting

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

[57] While we view our focus on capacity investments and connecting traffic as making sense given our sample of dominant incumbent markets, there are likely to be several ways to generalize the exogenous marginal cost model that would also generate significant limit pricing. This model has many additional parameters, and we have not tried to estimate them, partly because of the difficulties of consistently measuring capacity and connecting traffic across routes, which we noted in footnote 37, and neither have we tried to calibrate them to the observed price declines. We view our results as illustrating that one can generate significant limit pricing in a model with a richer cost structure, with the development of econometric methods to estimate the model left as a topic for future research.

[58] 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 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 tend to affect an incumbent's connecting demand too much.

demand will tend to increase the incumbent's marginal cost for serving local traffic given a particular level of capacity; and, second, the connecting demand of the two carriers can be positively correlated. This provides the incumbent with an incentive to signal that its connecting demand is low. 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.[59] We are interested in how local prices may change when entry is threatened.

Local Demand. We assume that local demand has exactly the same form, with the same parameters, as in Section 5.1.

Non-Local (Connecting) Demand. We assume that, whether entry has occurred or not, the incumbent faces non-local demand of

$$q_{I,t}^{NL}(p_{I,t}^{NL}, \theta_{I,t}^{NL}) = \theta_{I,t}^{NL} \frac{\exp(\beta_I^{NL} - \alpha^{NL} p_{I,t}^{NL})}{1 + \exp(\beta_I^{NL} - \alpha^{NL} p_{I,t}^{NL})} \tag{8}$$

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

$$\theta_{I,t}^{NL} = \rho^{NL} \theta_{I,t-1}^{NL} + (1 - \rho^{NL}) \frac{\underline{\theta_I^{NL}} + \overline{\theta_I^{NL}}}{2} + \varepsilon_t \tag{9}$$

where the normal distribution of ε_t is truncated to keep the parameter on the support. As a baseline, we assume that $\beta_I^{NL} = 0.33$ (the same as for local demand), $\underline{\theta_I^{NL}} = 100,000$, $\overline{\theta_I^{NL}} = 300,000$[60], $\rho^{NL} = 0.9$[61] and the standard deviation of ε is 15,000. $\alpha^{NL} = 0.006$ (for a price in dollars), which is 50% larger than its value for local demand. We assume that, if it enters, the

[59] In practice, there are many connections that use a particular segment, so there would potentially be hundreds or thousands of connecting prices that the potential entrant would have to track. All of these prices would be affected by competition and operational considerations on other parts of the network. Therefore, it seems reasonable to treat connecting prices as providing a potential entrant with little easy-to-use information about demand on a particular segment.

[60] Recall the market size for local traffic is just under 60,000.

[61] 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.

entrant will have non-local demand

$$q_{E,t}^{NL}(p_{E,t}^{NL},\theta_{E,t}^{NL}) = (\theta_E^{NL}+\tau\theta_{I,t}^{NL})\frac{\exp(\beta_E^{NL}-\alpha^{NL}p_{E,t}^{NL})}{1+\exp(\beta_E^{NL}-\alpha^{NL}p_{E,t}^{NL})} \tag{10}$$

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 $\theta_{I,t}^{NL}$.[62] $\beta_E^{NL} = 0.30$ (once again, the same as for local demand).

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

$$C_j(q_{j,t}^L, q_{j,t}^{NL}, K_{j,t}) = \gamma_j^K K_{j,t} + \gamma_{j,1}^L q_{j,t}^L + \gamma_{j,1}^{NL} q_{j,t}^{NL} + \gamma_{j,2}\left(\frac{q_{j,t}^{NL}+q_{j,t}^L}{K_{j,t}}\right)^{\upsilon}(q_{j,t}^L+q_{j,t}^{NL}) \tag{11}$$

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 fall tend to fall as well. In the baseline, $\gamma_{I,1}^L = 45$, $\gamma_{I,1}^{NL} = \gamma_{E,1}^L = \gamma_{E,1}^{NL} = 0, \gamma_{j,2} = 100$ 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 in both marginal and capacity costs, and, as in the simpler model, this 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,

$$C_{I,t}^A(K_{I,t},K_{I,t+1}) = \zeta(K_{I,t+1}-K_{I,t})^2 + \mathcal{I}(K_{I,t+1}\neq K_{I,t})\times\eta_{I,t} \tag{12}$$

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.

Entry Costs. In our baseline parameterization, the entry cost distribution is a truncated normal with mean \$50 million and standard deviation \$9 million (truncated below at \$0).

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

Timing. As before, 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 by solving games where $T = 100$. However, we have checked that we can generate very similar amounts of shading, and more shading in some examples, with a discount factor of 0.98, which we assumed in the earlier simulations, by adjusting the entry cost distribution.[63,64]

5.2.2 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. Appendix B explains how the model is solved for a given set of parameters. For this richer model there is no simple static condition that ensures

[63] For example, with $T = 100$ optimal incumbent capacity choices in the first and second periods of the game differ by less than one-thousandth of a seat in all states in a game where entry is blockaded, and by less than two-thousandths of a seat in the game with an entry threat.

[64] When the entrant is more patient, he is more willing to enter the market. On the other hand, a more patient incumbent is also more willing to sacrifice short-run profits to deter entry. These factors interact to determine how much entry costs have to be increased with the discount factor to maintain the same average degree of shading.

that there will be a unique signaling equilibrium under refinement, but the Appendix explains how we numerically verify the required conditions for existence and uniqueness in every period when solving the model recursively.

Several features of this model are worth mentioning. 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 $K_{I,t}$ 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 build up its capacity as another way of trying to deter entry, or it could choose to reduce its capacity, in order to commit to higher prices, if it expects entry to occur.[65] 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.

5.2.3 Simulation Results

To quantify the model's predictions for price and capacity changes when the entry threat emerges, we first solve for optimal capacity choices in a $T = 100$ game where entry is blockaded (so the incumbent acts as an unchallenged monopolist when choosing prices and capacity), and also in the game where there is an entry threat. Next, we use strategies in the initial period ($t = 1$) of the blockaded game to simulate 100 paths for capacities and $\theta_{I,t}^{NL}$ for 500 periods. The final states for these paths are then used as starting points for a set of simulations using $t = 1$ strategies from the game where the entry threat is present. In this way, we can see how prices and capacities change when the entry threat is introduced, assuming that it arrives as an unanticipated shock.

Our main result is that for our baseline parameters, we find significant limit pricing. In the first period, when the entry threat is introduced (so no entry has yet taken place) prices fall by

[65] Both strategies would require capacity adjustment costs to be large enough to imply some form of commitment to a pre-entry capacity level. 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.

12.7% on average, from \$558 to \$487. Across our 100 simulations, the smallest fall is 5%, and the largest 17%.[66] At the same time, capacities remain close to unchanged, consistent with our empirical results in Table 4: across simulations, the incumbent responds to the entry threat by reducing its capacity by 0.4% on average.[67] As there is an increase in demand when the local price falls, the incumbent's load factor increases (by 1.2%). In simulations where entry does not occur, the size of the price reductions (relative to the pre-entry threat period) tends to grow because of selection, a pattern noted in our discussion of our reduced-form results. For example, after 10 periods, the average decline is 14.6%, rather than 12.7%, whereas, even with selection (so that carriers with falling connecting demand will attract less entry), capacity is still very similar to what it was before the entry threat, falling by 0.7% on average.

We have also investigated what happens when we perturb some of the parameters of our model in order to understand what is most important for limit pricing. One change is to remove the correlation in the carriers' connecting demand, so that limit pricing is only signaling information on the incumbent's likely marginal costs post-entry, not the entrant's likely connecting demand.[68] In this case, prices fall by 6.4% on average when the entry threat is introduced, so that there is still quantitatively significant limit pricing. On the other hand, we can find larger price cuts, as high as 20% in some examples, when τ is increased.

A second change is to reduce the level of capacity adjustment costs. Adjustment costs can affect incentives to signal, because, without them, the potential entrant knows that the incumbent is likely to respond almost immediately to entry by adjusting its capacity, so that the post-entry marginal cost in the market for local traffic, where the carriers compete, may be unaffected by the incumbent's connecting demand. As an example, we reduced the convex component of the adjustment cost from 0.25 to 0.01 (reducing this component of the cost of a 1,000 seat change from \$250,000 to \$10,000). This change only reduces the amount of limit pricing slightly, so that on average prices fall by 12.5%, rather than 12.7%, when the entry threat is introduced. This change in parameters also has little effect on how the entry threat affects capacity investment

[66] Because we are starting in what is approximately a steady-state set of states, local prices would not, on average, change without the entry threat. The average *absolute* price change would be \$8 (1.4%) which is also smaller than the average changes that we see when limit pricing is introduced.

[67] This statistic is based on capacity choices which would be chosen in the first period of the entry threat if no entry had taken place. In this way we deal with the problem that there is entry in a selected set of the simulations.

[68] We do this by setting $\tau = 0$ and $\theta_E^{NL} = 66,667$, so that, on average, the entrant has the same connecting demand as it does in our base parameterization.

on average (on average, capacity falls by 0.2%), although, because adjustments costs are lower, capacity increases or decreases significantly in some simulations (by as much as 9.5% of previous capacity in one case).

We have also identified other sets of parameters where the model can generate even larger limit pricing effects. For example, if we change the mean and standard deviation of the entry cost distribution to \$60 million and \$3 million respectively (a standard deviation that is closer to that considered in the simple model), prices fall by an average of 20.8% when the entry threat is introduced and, once again, capacity changes only slightly (falling by 0.4%). The larger price decline reflects the fact that a fall in the standard deviation of entry costs makes the entry decision more sensitive to the incumbent's beliefs about $\theta_{I,t}^{NL}$. Alternatively, if we increase the assumed serial correlation parameter for $\theta_{I,t}^{NL}$ (ρ^{NL}) to 0.97 (from 0.9) and reduce the standard deviation of the innovations to 5,000 (from 15,000), the size of the average price decline increases to 15%, with, once again, incumbent capacity changing very little on average (falling by 0.4%).

6 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. 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. While we do make some restrictive assumptions (for example, that there is one firm with a single piece of private information), these assumptions allow us to extend one of the most widely-cited and important two-period entry deterrence models in the literature (Milgrom and Roberts (1982)) to allow for both dynamics and a rich, endogenous cost structure that is likely to reflect the cost structure of most industries that have dominant incumbents.

We exploit tractability to study whether our model of dynamic limit pricing can explain why incumbent carriers cut prices when Southwest becomes a potential entrant on a particular airline route. This is a natural setting to study, given that it provides the largest documented effect of potential competition on prices. 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. We also show that parameterized versions of our model can generate large price declines, including when we extend our model to allow for connecting demand, capacity investment and endogenous marginal costs. We believe that the evidence in favor of a limit pricing explanation is particularly strong when we consider the quarters when entry is first threatened, before the incumbent will have time to make operational changes that may help it to lower the probability of entry in the long-run if it can be deterred initially.

While we have explored one type of asymmetric information model and one application, we believe that our approach could be used to explore other empirical settings where asymmetric information models may explain 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). Readers should consult Gedge, Roberts, and Sweeting (2014) for a version of the proof assuming that the marginal cost of the entrant is time-varying but observed, which is the model solved in Section 5. It is essentially identical to the current proof with additional notation.

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 $c_{I,t}$. 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 point beliefs we will denote the believed value as $\widehat{c}_{I,t}$. If E does not have a point belief, we will denote their density as $q(\widetilde{c_{I,t}})$ and assume that only values on the interval $[\underline{c_I}, \overline{c_I}]$ can have positive density.

A.2 Useful Lemmas

We will make frequent use of several results:

Lemma 1 *Suppose that $f(x)$ 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.

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

$\blacksquare$

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 $\left[\underline{c_I}, \overline{c_I}\right]$. $\blacksquare$

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

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

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

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

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

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

$\Pi_{13}^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) \neq 0$ 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

$$\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) = -\beta g(\kappa_t^*(\widehat{c}_{I,t}))\frac{\partial \kappa_t^*(\widehat{c_{I,t}})}{\partial \widehat{c}_{I,t}} \left\{\mathbb{E}_t[V_{t+1}^I | c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I | c_{I,t}]\right\} \tag{14}$$

$\Pi_2^{I,t}(c_{I,t}, \widehat{c}_{I,t}, p_{I,t}) \neq 0$ 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 (13) and (14) 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

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

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 $\mathrm{I1}^{t+1}$ 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 $\mathrm{I3}^{t+1}$ 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): $\Pi_2^{I,t}(c_{I,t}, \kappa_t, p_{I,t}) = -\beta g(\kappa_t)\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\}$. This will not be equal to zero if $g(\cdot) > 0$ (true given Assumption 2 and the condition that an equilibrium level of κ_t' will satisfy $\underline{\kappa} < \kappa_t' < \overline{\kappa}$), and $\left\{\mathbb{E}_t[V_{t+1}^I|c_{I,t}] - \mathbb{E}_t[\phi_{t+1}^I|c_{I,t}]\right\} > 0$ (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. $\phi_t^E(c_{I,t}) > V_t^E(c_{I,t})$; and

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

$$\phi_t^E(c_{I,t}) = \pi_E^D(c_{I,t}) + \beta \int_{\underline{c_I}}^{\overline{c_I}} \phi_{t+1}^E(c_{I,t+1})\psi_I(c_{I,t+1}|c_{I,t})dc_{I,t+1} \tag{15}$$

$$\begin{aligned} V_t^E(c_{I,t}) = & \int_0^{\kappa^*(c_{I,t})} \int_{\underline{c_I}}^{\overline{c_I}} \left\{ \beta\phi_{t+1}^E(c_{I,t+1})\psi_I(c_{I,t+1}|c_{I,t}) - \kappa \right\} g(\kappa) dc_{I,t+1} d\kappa + ... \\ & \int_{\kappa^*(c_{I,t})}^{\overline{\kappa}} \int_{\underline{c_I}}^{\overline{c_I}} \beta V_{t+1}^E(c_{I,t+1})\psi_I(c_{I,t+1}|c_{I,t}) g(\kappa) dc_{I,t+1} d\kappa \end{aligned} \tag{16}$$

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 (15) and (16) 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 (15) and (16) 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

$\phi_{t+1}^E(c_{I,t+1}) > V_{t+1}^E(c_{I,t+1})$, (16) 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

$$\frac{\partial[\phi_t^E(c_{I,t})]}{\partial c_{I,t}} - \frac{\partial[V_t^E(c_{I,t})]}{\partial c_{I,t}} = \frac{\partial \pi_E^D(c_{I,t})}{\partial c_{I,t}} + ...$$

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

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:

$$V_t^I(c_{I,t}) = \max_{p_{I,t}} q^M(p_{I,t})(p_{I,t} - c_{I,t}) + ... \tag{17}$$

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

$$\phi_t^I(c_{I,t}) = \pi_I^D(c_{I,t}) + \beta\mathbb{E}_t[\phi_{t+1}^I|c_{I,t}] \tag{18}$$

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 (17) and (18), 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

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

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,

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

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

$\phi_T^E(c_{I,T}) > V_T^E(c_{I,T})$, $V_T^I(c_{I,T}) > \phi_T^I(c_{I,T})$, $\frac{\partial \phi_T^E}{\partial c_{I,T}} > \frac{\partial V_T^E}{\partial c_{I,T}} = 0$, $\frac{\partial V_T^I(c_{I,T})}{\partial c_{I,T}} < \frac{\partial \phi_T^I(c_{I,T})}{\partial c_{I,T}} < 0$.[69]

69 $\frac{\partial V_T^I(c_{I,T})}{\partial c_{I,T}} - \frac{\partial \phi_T^I(c_{I,T})}{\partial c_{I,T}} = q_I^D(c_{I,T}) - q^M(p^{\text{static monopoly}}(c_{I,T})) - \frac{\partial \pi_I^D}{\partial a_E^D}\frac{\partial a_E^{*D}}{\partial c_{I,T}} < 0$ by Assumption 4.

B Solution Method for the Dynamic Limit Pricing Model with Capacity Adjustment

In this Appendix we provide a step-by-step guide to how we solve the dynamic model with connecting traffic and capacity choices. At the end of the description, we note how the method is simplified when we treat marginal costs as being constant and evolving exogenously.

B.1 Preliminaries

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 5, we use a 60-point grid for $\theta_I^{NL} \in [100,000, 300,000]$, a 50-point grid for $K_I \in [8,000, 58,000]$, and a 48-point grid for $K_E \in [4,000, 52,000]$. In addition, we specify a 300-point grid for the incumbent's local price (p_I^L) which runs from \$200 below the lowest monopoly price for local traffic (i.e., the monopoly price with maximum capacity and least connecting traffic) to 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.[70] The second condition can be confirmed analytically as, holding prices and capacity fixed, marginal costs increase in θ_I^{NL}.

[70] 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.

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.

B.2 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.

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

B.3 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, $K_{I,t+1}^*(\theta_{I,t}^{NL}, K_{I,t})$, of a monopolist incumbent that decides to change its capacity. For each $(\theta_{I,t}^{NL}, K_{I,t})$ 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.

$$CV_I(K_{I,t+1}|\theta_{I,t}^{NL}, K_{I,t}) = \beta \int_{\underline{\theta_I^{NL}}}^{\overline{\theta_I^{NL}}} V_{t+1}^I(\theta_{I,t+1}^{NL}, K_{I,t+1})\psi(\theta_{I,t+1}^{NL}|\theta_{I,t}^{NL})d\theta_{I,t+1}^{NL} - \zeta(K_{I,t+1} - K_{I,t})^2$$

where the integration is performed using the trapezium rule. We then find $K_{I,t+1}^*(\theta_{I,t}^{NL}, K_{I,t})$ 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 $K_{I,t+1}^*(\theta_{I,t}^{NL}, K_{I,t})$

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

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

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 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.[71] 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.[72] 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. The signaling payoff function is

$$\begin{aligned}\Pi^{I,t}(\theta^{NL}_{I,t}, \widehat{\theta^{NL}_{I,t}}, p^L_{I,t}, K_{I,t}) = {} & \pi^M_I(p^L_{I,t}, p^{*NL}_I(p^L_{I,t}), \theta^{NL}_{I,t}, K_{I,t}) + ... \\ & (1 - G(\kappa^*_t(\widehat{\theta^{NL}_{I,t}}, K_{I,t}))V^I_{int-t}(\theta^{NL}_{I,t}, K_{I,t}) + ... \\ & G(\kappa^*_t(\widehat{\theta^{NL}_{I,t}}, K_{I,t}))\phi^I_{int-t}(\theta^{NL}_{I,t}, K_{I,t}, 0)\end{aligned}$$

[71] 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.

[72] 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.

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 (which they do for our chosen parameters), 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 `ode113` 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.

B.4 Simplifications for the Simpler Model with Constant and Exogenous Marginal Costs

When marginal costs evolve exogenously and there is no connecting traffic and capacity investment, solving the model only involves a subset of the steps above. Before solving the dynamic model we specify a 100-point grid for c_I and c_E, and for each of the cost combinations, we solve for each firm's single-period profits in the specified complete information duopoly stage game that follows entry and the incumbent's profits when it prices as a static monopolist. We specify a 1,000-point price grid on which we compute $\frac{\partial \pi_I^M(p_I, c_I)}{\partial p_I} = q^M(p_I) + \frac{\partial q^M(p_I)}{\partial p_I}(p_I - c_I)$ at each of the 1,000 prices for each level of 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 at all points in the cost grid. With these values computed, we solve the dynamic game.

Step 1. Consider period T. Calculate the incumbent's static monopoly profits for each discretized value of c_I (in this period it does not face the threat of entry and so it prices as a static monopolist). The incumbent's static monopoly and duopoly profits define V_T^I and ϕ_T^I for each value on the grid. For the potential entrant $V_T^E = 0$ and ϕ_T^E is the static duopoly profit.

Step 2. Consider period $T-1$.

(a) For a given value of $c_{E,T-1}$, use the assumed form of the transition processes for marginal costs to calculate the value of $\mathbb{E}_{T-1}[\phi_T^E | c_{I,T-1}, c_{E,T-1}]$ for each value of $c_{I,T-1}$.

As $\mathbb{E}_{T-1}[V_T^E | c_{I,T-1}, c_{E,T-1}] = 0$ and $\kappa_{T-1}^*(c_{I,T-1}, c_{E,T-1}) = \beta \mathbb{E}_{T-1}[\phi_T^E | c_{I,T-1}, c_{E,T-1}]$, we compute $g(\kappa^*_{T-1})$ and $\frac{\partial \kappa^*_{T-1}(c_{I,T-1}, c_{E,T-1})}{\partial c_{I,T-1}}$ for each of these values.

(b) We solve for the pricing strategy of the incumbent as a function of its marginal cost, by solving the differential equation starting from the boundary solution that the firm with the highest marginal cost sets the static monopoly price

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

This is done using `ode113` in MATLAB. As we solve the differential equation we interpolate, using cubic splines, the values of $g(\kappa^*_{T-1})$, $\frac{\partial \kappa^*_{T-1}(c_{I,T-1}, c_{E,T-1})}{\partial c_{I,t}}$, $\{\mathbb{E}_{T-1}[V^I_T | c_{I,T-1}, c_{E,T-1}] - \mathbb{E}_{T-1}[\phi^I_T | c_{I,T-1}, c_{E,T-1}]\}$ and $\frac{\partial \pi^M_I(p_{I,T-1}, c_{I,T-1})}{\partial p_{I,T-1}}$ from the relevant grid points.

(c) Given the entry and pricing strategies we can calculate $V^j_{T-1}(c_{I,T-1}, c_{E,T-1})$ and $\phi^j_{T-1}(c_{I,T-1}, c_{E,T-1})$ for both firms (i.e., the values of each firm as a monopolist/potential entrant/duopolist) as appropriate given the cost state.

Step 3. Consider period $T-2$. Here we proceed using the same steps as in Step 2, except that $\kappa^*_{T-2}(c_{I,T-2}, c_{E,T-2}) = \beta\{\mathbb{E}_{T-2}[\phi^E_{T-1} | c_{I,T-2}, c_{E,T-2}] - \mathbb{E}_{T-2}[V^E_{T-1} | c_{I,T-2}, c_{E,T-2}]\}$.

Step 4. Repeat Step 3 for all previous periods.

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, San Jose-Orange County(*), St. Louis-Tampa

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

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

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

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

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

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

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.[73] 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 F 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.

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

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

where o is the origin airport, d is the destination airport and Q_t are quarter dummies. $\text{Passengers}_{o,d,t}$ is the number of DB1 passengers with itineraries in either direction on the route, independent of whether they use direct or connecting service.[74] 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.

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

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

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

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

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

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

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

E Reduced-Form Results for the Distribution of Prices

Tables E.1-E.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 E.4 shows the results for the percentiles of the yield distribution.

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

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

Notes: Estimates of specification (5) when dependent variable is log of the 25th percentile passenger-weighted fare ("Fare") or this fare divided by the non-stop route distance ("Yield"). The adjusted R^2s are 0.75 ("Fare") and 0.78 ("Yield"). Other notes from Table 3 apply here.

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

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

Notes: Estimates of specification (5) when dependent variable is log of the median passenger-weighted fare ("Fare") or this fare divided by the non-stop route distance ("Yield"). The adjusted R^2s are 0.73 ("Fare") and 0.82 ("Yield"). Other notes from Table 3 apply here.

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

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

Notes: Estimates of specification (5) 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 0.81 ("Fare") and 0.84 ("Yield"). Other notes from Table 3 apply here.

Table E.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
$SWPE_{m,t}$	0.0255	0.0439	-0.0023
	(0.0283)	(0.0375)	(0.0501)
$\widehat{\rho_m} \times SWPE_{m,t}$	-0.676**	-0.954***	-0.939**
	(0.259)	(0.329)	(0.359)
$\widehat{\rho_m}^2 \times SWPE_{m,t}$	0.835***	1.157***	1.212**
	(0.316)	(0.428)	(0.500)
Observations	3,622	3,622	3,622

Notes: Notes from Table 4 apply here.

F Evidence of Dynamic Demand

As explained in Section 4, one interpretation of why incumbents cut prices when entry is threatened is that these price cuts may increase consumer loyalty. This might help the incumbent to deter entry, by reducing Southwest's expected demand, and/or it might increase the incumbent's expected profits in the duopoly game that follows entry.[75] In this Appendix we provide some econometric evidence against the hypothesis that lower prices significantly raise future demand.

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

[75]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.

of the 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 incumbent sample markets in all periods, including Phase 2, when entry is threatened.

The estimated coefficients are shown in Table F.1, where we increase the number of lagged prices included in columns (2)-(5). In the final column we only include the lagged price from the same quarter in the previous year, as there might be some travelers who tend to make trips in particular seasons. The F-statistics in the first-stage regressions (not reported) are all greater than 50. We observe that none of the coefficients on the lagged prices are statistically significant and that they vary in sign (eight are positive (i.e., the 'wrong sign'), and three are negative). In each specification the coefficient on the current price is statistically significant at conventional significance levels. Table F.2 repeats the analysis just using data from phases 1 and 3, so that the estimates are more consistent with those in Appendix I.1 (where observations for Southwest are also included). Once again, none of the lagged coefficients are statistically significant.

One might argue that, because of the size of the standard errors, we cannot rule that the true lagged coefficients are negative and 'large enough' to justify reductions in current prices, although, of course, one would need to argue that in addition these price cuts are only profitable when entry is threatened to explain why prices fall in Phase 2 in the data. For this reason, we should point out that there seem to us to be at least two other problems with the customer loyalty story. First, it is not obvious that the types of customers, typically business travelers, that are likely to be heavily invested in frequent-flyer programs are either numerous enough or have demand that is elastic enough to be able to rationalize why a carrier would want to cut all of its prices when most of the discounts would likely go to other travelers. It would surely be more profitable to offer frequent-flyers more direct and targeted benefits such as awarding them with additional miles when they take flights, a kind of discount that would not show up in our price data. Second, it is not clear that, given its commitment to charge relatively low maximum prices, that Southwest's entry strategy would be so sensitive to whether the incumbent had been able to 'lock-up' the demand of business travelers to whom the incumbent traditionally charges high prices.

Table F.1: Nested Logit Demand Estimates for the Incumbent with Lagged Prices: All Phases

	(1)	(2)	(3)	(4)	(5)	(6)
Fare ($100s)	-0.355***	-0.222*	-0.275**	-0.294**	-0.476***	-0.354***
	(0.0398)	(0.119)	(0.132)	(0.126)	(0.114)	(0.0573)
Inside Share	0.687***	0.726***	0.739***	0.692***	0.809***	0.747***
	(0.0939)	(0.0974)	(0.102)	(0.105)	(0.108)	(0.104)
Fare_{t-1}		-0.0994	-0.0419	0.0126	0.185	
		(0.109)	(0.197)	(0.199)	(0.185)	
Fare_{t-2}			0.0246	0.0194	-0.0930	
			(0.105)	(0.184)	(0.190)	
Fare_{t-3}				0.0120	0.0818	
				(0.0960)	(0.193)	
Fare_{t-4}					0.0316	0.0516
					(0.120)	(0.0422)
Observations	5,309	5,071	4,864	4,680	4,515	4,688

Notes: Specification also includes 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. Robust standard errors in parentheses. ***,** ,* denote statistical significance at the 1, 5 and 10% levels respectively.

Table F.2: Nested Logit Demand Estimates for the Incumbent with Lagged Prices: Phases 1 and 3

	(1)	(2)	(3)	(4)	(5)	(6)
Fare ($100s)	-0.402***	-0.225*	-0.248*	-0.276**	-0.408***	-0.342***
	(0.0426)	(0.122)	(0.129)	(0.116)	(0.114)	(0.0613)
Inside Share	0.602***	0.628***	0.615***	0.546***	0.621***	0.568***
	(0.0992)	(0.104)	(0.108)	(0.112)	(0.116)	(0.111)
Fare_{t-1}		-0.126	-0.129	-0.0546	0.0778	
		(0.112)	(0.195)	(0.189)	(0.179)	
Fare_{t-2}			0.0709	0.0907	-0.0121	
			(0.112)	(0.187)	(0.191)	
Fare_{t-3}				-0.00656	0.0599	
				(0.0966)	(0.197)	
Fare_{t-4}					0.0430	0.0563
					(0.126)	(0.0464)
Observatons	3,922	3,706	3,515	3,341	3,203	3,352

Notes: Same as Appendix Table F.1.

G 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 1,872 markets to predict the probability of entry by Southwest at the route-level. There is one observation per market, and the dependent variable (Entry$4_{m,t}$) is equal to 1 if Southwest enters market m within four quarters of becoming a potential entrant at time t (recall that Southwest becomes a potential entrant when it has operations at both endpoints).

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

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: our estimated market size based on our gravity model described in Appendix D (also Market Size^2). The size is measured in the quarter when Southwest becomes a potential entrant;
- Slot: a dummy that is equal to 1 if either endpoint 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 HHI, based on passenger numbers, for the route in the quarter that Southwest became a potential entrant.

For each of the endpoints separately, we also include:

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

The results are reported in Table G.1.

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

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

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

H 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 EE first-stage probit (see Appendix G). For each market, we first calculate the mean of the variable across Phase 1 observations (i.e., before Southwest is a potential entrant), 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. In other cases, for example, average endpoint population, 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.

Table H.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	0.200	0.457	0.861	0.022**	0.000***	0.000***
Southwest (dummy)	(0.406)	(0.505)	(0.351)			
Incumbent is a legacy	0.914	0.771	0.889	0.035**	0.192	0.191
carrier (dummy)	(0.284)	(0.426)	(0.318)			
Non-stop Distance	1,745.9	1,139.3	879.7	0.001***	0.083*	0.000***
(roundtrip)	(743.3)	(730.2)	(481.3)			
Market Size	2,408.4	3,458.1	7,707.5	0.035**	0.000***	0.000***
	(1,559.5)	(2,413.6)	(4,987.6)			
Average endpoint	2,793,204	2,466,516	3,279,128	0.441	0.084*	0.213
city population	(1,729,275)	(1,797,930)	(2,093,279)			
One or both endpoint airport is hub	0.829	0.600	0.583	0.480	0.888	0.051*
for dominant incumbent	(0.382)	(0.497)	(0.500)			
One or both endpoint cities is	0.486	0.571	0.694	0.401	0.289	0.203
multi-airport market	(0.507)	(0.502)	(0.467)			
One or both endpoints is a	0.057	0.057	0.222	1.000	0.046**	0.039**
leisure destination	(0.236)	(0.236)	(0.421)			
Phase 1 route HHI	0.792	0.904	0.944	0.001***	0.127	0.000***
	(0.138)	(0.128)	(0.097)			
Phase 1 proportion of traffic	0.848	0.845	0.817	0.906	0.348	0.562
making connections	(0.112)	(0.098)	(0.141)			
Phase 1 load factor	0.661	0.583	0.591	0.003***	0.743	0.002***
	(0.097)	(0.107)	(0.093)			
Direct Fare ($)	526.59	450.09	433.84	0.022**	0.594	0.008***
	(147.00)	(136.63)	(117.80)			
Number of markets	35	35	36			

Notes: The left-hand columns report the mean of the variable during Phase 1 (before Southwest is a potential entrant) 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). *,**,*** denote statistical significance at the 10%, 5% and 1% levels respectively. 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.

I Demand and Cost Parameters for the Dynamic Limit Pricing Model

In this Appendix we describe how we estimate/choose the parameters that we use in Section 5, to illustrate the outcomes of the simple, exogenous marginal cost version of the model. We make use of many of the parameters in the extended version of the model where marginal costs are an endogenous function of the firms' capacity choices.

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.[76] Markets are non-directional, and we use our gravity model-based definition of market size (Appendix D), with travel on carriers other than the dominant incumbent and Southwest included in the outside good.[77] We do, however, control for the number of other carriers that fly any passengers non-stop in our specification of utility.

Viewing each carrier in the market as offering a single product, we assume the standard nested logit indirect utility specification with a single '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

[76] 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.

[77] 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.

or is a leisure destination) and a set of dummies for the number of other firms serving the market non-stop.

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

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

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.[78] 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[79], 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 the model using $\widehat{\alpha} = -0.408$ and $\widehat{\lambda} = 0.762$, and assume a market size of 58,777, which is the mean size (during Phase 2) of the 65 markets for which we have Phase 2 observations. We set θ_j equal to 0.33 and 0.30 for the incumbent and potential entrant respectively and fix the $\xi_{j,t}$s to be equal to zero so that, ignoring price, carrier quality does not vary over time. The choice of θ for the incumbent matches the average value implied by the estimates for incumbent carriers in Phase 3, while the value for the potential entrant allows us to match the average difference in incumbent and Southwest qualities in Phase 3 estimated using a route-quarter fixed effects regression (not reported).

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

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

I.2 Marginal Costs

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

To estimate the ρ^{AR} and the average difference in marginal costs, we use the 2SLS demand estimates and back out the marginal cost for each carrier-route-quarter observation assuming that pricing in Phases 1 and 3 is characterized by the standard static monopoly/Bertrand Nash first-order conditions (recall that Phase 2 observations, where the incumbent may be limit pricing, are not used for estimation). To make comparisons across routes, we transform these marginal costs to \$s-per-mile of the non-stop route. The median and mean marginal costs calculated in this way are \$0.13/mile and \$0.16/mile. A route-quarter fixed effects regression using observations from Phase 3 (not reported) indicates that, on average, Southwest's marginal cost was \$0.055/mile lower than the incumbent's (difference significant at the 1% level).[80]

We estimate ρ^{AR} by regressing the implied per-mile marginal costs on the one-period lagged value, controlling for observed route characteristics (such as distance, market size and the presence of slot constraints at either endpoint), carrier dummies, a full set of quarter dummies and, as a measure of a component of costs that is presumably observed by carriers, the one-quarter lagged jet fuel price interacted with route distance. Column (1) of Table I.2 shows the estimates when we pool observations for all carriers. As the implied marginal costs are likely to be measured with error (partly because market shares and average prices are based on the limited sample of passengers included in the DB1 data), in column (2) we instrument for the lagged marginal cost with the third through fifth lags of marginal cost. The estimated persistence of marginal costs increases significantly. In the third and fourth columns, we provide 2SLS estimates for the

[80] The average total operating cost per available seat mile (CASM) reported by legacy carriers in 2010 (Dept. of Transportation Form 41, as reported by the MIT Airline Data project, http://web.mit.edu/airlinedata/www/default.html) was \$0.148. Between 1995 and 2010, the average difference in reported CASMs between legacy carriers and Southwest was \$0.037. An alternative measure, operating costs per equivalent seat mile (CESM), which adjusts for the fact that different airlines fly routes of different lengths, as we are doing when we include route fixed effects, gives an average difference of \$0.061. Therefore, while none of these statistics are trying to measure what economists would define as marginal costs, they provide some evidence that both the level of our marginal cost estimates and the estimated difference between the marginal costs of legacy carriers and Southwest have roughly the correct magnitude.

incumbent carriers and Southwest separately. In both cases $\widehat{\rho^{AR}} \approx 0.97$ and we use this value in the calibration. We set σ_{ε}, the standard deviation of innovations to marginal cost for our representative 1,200 mile route, equal to \$36.[81]

In our parameterization, we consider a market with a round-trip distance of 1,200 miles, close to the median for the dominant incumbent markets. Examples in our sample that are close to this length include Los Angeles-Salt Lake City and Minneapolis-Tulsa, and this distance implies an average marginal cost advantage for Southwest of close to \$70. We choose supports of $[\underline{c_I}, \overline{c_I}] = [\$160, \$280]$ and $[\underline{c_E}, \overline{c_E}] = [\$90, \$210]$. The width of these supports is chosen so that our assumption that $q_I^D(c_{I,t}, c_{E,t}) - q^M(p_I^{\text{static monopoly}}(c_{I,t})) - \frac{\partial \pi_I^D(c_{I,t}, c_{E,t})}{\partial a_{E,t}} \frac{\partial a_{E,t}^*}{\partial c_{I,t}} < 0$, which is the key sufficient condition for existence and uniqueness of the equilibrium we are looking at, holds for all possible costs.

I.3 Entry Costs

In our baseline specification we assume that E's entry costs are drawn from a truncated normal (support of $[\$0, \$100 \text{ million}]$) where the untruncated distribution has a mean of \$55.4 million and a standard deviation of \$2 million. The mean and standard deviation parameters were selected, based on a coarse grid search, so that the average degree to which the incumbent shades prices below the static monopoly price when strategies are approximately stationary at the start of the game is similar to the size of the price cuts observed in markets with intermediate probabilities of entry when Southwest becomes a potential entrant. As noted in the text, we still get quantitatively significant limit pricing if we consider much lower mean entry costs.

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

Table I.1: Nested Logit Demand Estimates

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

Notes: Specification also includes a linear time trend, quarter of year dummies, market characteristics (distance, distance^2, indicators for whether the route includes a leisure destination or is in a city with another major airport) and dummies for the number of competitors offering direct service. The instruments used for 2SLS are described in the text. Robust standard errors in parentheses. ***,** ,* denote statistical significance at the 1, 5 and 10% levels respectively.

Table I.2: Marginal Cost Evolution Estimates

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

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